Viaduct over Guadalhorce River and A-92 Highway, Málaga, Spain

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DOI: 10.2749/101686614X13830788505838

Abstract

The Guadalhorce Viaduct, built as part of the high-speed line Antequera–Peña de los Enamorados (south Spain), has a length of 2525,50 m and consists of 49 spans of 51,25 m length each. It is one of the longest bridges of its type in the country and is situated in a medium-risk seismic zone. The superstructure consists of a continuous single-cell post-tensioned box-girder of 3,40 m depth. The main span, which crosses the A-92 Highway, is 90 m long and is reinforced by two steel tied arches. This span, along with its backward and forward spans, was resolved with a steel–concrete composite box-girder with a constant depth of 3,40 m. A point of fixity is materialized in a delta-shaped post-tensioned concrete pier located in an intermediate area of the bridge in order to meet the friction, braking, and seismic longitudinal forces induced by the large length of the viaduct. Hence, expansion joints are placed at both abutments. Span-by-span erection is being followed by means of two self-launching formwork gantries working simultaneously, starting from each abutment, and moving toward the delta-shaped pier. Temporary fixed points were required during the erection process and set at the piers placed just before the gantry. The viaduct is currently under construction.

Keywords: post-tensioned box-girder; steel tied arch; temporary fix point; self-launching gantry; delta-shaped pier.

Introduction

The need for the Guadalhorce Viaduct project arises from the necessity to give way to the Antequera–Granada high-speed railway line. The bridge is located in the Guadalhorce River floodplain, and thereby requires such a large length.

Fig. 1: General view of the bridge

The main obstacles for the viaduct to overcome were bridging the A-92 Highway that crosses underneath one of its spans and the effects of the horizontal forces due to the large length. To resolve these issues, a steel tied arch and a post-tensioned concrete delta-shaped pier were designed and incorporated into the structure (Fig. 1).

The bridge has a constant slope of 2.5% in the vertical alignment, whereas the plan view shows that the spans lie inside a 3100-m radius with leftward circular alignment, followed by two clothoid alignments, and ending with a 2200-m radius rightward circular alignment.

The deck houses a double-track railway platform containing 10.10-m width of ballast, service sidewalks, and several devices for the installation of the railway at both sides, resulting in a total deck width of 14 m, that is normal in the high-speed Spanish railways.1

Two section types are present in the bridge: a post-tensioned concrete box-girder and a steel–concrete composite box-girder, both with a constant depth of 3,40 m. Both sections are continuous throughout the entire viaduct (Fig. 2).

Typical Post-Tensioned Spans

The Guadalhorce Viaduct presents some singularities due to both its length (2525,50 m) and the need to have a long-length span over the A-92 Highway. Consequently, two different superstructure types may be found: one used to span the highway and another used to resolve the rest of the viaduct.

The total number of spans is 49, each 51,25 m long, except for the one that crosses the highway, which has a length of 90 m.

The typical span consists of a continuous single-cell post-tensioned box-girder of 3,40 m depth. This yields a depth:length ratio of 1:15, which is common for this type of bridges.2–4 The
post-tensioning arrangement consists of four families of four tendons per family. Each tendon is compounded of 27 strands of 15.2 mm diameter and the tensile strength is equal to 1860 N/mm². The four families follow a vertical alignment that adapts to the flexural bending moment acting on the superstructure.

Arch Span

The longest span of the viaduct is resolved with two steel tied arches. The sag is 17 m long, which yields a sag:length ratio of 1:5. The position of both arches as well as their truss geometry respects the skew angle formed by the viaduct alignment and the highway, improving the aesthetics. The transversal distance between arch axes is 16 m and they comprise a 1.50 × 1.50 m² section with slots at the sides. The truss diagonals consist of six tubular shapes per arch of 1 m diameter and 20 to 30 mm depth that creates a triangular structure.

The deck type used for the span over the highway, along with its backward and forward spans, is a steel–concrete composite box-girder design with a constant depth of 3.40 m measured at the axis of the bridge. The section comprises a bottom flange of 5.50 m width, sloped webs at both sides 7 m apart at the top slab, and lateral overhang flanges of 3.50 m length. The top reinforced concrete slab is 0.45 m deep at the axis, decreasing to 0.375 m when reaching the webs and 0.20 m at the tip of the overhang flanges. Double composite action has been designed at the pier section in order to guarantee the stability of the bottom flange and decrease the steel plate thickness. This kind of section has already been successfully used in other bridges.5

Piers

The deck is supported by 48 reinforced concrete piers. The maximum registered height is 27 m, although the viaduct is placed in a flat valley and all the piers are of similar height.

The typical pier consists of a constant elliptical section shaft, with 4.50 m transversal axis and 3 m longitudinal axis. A variable elliptical section pier cap, which progressively widens throughout the 4 m height in order to house the deck-bearing devices, is placed above the shaft.

The piers that support the arches consist of two frames, located at each side of the longest span, made of two reinforced concrete shafts topped by a...
lifetime, such as thermal expansion and contraction, concrete shrinkage, and creep and braking of the train passing over the deck.

