Viaducts in the Etihad Rail Network Abu Dhabi and Dubai, UAE

Viaductos en Red Ferroviaria Etihad. Abu Dabi y Dubái, EAU

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ABSTRACT

The Etihad Rail network is the UAE's national railway system, connecting key trade, industry, and population centers across the country and forming part of the Gulf Cooperation Council (GCC) railway network. This paper describes the design of the main bridges in segments 2B and 2C for the crossing over important highways in the vicinity of Abu Dhabi and Dubai, with relatively long spans and irregular span arrangements. Different typologies were used, such as prestressed concrete box girders, U-trough beams and pergolas. Automation in design, using parametric structural models, was implemented. A few bridges are described in more detail as representative examples.

RESUMEN

La red ferroviaria de Etihad es el sistema ferroviario nacional de los Emiratos Árabes Unidos, y forma parte de la red ferroviaria del Consejo de Cooperación del Golfo (GCC). Este documento describe el diseño de los puentes principales en los segmentos 2B y 2C para el cruce de importantes autopistas en las cercanías de Abu Dabi y Dubái, con vanos relativamente largos y disposiciones de vanos irregulares. Se utilizaron diferentes tipologías, como tableros de hormigón pretensado, secciones en U y pérgolas. Se implementó la automatización en el diseño, utilizando modelos estructurales paramétricos. Se describen en detalle varios puentes como ejemplos representativos.

KEYWORDS: viaducts, prestressed concrete, railway, rail-structure interaction.
PALABRAS CLAVE: viaductos, hormigón pretensado, ferrocarril, interacción vía-estructura.

1. Project Background

The Etihad Rail project is a flagship initiative in the United Arab Emirates (UAE) aimed at establishing the country's first national railway network, connecting the seven emirates and facilitating the transportation of both passengers and freight. The planned network will span approximately 1,200 kilometers, linking ports, industrial hubs, and major urban areas while also integrating with neighboring countries such as Saudi Arabia and Oman, playing a critical role in integrating the UAE with the railway networks of other Gulf Cooperation Council (GCC) countries.

The main objective of the network is to improve connectivity and facilitate trade through an efficient, safe, and sustainable transportation system across the region.

It will run from the Saudi Arabian border at Al Ghuwaifat in the West, via or close to the cities of the Gulf coast, to the Northern Emirates and the East coast. There will also be a line running from Abu Dhabi to Al Ain, with and intended connection into the Sultanate of Oman, as well as an existing branch line to the gas facilities at Shah and Habshan.

The design works described in this paper were undertaken during Stage 2, which extends the Stage 1 railway network to the border with Saudi Arabia as well as to Jebel Ali Port. From Jebel Ali Junction, the network extends north through Dubai and the Northern Emirates to Fujairah Port.

