Structural Engineering International

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tsei20

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Kenneth W. Shushkewich (Principal)

To cite this article: Kenneth W. Shushkewich (Principal) (2020) Design of Haunched Single Span Bridges, Structural Engineering International, 30:4, 580-591, DOI: 10.1080/10168664.2020.1801368

To link to this article: https://doi.org/10.1080/10168664.2020.1801368

Published online: 25 Sep 2020.

Design of Haunched Single Span Bridges

Kenneth W. Shushkewich, Principal, KSI Bridge Engineers, San Francisco, CA, USA.
Contact: kenshushkewich@hotmail.com
DOI: 10.1080/10168664.2020.1801368

Abstract

A novel method for the design of variable depth single span bridges having maximum depth at the ends and minimum depth at midspan is presented. These bridges are intended to be used for long span river crossings or highway overpasses, where only a single span is required, and the vertical clearance below needs to be maximized, and/or an aesthetically pleasing graceful shape is desired. The design is made possible by "fixing" the ends to "lock-in" negative moments, so that the positive moments at midspan are greatly reduced, and a shallow section may to be used. The method is developed and presented in two parts. The first part discusses and unifies the behavior of three very famous bridges (the Luzancy Bridge in France designed by Eugène Freyssinet, the Gänstor Bridge in Germany designed by Ulrich Finsterwalder, and the Pinzano Bridge in Italy designed by Silvano Zorzi). The second part describes the method in detail by virtue of a complete design example. Application of the method to other bridges is included, and abutment treatments to enhance the visual qualities are presented. This innovative bridge type will be of interest to those looking for a practical and elegant new bridge solution for long span bridges.

Keywords: behavior; design; inclined leg bridge; rigid frame bridge; shallow arch bridge; Luzancy Bridge; Gänstor Bridge

These bridges can be used for long span river crossings or highway overpasses, where only a single span is required, and the vertical clearance below needs to be maximized, and/or an aesthetically pleasing graceful shape is desired.

This innovative bridge type will be of interest to owner agencies, bridge designers, and design/build contractors looking for a practical and elegant new bridge solution for long span bridges.

Introduction

The design of variable depth single span bridges having maximum depth at the ends and minimum depth at midspan is presented. The design of these bridges is made possible by "fixing" the ends to "lock-in" negative moments, so that the positive moments at midspan are greatly reduced, thus allowing a shallow section to be used at midspan.

Although haunched single span bridges have been designed and constructed for a great many years, no attempt to unify the behavior of these bridges has been made, and no systematic approach for the design of these bridges has ever been presented. This paper fills this void by presenting a design method that can be used for a wide variety of prestressed concrete and structural steel bridges.

In general, three types of haunched single span bridges have been built:

(1) Rigid frame bridges—The bridge superstructure is made monolithic with the substructure (abutments).
(2) Bridges with ballast—The bridge has short cantilever extensions at the ends where ballasted material (weight) is added.
(3) Bridges with tie-downs—The bridge has short cantilever extensions at the ends where tie-downs (rock/soil anchors) are activated.

Only bridges with tie-downs will be considered here, as these bridges are economical and may be presented as a general design method.

The first half of this paper provides insightful observations and comments about the behavior of haunched single span bridges with historical reference to three very famous bridges, while the second half presents a methodical design approach for the design of these bridges.

Historical reference is made to the Luzancy Bridge in France designed by Eugène Freyssinet, the Gänstor Bridge in Germany designed by Ulrich Finsterwalder, and the Pinzano Bridge in Italy designed by Silvano Zorzi.

A complete design example for a cast-in-place segmental bridge with tie-downs is presented, after which a variety of applications of this design method are discussed, and abutment treatments that enhance the visual qualities of this bridge type are presented.

Bridges with Tie-Downs

Consider a simply supported variable depth box girder bridge with span length "L" having short cantilever extensions at the ends of length "a" (*Fig. 1*). Vertical supports carry the reactions R for this simply supported bridge. Since the maximum positive bending moment occurs at midspan, it will not be possible to have the shallowest section at midspan as shown.

Let us now apply downward vertical tie-down forces F at the ends of each cantilever extension. These forces "lock-in" a negative moment at each end ($M^- = F \times a$), which reduces the positive moment at midspan to allow the very shallow section to be used as shown.