Once the fixity point is defined, the pier design is created by the effect of the longitudinal earthquake forces acting on the deck. In the transversal direction, as most of the piers have similar height and considering the length of the structure, each pier absorbs noticeably a proportional fraction of the force corresponding to its tributary length.

Deep foundations are needed for the pier. Measuring $16.5 \times 21.0 \times 5.0$ m, each of them houses 18 drilled shafts of 1.80 m diameter spaced 4.50 m between axes (Fig. 5).

**Bearings and Rail Expansion Devices: Monitoring**

The bearing devices used on the viaduct consist of sliding bearings that incorporate a PTFE (PolyTetraFluoro Ethylene, Teflon) surface and have suitable guides that restrict the movements. Two bearing devices are placed on each abutment and pier. One of them is a free bearing allowing movement in all directions, while the other one is a guided bearing that allows movement only in the longitudinal direction to accommodate thermal expansion/contraction of the deck.

Two rail expansion devices, with maximum opening of 1200 mm, are located at both abutments. To adjust the movement of the expansion devices, a monitoring system that continuously assesses structure integrity is installed in the bridge. It tracks movements and measures temperature of the concrete wherever sensors are embedded.

The monitoring system records the real gap between the abutment and the superstructure, which depends on the bridge, materialized in a delta-shaped pier. It consists of two sloped post-tensioned concrete shafts joint at the basement by a horizontal beam. The two shafts ($2.85 \, \text{m along the longitudinal axis and} \, 5.50 \, \text{m along the transversal axis}$) converge at the deck creating the fixity point of the viaduct for the nonaccidental horizontal forces induced in the bridge deck during its lifetime.

The foundations of the piers supporting the span over the A-92 Highway consist of $12 \times 12 \, \text{m}^2$ spread footings, with 3.50 m depth. Each of them houses eight drilled shafts of 1.80 m diameter, placed along three rows spaced 4.50 m apart in both directions (Fig. 4).

**Delta-Shaped Pier**

The large length of the viaduct has led to the introduction of a fixity point, located in an intermediate area of the bridge, materialized in a delta-shaped pier. It consists of two sloped post-tensioned concrete shafts joint at the basement by a horizontal beam. The two shafts ($2.85 \, \text{m along the longitudinal axis and} \, 5.50 \, \text{m along the transversal axis}$) converge at the deck creating the fixity point of the viaduct for the nonaccidental horizontal forces induced in the bridge deck during its lifetime.

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thermal and time-dependent movements. Recorded gap–temperature graph (Fig. 6a) shows both variables are in the same phase. The gap can be expressed in terms of the recorded temperature and a time-dependent function by means of the empirical formula (1). Recorded gap–expected gap graph (Fig. 6b) shows good correlation between both variables:

\[ g = g_{\text{ini}} = \alpha \cdot T \cdot L + \beta \cdot \text{rhe}(n, r, t) \cdot L \] (1)

where \( g \), expected gap at a given time; \( g_{\text{ini}} \), initial gap; \( \alpha \), thermal expansion coefficient of concrete; \( T \), temperature of the concrete at a given time; \( L \), distance from abutment to the center of mass of the deck; \( \beta \cdot \text{rhe}(n, r, t) \cdot L \), movement caused by the time-dependent action; \( \beta \), long-term strain caused by shrinkage and creep of concrete; \( \text{rhe}(n, r, t) \), time evolution coefficient of shrinkage and creep (0 at the beginning; 1 at the end); \( n \), end time of shrinkage and creep (in years); \( r \), time when shrinkage and creep are initially considered; and \( t \), age of concrete at the time when shrinkage and creep are initially considered (in years).

Empirical formula (1) is obtained by linear correlation between the recorded gap \( g \) and the recorded temperature \( T \) and the time evolution coefficient of shrinkage and creep \( \text{rhe}(n, r, t) \). With this formula, it is possible to determine the real values of \( \alpha \) and \( \beta \) coefficients for the concrete used in the deck.

The real value of the thermal expansion coefficient of concrete \( \alpha \) used in the viaduct is 10 to 20% smaller than the usual values of the codes in force.6,7 As is well known, the presence of limestone aggregate in the concrete may lower the thermal coefficient value.6,8

The theoretical time-dependent movement at the gap is known by means of a step-by-step analysis model that counts the real concrete ages according to the erection procedure. The comparison of the theoretical time-dependent movement and the time-dependent term of the empirical formula (1) reveal that the real time-dependent movement is about 90% of the theoretical movement.

**Construction Procedure**

The spans of the entire bridge, except for the one over the A-92 Highway, will be assembled by means of a self-launching formwork gantry, as per the sequence described below:

- Construction of substructure components (piers and abutments).
- Installation and assembly of the auxiliary equipment for the deck construction (self-launching formwork).
- Casting of concrete deck in subsequent phases; construction to begin from the abutments and advance toward the fixity point.
- Finishes: superstructure (ballast, sleepers, rails, culverts, parapets, barriers, etc.).