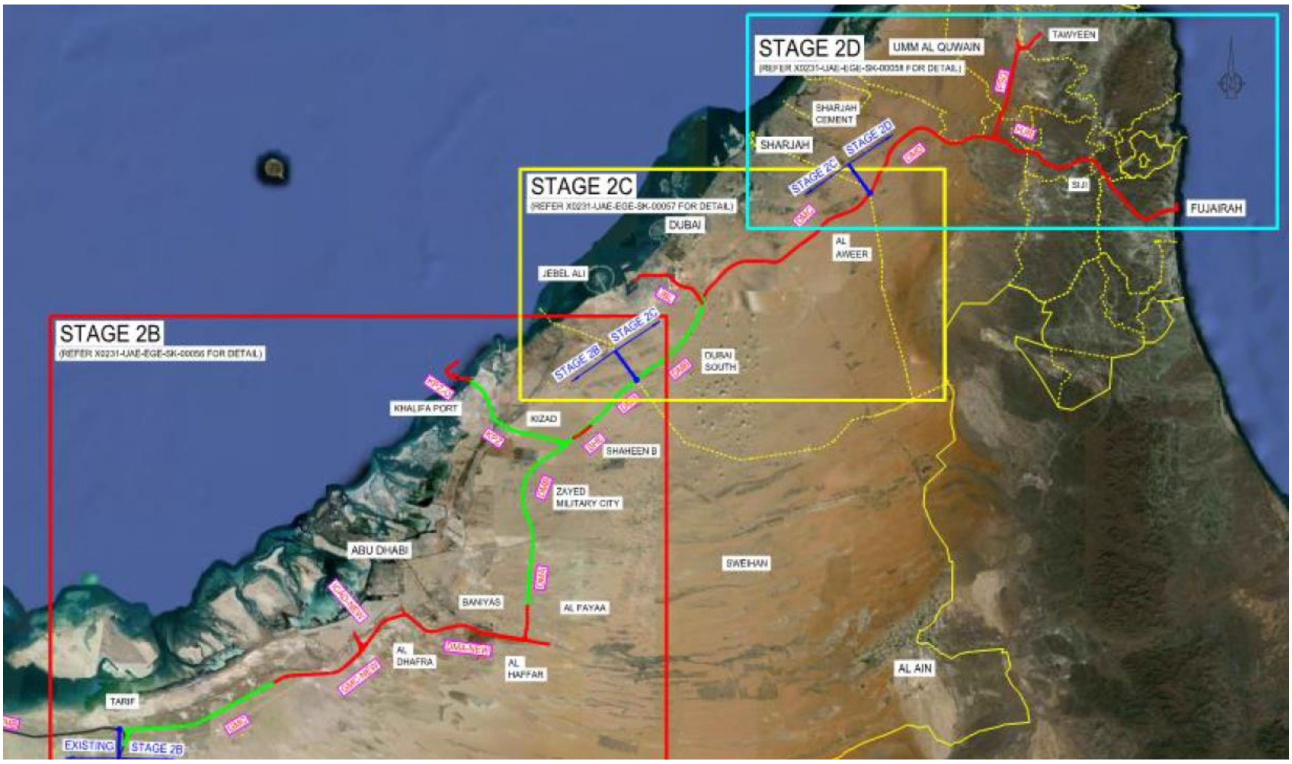


Figure 1. Etihad Rail Network Stages 2B, 2C and 2D.

WSP was appointed by CRCC-GHANTOOT JV (Contractor) as the Designer of Etihad Rail Packages 2B and 2C.

Segments 2B and 2C extend in the vicinity of Dubai and Abu Dhabi, with lengths of 235 and 98 km respectively. These two sections include a large number of bridges, and WSP Spain was responsible for the design of more than 20 of them, ranging from long viaducts with up to 21 spans to smaller structures designed to cross over existing utilities.

The design of the structures made use of a wide variety of technical solutions. Thirteen prestressed concrete box girder structures, five varying depth U-shaped cross-sections girders decks, a pergola with prestressed prefabricated beams and two concrete slabs, were designed, meeting the client's strict technical requirements, agreed at the beginning of the project.

2. Basis of Design

2.1. General approach

CRCC-GHANTOOT JV assigned WSP the responsibility for the design of segments 2B and 2C, adopting a collaborative model of joint design and construction work.

The design was carried out using a "fast track approach", where each bridge was divided into substructure and superstructure packages to facilitate construction and allow the start of the works while the design of the superstructure was still ongoing. In this model, AECOM served as the Independent Checker.

The design basis, which were agreed upon at the beginning of the project with the client (Etihad Rail), established that the bridges had to comply with AASHTO, AREMA, and Eurocodes standards, thus ensuring the safety and functionality of the structures according to international standards. The viaducts that WSP Spain designed were all railway structures, so AASHTO was not applicable to them.

For the structural analysis and design, the calculation software MIDAS CIVIL was used, selected by the final client for its ability to handle complex models and large volumes of data.

Additionally, for the RSI analysis, SOFiSTiK software was used due to its capability in quickly obtaining results when evaluating different solutions, particularly articulation alternatives of long viaducts. Given the significant number of bridges in these sections, parametric modeling was prioritized in both MIDAS and SOFiSTiK. Finally, all the design calculations and reports had to be submitted using MIDAS as required by the client, and in-house spreadsheets.