Now, instead of looking at vertical supports and tie-downs, let us look at inclined supports and tie-downs. The vertical component of the tie-down forces F_V "lock-in" a negative moment at each end ($M^- = F_V \times a$) to reduce the positive moment at midspan, while the horizontal component of the tie-down forces F_H adds compression to the deck (the horizontal component of the support reactions R_H also adds compression to the deck —these will be discussed later).

Note that inclined supports reduce the overall span length required for the main span, and inclined tie-downs allow the same foundation to be used for both the support and the tie-down. In fact, the self-weight of the bridge can resist the tie-down force so that soil/rock anchors will not be

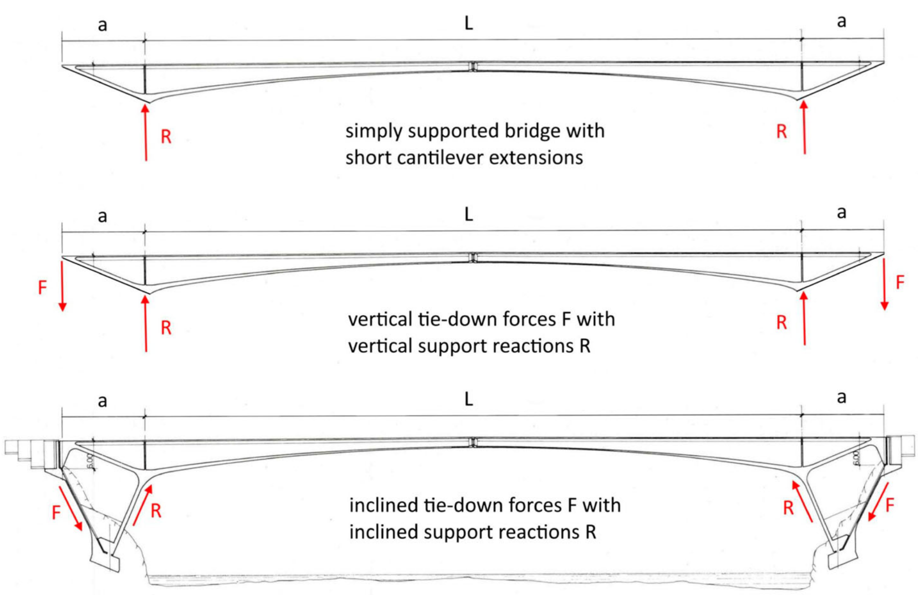

Fig. 1: Single span haunched bridges

required, and only inclined prestressing tendons will be needed to transfer the tie-down force from the deck to the foundations.

The required negative moment M^- can be provided by having a short cantilever extension "a" with a large tie-down force "F", or a long cantilever extension with a small tie-down force. Clearly, a short cantilever extension is desirable, as the total structure length will be a minimum. However, a short cantilever extension needs to transmit a large shear force (equaling the tie-down force) through the length of the cantilever extension to the abutment. If the cantilever extension is too short, vertical prestressing will be required to transmit the shear force in the deck, and if is much too short the section will not work. Thus, an optimum cantilever extension length needs to be found.

Also, the force in the tie-downs may be adjusted or "tuned" in order to have the desired distribution of positive and negative moment. *Figure 2* shows a haunched single span box girder bridge having a main span of 82.0 m and cantilever extensions of 6.1 m on each side. The cross section for this bridge is the same as that used later in the design example as shown in *Fig. 7*.

The seven self-weight bending moment diagrams shown are for different tie-down forces, which yield different degrees of fixity going from 0% fixity to 120% fixity in increments of 20%. (100% fixity is the condition where rotation is restrained at the abutments.) What is interesting to see is the distribution of positive and negative moments that can be attained by varying the fixity force in the tie-downs.

With 0% fixity (simply supported) most of the moment is positive moment (97%), whereas with 120% fixity most of the moment is negative moment (97%). With 60% fixity half the moment is positive moment and half the moment is negative.

The case of 100% fixity gives 81% negative moment and 19% positive moment for this variable depth bridge, and not 66% negative moment and 33% positive moment as would be expected for a constant depth bridge (ie. $wL^2/12$ and $wL^2/24$). This case is represented by 80% fixity for this variable depth bridge.