To fulfill the construction deadline, two self-launching formwork gantries are employed simultaneously in the viaduct, and so two different gantry suppliers were required. For the construction of the first segment (spans located prior to the steel arch), an upper self-launching formwork is used consisting of a gantry placed above the deck, while for the second segment, a lower self-launching formwork is used and the gantry is placed below the deck.

Temporary shoring towers will be installed for the assembling of the steel tied arch. The composite deck segments, previously assembled at the worksite, will be erected by cranes and supported by the towers.

**Temporary Longitudinal Fix Points**

Temporary fix points are needed during the construction stage in order to absorb the longitudinal effects until the connection between all the components and the delta-shaped pier takes place.

The usual way of controlling these effects consists of fixing the deck to the abutment during the construction stage. However, placing the temporary fix point at the abutment in this long viaduct could lead to high relative movements during the concrete hardening between the previous and the currently cast span. It was then decided that the temporary fix points would be placed in the pier(s) of the previous cast spans.

To this purpose, the actions considered during each construction stage
to be acting on the piers, apart from the self-weight of the components, are the first-order longitudinal accidental eccentricity at the pier head, longitudinal force due to friction of the sliding bearings, second-order effects, superimposed deformations due to thermal and shrinkage/creep effects, and earthquake forces assuming a ten-year return period.

The number of temporary fixed piers in every phase depends on the superstructure length previously cast and, consequently, on the friction forces of the sliding bearings. The number of fixed piers increases from one to four, the biggest number being the worst scenario.

The special device designed to fix the pier(s) consists of a group of steel structures embedded on the deck and the pier. The sizes of the steel structures have been determined in accordance to the maximum longitudinal force that acts on the pier. The longitudinal lock force acting on the deck is transmitted by means of hydraulic jacks.

**Structural Analysis**

A unique three-dimensional (3D) beam model for the entire viaduct was created, including a step-by-step analysis of each construction stage. This model allows an in-depth study of the time-dependent effects, the thermal behavior between concrete and steel, and the seismic response of the structure. Seismic effects are considered in the model because the viaduct is situated in a medium-risk seismic zone. The seismic design was made according to the Spanish seismic code for bridges NCSP-07,\(^9\) which is quite similar to the Eurocode 8.\(^10\) The basic ground acceleration of the site is 0.09g, whereas the considered design ground acceleration was 0.113g. As per Eurocode 8, ground type C is found in the first 10 m and type A in the following 20 m. The seismic effects were determined by means of a modal response spectrum analysis, using a linear elastic model of the structure and the design spectrum given by the Spanish standard NCSP-07.

When obtaining the natural period of vibration in the longitudinal direction, the axial flexibility of the superstructure (due to large length of the viaduct) comes into play, as well as the bending

![Fig. 7: First longitudinal vibration mode](image)

**Fig. 8: Shell FE-modeled connection nodes:** (a) stress distribution diagrams, (b) adopted solution: double longitudinal exterior gussets
stiffness of the delta-shaped pier foundation. Periods of 2.17 and 2.04 s for the longitudinal vibration modes of the left and right semi-bridge, respectively, are obtained, which are placed in the long-period portion of the response spectrum. As these values are quite close, the Square Root of the Sum of the Squares (SRSS) combination method is not considered accurate enough; hence the Complete Quadratic Combination (CQC) combination method was used instead.10 The deformation of the delta-shaped pier foundation was studied. The maximum longitudinal seismic force obtained in the delta-shaped pier is 72,500 kN (Fig. 7).

Several options were studied when designing the connection nodes of the truss diagonals with both the longitudinal ties and the steel arches. The fatigue effects due to the railway traffic (highly important in high-speed line bridges) and the stress concentrations at the connection nodes were analyzed.

Various finite element (FE) models by shell elements were made, covering the following variables: intersection of tubes, gap between tubes, single or double gusset, and longitudinal or transversal gussets. According to the analysis of the several solutions the double longitudinal exterior gussets was the best solution, as shown in Fig. 8. This solution allows a better distribution of stress, offers better and direct transmission of forces between the tubes and the arch and tie girder, and improves the fatigue behavior.

Conclusion

The Guadalhorce Viaduct has excelled in establishing itself as one of the longest bridges of its type in the country. A post-tensioned concrete box-girder section spans 2.5 km with a delta-shaped pier as a unique fixity point. An accurate analysis of the thermal and time-dependent coefficients of the concrete could increase the length of this type of bridge, since a smaller value of concrete strain would lead to a larger maximum length of viaduct for the same rail expansion device opening.

References


SEI Data Block

Owner: ADIF, Ministerio de Fomento, Spain
Contractor: ACCIONA, Spain Torres Cámara, Spain
Site supervision: GETINSA, Spain GUIA, Spain
Structural design: APIA XXI - Louis Berger DCE, Santander, Spain
Concrete (m³): 64530
Reinforcing steel (t): 14308
Prestressing steel (t): 1280
Structural steel (t): 1590
Total cost (EUR million): 65
Service date: September 2015 (expected)