This methodology not only served to optimize time but also ensured that the proposed solutions were technically aligned with the project requirements.

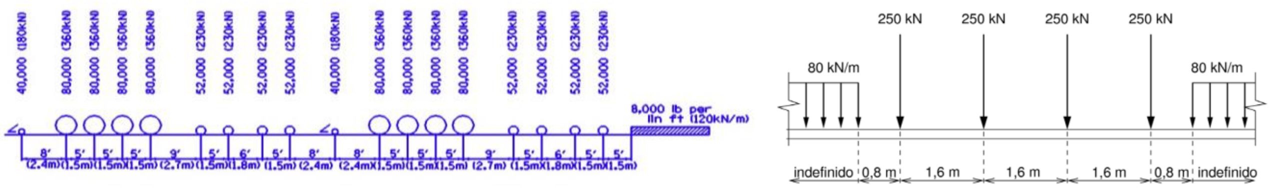
The approval process for the plans and calculations involved several key steps. The initial design was carried out by WSP and reviewed by AECOM, as CAT3 checker. All comments and feedback were reconciled to ensure all concerns were addressed, and the process had to finish with the reviewer sealing the final plans and calculations, which were submitted for approval by JACOBS, which was the Project Management Consultancy, and once approved, given green light for construction.

During construction, optimizations were made, such as the redesign of certain elements to accommodate the contractor´s preferences on site.

2.2. Superstructure design

One of the primary challenges of the project was designing the superstructure of bridges that spanned existing highways while maintaining strict clearance heights. This imposed significant constraints on the selection of superstructure depths, which had to be kept under certain values. In continuous bridges, the necessary unbalanced spans complicated significantly the design of the prestressing.

Although the average slenderness of the bridges, in the vicinity of 1/15, does not seem particularly demanding in general terms, the specific conditions of the project, with higher loads than usual in the mentioned codes, made the design especially challenging.



E80 Cooper train **UIC71 train**

Figure 2. Train loadings

The factors that contributed to this were the following:

1. **E80 Cooper train higher load**: This train loading consists of 18 point loads ranging from 180 to 360 kN, spaced between 1.5 and 2.7 m, resulting in a total load of 5080 kN, along with a distributed load of 120 kN/m. Comparatively, the UIC71 train only consists of 4 point loads of 250 kN spaced 1.6 m apart (1000 kN in total) and a distributed load of 80 kN/m. For the E80

loading, the impact load factor was taken as 1.20 as a minimum for the superstructure, and it was not considered for the substructure. In the case of the UIC71 train loading, the impact load factor was much lower (1.05 approximately), but a classification coefficient of 1.21 was applied additionally. Therefore, on a typical 120 m long structural unit, the E80 represents approximately 50% more load than the UIC71.

2. **Dead load**: The dead load was 167 kN/m for box girder viaducts, approximately 7.5% higher than the one of a similar bridge designed in Spain.
3. **Self-weight:** A 5% increase in the self-weight of the superstructure was considered.
4. **Stress limitations**: The AREMA standard is more stringent when it comes to limit stresses, in comparison with the Eurocodes. In particular, the allowable stress values for compression and tension in initial and service states were significantly more stringent, requiring adjustments in an otherwise typical design to satisfy the requirements, as shown in the following table.

Table 1. Comparison of stresses according to standards

		AREMA	EC
T=0	Compression	0.55*fci	0.6*fci
	Tension	0.25*√fci	$0.3*fci^{2/3}$
T=inf.	Compression	0.4*fck	0.6*fck
	Tension	0	$0.3*fck^{2/3}$

Figure 3. Viaduct with simply-supported spans in Segment 2C.

2.3. Substructure design and seismic requirements

The design of a viaduct's substructure is entirely influenced by its articulation. The distribution of lateral forces depends on how the deck is connected to the piers in both transverse and longitudinal directions.