In general, the negative moment is a combination of the moment due to the self weight of the cantilever extension as well as the moment due to the tie-down force. This is why the simply supported case (no tie-down force) has 3% negative moment. As the cantilever extensions become longer, a larger portion of negative moment is carried by the self weight. For this type of example, a cantilever extension length of 8.20 m (0.10 L) carries 5% of the negative moment, while a length of 16.40 m (0.20 L) carries 21% of the negative moment.

It may be noted that If the tie-down was a reaction (support) instead of an action (force), then the bridge would be a three span continuous bridge, and there would be unfavorable secondary moments. These would cause additional secondary stresses due to thermal gradient, diminish the primary effects of the prestressing, and cause moment redistribution under the effects of creep and shrinkage.

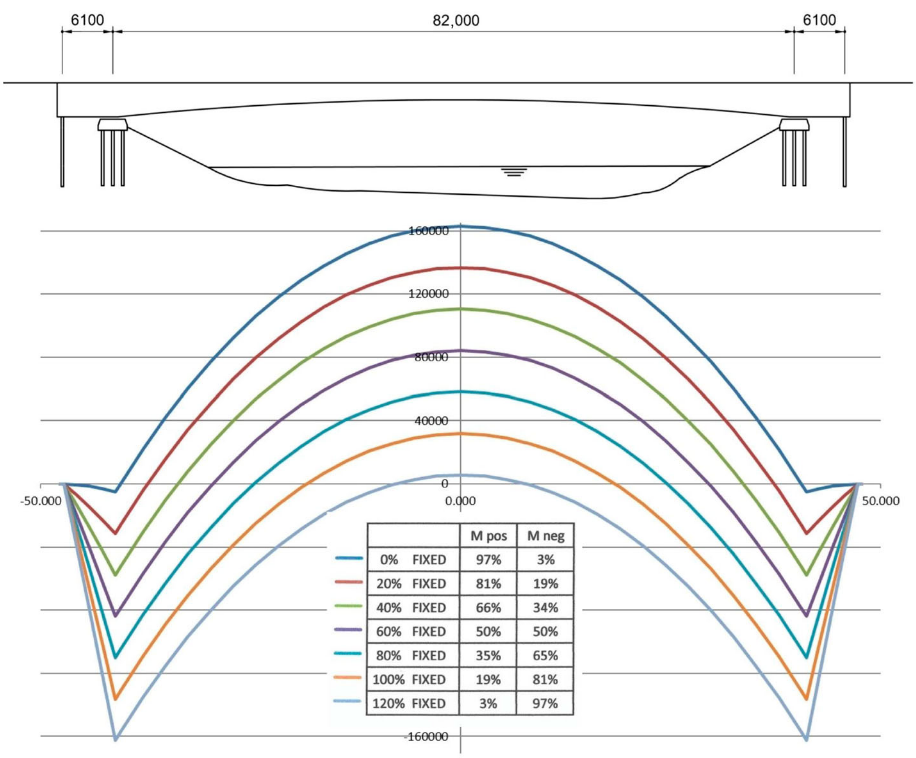

Fig. 2: Tie-down force study

Three Famous Bridges

Three historically significant and beautiful bridges with three different variations of vertical / inclined supports and vertical / inclined tie-downs are described here.

Luzancy Bridge

The Luzancy Bridge[1–5] in France is a very slender bridge over the Marne River (*Fig. 3*). It was designed by Eugène Freyssinet and is a very special bridge (see Appendix A). It is the first precast segmental bridge ever built. It has a main span length of 55 m. Construction started in 1941 (shortly after Freyssinet patented the very first post-tensioning anchorage in 1939), but because of the war was not completed until 1946.

Freyssinet designed this bridge to replace a suspension bridge. The requirements were that this girder bridge span from shore to shore, while maintaining both the roadway profile and the navigation channel. Thus, he could only have a section depth of 1.27 m at midspan for a span of 55 m, and this is why the resulting bridge is very light in appearance, having a remarkable span to depth ratio of 43. The bridge has been described as a two-hinge portal frame.

Note the red arrows in the line diagram. The upward red arrow shows an inclined support, while the downward red arrow shows an almost vertical tie-down. The vertical component of the tie-down force acting on the short cantilever extension “locks-in” a negative moment at each end, which reduces the positive moment at midspan, thus allowing the very shallow 1.27 m deep section to be used.