In general, the fixed points for longitudinal displacements are established for each structural unit of a bridge using an integral pier that is monolithic with the deck. Long viaducts must be split into several structural units for reasons related to the rail-structure interaction analysis, as will be explained later.

In many of the bridges, spans are simply supported, and in this case, the longitudinally fixed point is established by bearings that are restrained in the longitudinal direction.

The transverse reactions, particularly during a seismic event, are resisted by guided spherical bearings that are aligned along the bridge axis.

The design of the piers of a railway bridge is determined by the braking and traction forces of the train (fixed point) and especially by the seismic forces (for all of them), depending on the specific case.

According to the design basis, rail bridges must satisfy the performance criteria in the following 3 limit states, which ensure their functionality and stability during seismic events.

In the **Service Limit State**, structures are checked to ensure that stresses, deformations, vibrations and track misalignments satisfy the permissible limits. Critical members are considered within elastic range with an average return period of 100 years and a PGA (Peak Ground Acceleration) of 0.08 g. This verification ensures that the bridge works properly under normal service conditions without experiencing significant damage

The **Ultimate Limit State** evaluates the strength and stability of the critical members under more severe conditions, allowing some components to respond outside the elastic range. A return period of 475 years and a 0.15 g PGA are considered.

Lastly, the **Survivability Limit State** ensures that the structure can withstand a severe seismic event without collapsing, even with significant structural damage. A return period of 2475 years and an acceleration of 0.26 g are considered.

3. Viaducts

The viaducts of segments 2B and 2C not only stand out for their functional relevance within the Etihad Rail network but also for the technical challenges involved in their design and construction.

Table 2 includes a summary of the bridge types

Table 2. Bridge types and span arrangements

Segment	Bridge	Type of deck	Arrangement	Spans	Depths	No. spans	No. units
2B	34+100	Box girder	Simply supported	35/50/50/35	2.65/2×3.75/2.65	4	4
	51+713	Box girder	Simply supported	36/36	2,65	2	2
	7+485	Box girder	Simply supported	47,7	3,75	1	1
	9+140	Box girder	Simply supported	46	3,75	1	1
	10+400	Box girder	Continuous	36.5+36 / 36+36.5	2,65	4	2
	13+796	Pergola	-	21.3/23.8/23.8	1,55	3	3
	3+807	U-trough	Simply supported	47/47	3.90-6.40	2	2
	4+102	Box girder	Simply supported	40/44/40	3/3.75/3	3	3
	11+500	U-trough	Simply supported	46,1	3.90-6.40	1	1
	12+150	Box girder	Simply supported	47/48/47	3,75	3	3
	12+612	U-trough	Simply supported	46,1	3.90-6.40	1	1
	16+500	U-trough	Simply supported	35.81/36.35/36.35/35.81	3.50-5.00	4	4
	16+960	Box girder	Simply supported	36	2,65	1	1
	71+240	U-trough	Simply supported	30	3.00-4.20	1	1
	28+183	Box girder	Simply supported	25/35	2/2.65	2	2
	45+235	Slab	Simply supported	17.2/27.3	1.5/2.4	2	2
	45+860	Slab	Simply supported	19.5/15.1/15.3/17.5/22.4/22.3/ 8.5/20.9	2.4/3×1.5/2×2.4/1/1.8	8	8
	5+727	Slab	Simply supported	14,42	3	1	1
2C	12+680	Box girder	Continuous	3×40/3×40/4×40/40/40/40/40/36/ 44.5+52+57+41.6/34	3×2.65/5×3/4/3	20	10
	5+090	Box girder	Continuous	3×40/4×40/40/40/40/40/45+ +65+45/42.6/39.2/39.2/45+2×65+45	2×2.65/4×3/4.15/3×3.2/ 4.15	21	11
	6+648	Box girder	Continuous	33+43+43+33/34.8+45+45+33.5/42/ 32.87+25+35/35/35/42	3,2	15	7

In segment 2B, viaducts 3+807, with a variable U-shaped cross section superstructure, and 13+796, a pergola with precast transverse beams, stand out and the former will be described here. The second one is shown below.

In section 2C, viaducts 5+090 and 12+680 are notable for their total length, the number of structural units, the use of straddle bents in piers 16 and 18 of 12+680, and the use of different depths for the deck. The latter is described in detail in the following section.

Figure 4. Bridge 13+796 in Segment 2B.

3.1. Viaduct 12+680 in segment 2C.

Viaduct 12+680 of segment 2C is an extensive structure composed of multiple structural units of varying lengths. Most units are continuous over several spans, while some simply supported spans are inserted in order to comply with the RSI analysis requirements. Since these considerations were not made at the conceptual design stage of these viaducts, the arrangements of the structural units may not be the expected for a viaduct like this one.

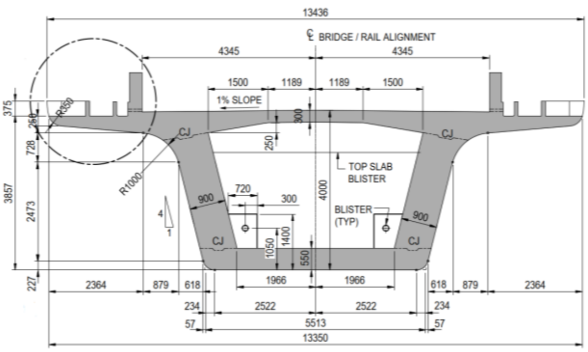


Figure 5. Viaduct 12+680 deck cross section.

The first three units are continuous. The viaduct begins with two units of 3 spans of 40 m each, followed by a third unit of 4 spans of 40 m. This is continued by 5 simply supported spans of 40 m except the last one, which is 36 m long. Finally, the viaduct has another unit with 4 spans of 44.5 m, 52 m, 57 m, and 41.5 m, and a final simply supported span of 34 m.

The depth of the deck varies depending on the structural units and their maximum span length, with depths of 2.65 m for the continuous spans of 40 m, 3.00 m for the simply supported spans, and 4.00 m for the unit with a span of 57 m, with slenderness ratios of approximately 1/15.

The RSI (Rail Structure Interaction) analysis was crucial in defining the final articulation and forced some decisions after finding that some of the checks were not being satisfied. The exercise led to the inclusion of some simply supported spans in the middle of the viaduct, reducing the stresses that were being found in the rails.

Figure 6. Viaduct 12+680. First structural units.

3.1.1. Substructure

The substructure is composed of the two abutments, 17 standard piers, and two prestressed straddle bents (o portal frames), all founded on 1.50 m or 2.00 m diameter piles with lengths from 28 to 40 m. To ensure functionality, sliding spherical bearings were used, many of them guided or fixed in order to resist the lateral reactions.

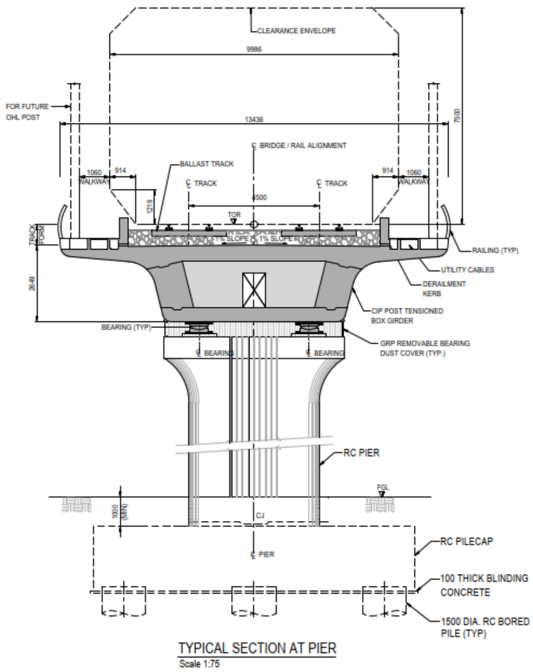


Figure 7. Typical pier.