The cross section of the bridge is comprised of three box girders that were individually cast and erected, and interconnected to give a five cell box girder having a deck width of 8.00 m. The roadway consists of two 3.00 m lanes and 1.00 m sidewalks.

The bridge is post-tensioned longitudinally, transversely, and vertically with 12 × 5 mm diameter wire tendons. The longitudinal post-tensioning consists of 8 cantilever tendons at the top that drape down and anchor at the bottom, and 16 continuity tendons at the bottom that drape up and anchor at the top. The tie-down (tension tie) is also post-tensioned. It has an anchorage at the top and a loop at the bottom. Flat jacks and reinforced concrete shims are located where the lower inclined element frames into the abutments. They have been used to further compress the bridge as well as to make adjustments for the effects of creep.

With the great success of the Luzancy Bridge, Freyssinet used this same solution to build five similar bridges having spans of 74 m on the Marne River between 1947 and 1951. These five bridges are the Ussy, Annet, Tribardou, Changis, and Esbly bridges. The span to depth ratio for these bridges is 86, which is double the value of 43 for the Luzancy Bridge. These are extremely slender bridges!

Gänstor Bridge

The Gänstor Bridge[6] in Germany is a very elegant bridge over the Danube River in Ulm (*Fig. 4*). It was designed by Ulrich Finsterwalder and has a main span length of 82.4 m.