In the four continuous units, the fixed point for each one was established on one of the piers through a monolithic solution, keeping the maximum longitudinal displacements under the required limits. In the last continuous unit, the fixed point was located on the central pier, while the two adjacent piers were configured as prestressed straddle bents integrated into the deck, with spans of 32m and 35m, supported on columns with sliding spherical bearings that allowed longitudinal movements.

Since the base of the piers were expected to undergo plastic deformation, details that provided the required ductility were adopted, through an adequate confinement of the concrete.

Initially, the concept design prioritized redundancy by incorporating continuous structural units. However, this approach was later revised to meet RSI requirements.

3.1.2. Superstructure

Designing according to AREMA standards results in a significantly more robust design compared to the Eurocodes and EHE-08 standards.

In order to meet all the requirements included in the basis of design, while keeping the depth at its value to provide the necessary vertical clearance, it was necessary to increase the concrete strength to 55 MPa.

The prestressing of the simply supported spans consists of 4 families of 4 tendons with 29 strands each.

In the units with the continuous deck, the main prestressing was formed by 4 families of 4 tendons with 31 strands each, rising at the piers and descending in the spans. Additionally, up to 17 tendons with 19 strands were added in the top flange at minimum negative moment, and 27 tendons with 19 strands in the bottom flange, running through the spans and splicing over the piers.

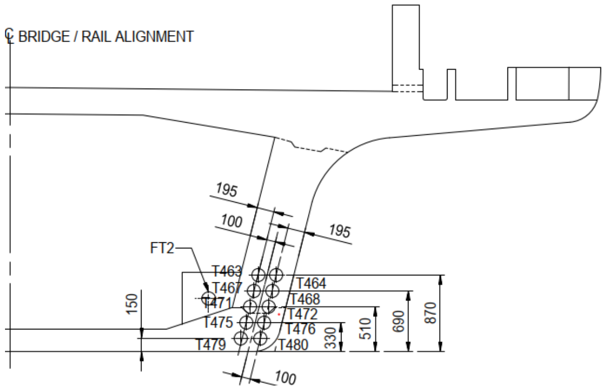


Figure 8. Deck cross section and prestressing (permanent and allowance for future PT).

According to the design basis, a provision for no less than 5% of the total post-tension force was left as future prestressing of unbonded external tendons, for positive moment.

The anchors of the internal prestressing were alternated, leaving the necessary physical space for the plates and the jacks.

The portal piers (or straddle bents) are post-tensioned concrete elements constructed on-site, with a robust transverse beam that is monolithic with the deck, simply supported on concrete columns, as shown in the following figure, where the two portal frames are visible.

Figure 9. Viaduct 12+680. Last structural units with the portal frames

The one with the longest transverse span, which measures 35 m, has a prestressing that consists of 9 straight tendons of 31 strands placed at the top and 32 tendons with 31 strands each at the bottom. The prestressing arrangement had to avoid clashing with the main longitudinal prestressing of the main box girder.

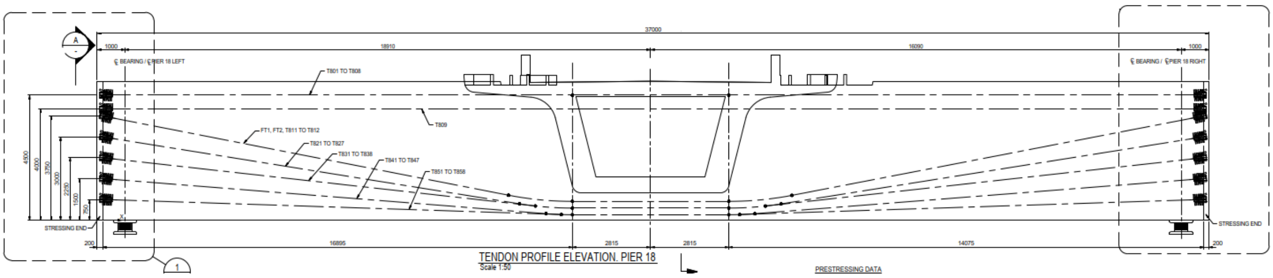


Figure 10. Prestressing of the portal frames beams (straddle bents).

3.1.3. Rail-Structure Interaction (RSI)

The design considered the Rail-Structure Interaction (RSI) and normal stress variations of continuous welded rail on the structure due to temperature variations and train loads, as required by the Basis of Design. This exercise is particularly important in long viaducts like this one.

The analysis was carried out as per EN 1991-2 Section 6.5.4 and UIC-774-3, considering, and also using the vertical loads as defined in AREMA even though this code does not address clearly this phenomenon. Effects like uniform and gradient temperature, creep and shrinkage, acceleration and braking, etc., were considered, checking and making the necessary changes in the articulation of the viaduct to satisfy the required checks.

The general approach that had been followed in other bridges in the project designed by others, which favored simply supported spans to avoid the need to run an RSI analysis, was not valid here because the maximum span length would have required a depth that was not compatible with the required clearance over the highway.

The RSI analysis was run following an automated approach using the software SOFiSTiK, checking a range of different bridge articulation configurations in order to find the solution that would minimize and preferably eliminate the use of track expansion joints, until the final and adopted one was determined, which was then reproduced with MIDAS for final approval, as required by the final client.

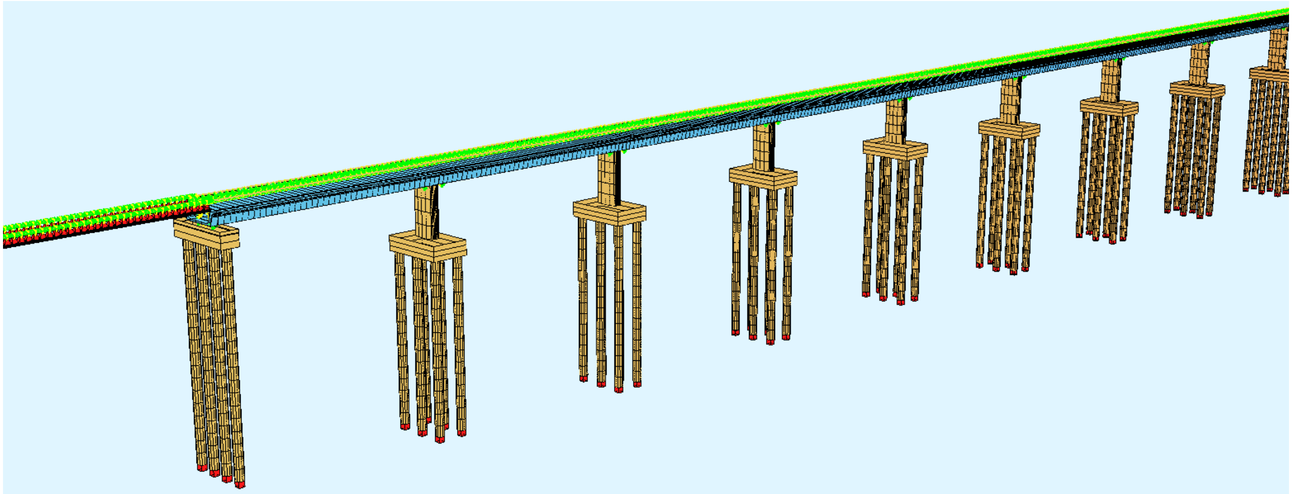


Figure 11. SOFiSTiK model for RSI analysis

3.2. Viaduct 3+807

The 3+807 viaduct exemplifies the series of structures within the KPZ alignment of Stage 2B, which links Jebel Ali port to the broader railway network. These viaducts feature a U-shaped cast in placed prestressed concrete cross-section for the superstructure, enhanced with architectural rounded shapes on the lateral webs that elevate their aesthetic appeal, while keeping it structurally highly efficient. The section is casted in two stages over temporary formwork, with the construction joint located at the bottom of the webs.