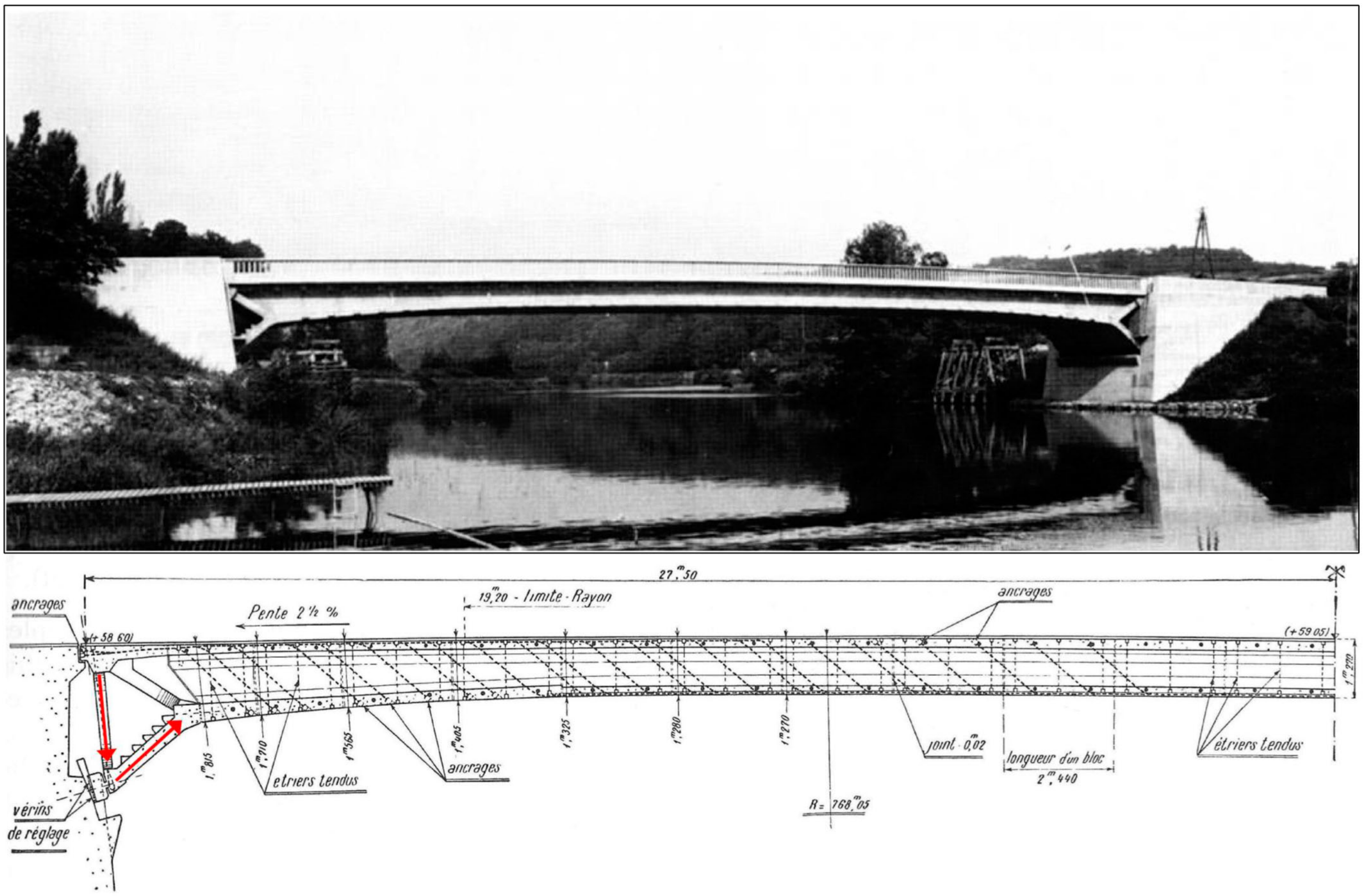

Fig. 3: Luzancy bridge (55 m span)