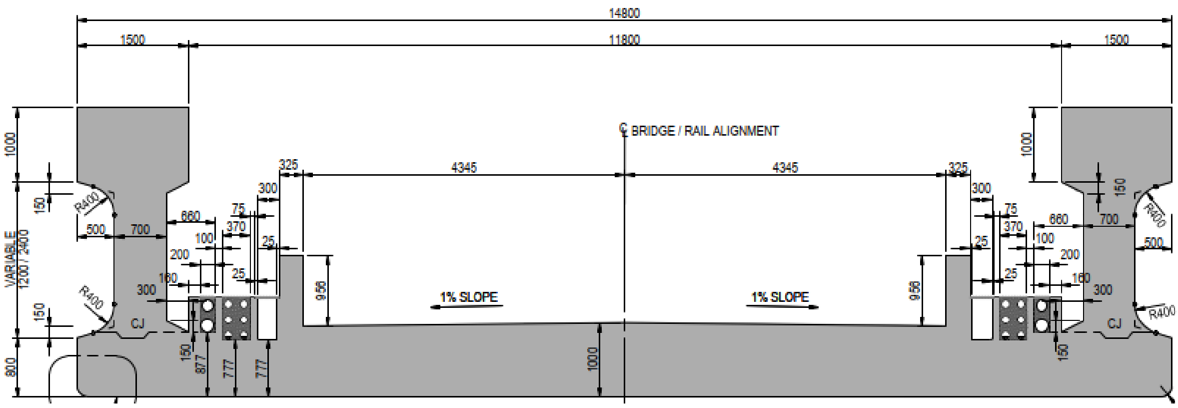


Figure 12. Viaduct 3+807 cross section.

Figure 13. U-trough section simply-supported spans in Segment 2B.

This specific bridge consists of two simply supported spans, each with a length of 47 m, featuring the already mentioned “U-trough” deck cross-section, with varying depth, maximum at midspan with 6.40 m, and minimum at the supports, with 3.90 m.

The prestressing is defined with 5 families, each consisting of 4 tendons with 31 strands, and the parabolic layout that corresponds to a simply supported span.

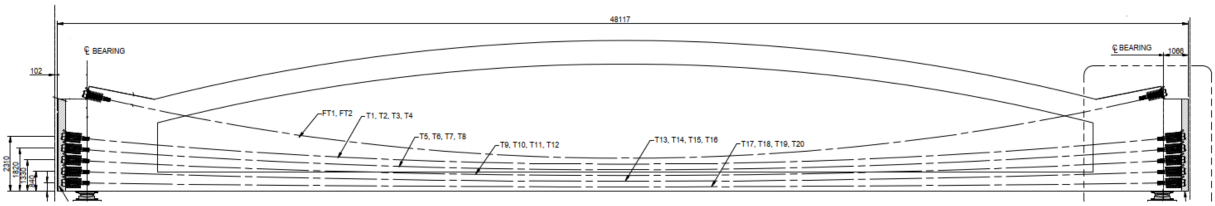


Figure 14. Viaduct 3+807. Prestressing arrangement.

As it also happened with the previously described viaduct of Stage 2C, a provision of 5% of the total post-tensioning force has been allocated for future prestressing. In this case, the prestressing runs through the webs and the future prestressing must be positioned above the section at the supports, as can be seen in the picture and the figure above.

The U is supported by two standard piers, measuring 2 x 3 m at the base and 4.1 x 3 m at the top, with the same transverse spacing as the center of the webs of the deck (see photo above).

Since the spans are simply supported, the RSI analysis is not necessary because the design inherently meets the requirements.

Acknowledgments

The structures designed in this project are part of the Etihad Rail network, which is the promoter and operator of the national railway network of the United Arab Emirates.

As the lead engineering firm for the design of the structures, WSP worked with the construction companies in the Joint Venture CRCC-GHANTOOT. AECOM served as the Independent Checker.

The project was developed between 2019 and 2022. Construction started in April of 2020, and finalized in February of 2023.

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