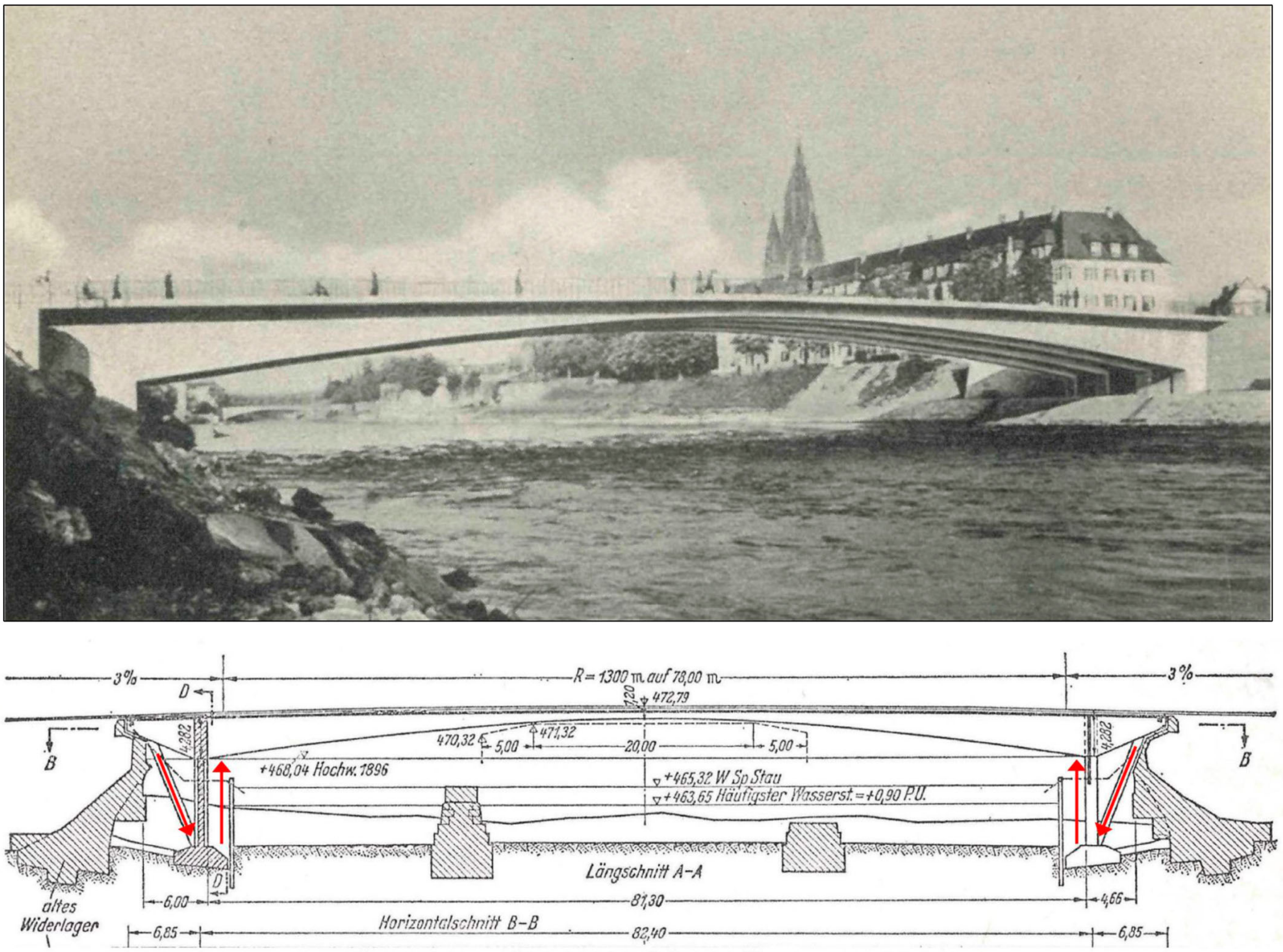

Fig. 4: Ganstor bridge (82.4 m span)

Construction was completed in 1950. The bridge replaced a three-arch bridge that was destroyed in the war.

The red arrows in the line diagram show that the bridge has vertical supports and inclined tie-downs, features that are hidden by the abutment walls in the photo.

The section depth for this 82.4 m span varies parabolically from 4.282 m at the abutments to an amazing 1.20 m at midspan. This 1.20 m depth allows the vertical clearance requirement for the navigation channel to be maintained (without having to raise the road). The span to depth ratio is thus 19 at the abutments and an amazing 69 at midspan.

The cross section of the bridge is comprised of four girders, and these girders not only have a parabolic variation in depth, but they also have a parabolic variation in width from 1.40 m to 0.70 m. This has been done to minimize the self weight as much as possible. This reduction in girder width occurs on the inside faces only, so that the outside faces of the bridge are uniform as can be seen in the photo. The overall deck width is 18.60 m.

As mentioned, the bridge replaced a three-arch bridge. The abandoned abutment and pier foundations can be seen in the line diagram. The abandoned abutment foundations have limited the cantilever extensions to a length of 6.85 m, which is quite short for a 82.4 m span (a ratio of 0.083 L). This means that large tie-down forces are required to provide the large negative moments required at the ends, to offset the small positive moment that can be tolerated at midspan. Each large tie-down force is transferred as a large constant shear force through the end cantilever to the abutment. Vertical prestressing bars have been provided to carry these large shear forces. The longitudinal prestressing consists primarily of top tendons over the abutments with only a few continuity tendons that travel the length of the bridge.

At the same time that Finsterwalder was constructing the Gänstor Bridge[6] over the Danube River (82.4 m span), he was also constructing the Balduinstein Bridge[7] over the Lahn River (62.1 m span). Both of these bridges are haunched single span river crossings, and they look quite similar. However, the Gänstor Bridge uses tie-downs to achieve the haunched design, while the Balduinstein Bridge uses ballasted ends to achieve the same result. More importantly, whereas the Gänstor Bridge was constructed on falsework, the Balduinstein Bridge was the first bridge ever to be constructed by cantilevering segments over the river. This is the first cast-in-place segmental bridge, and its success allowed Finsterwalder to construct the Rhine River Bridge[7] at Worms (101.65–114.20–104.20 m spans), which became the first cast-in-place segmental bridge constructed in true balanced cantilever fashion.

Whereas Eugène Freyssinet was the first to use precast segments for the construction of the Luzancy Bridge, Ulrich Finsterwalder was the first to use cast-in-place cantilever construction for the segments of the Balduinstein Bridge, and then cast-in-place balanced cantilever construction for the Rhine River Bridge at Worms. The circle was then completed by Jean Muller (a disciple of Eugène Freyssinet), who combined the precast segments of Freyssinet with the balanced cantilever construction of Finsterwalder on the Choisy-le-Roi Bridge[8] over the Seine River near Paris in 1962. This was the first match-cast precast segmental bridge built in balanced cantilever.

Pinzano Bridge

The Pinzano Bridge[9] in Italy is a very beautiful bridge over the Tagliamento River (*Fig. 5*). It was designed by Silvano Zorzi. It has a main span length of 163 m and an overall length of 185 m. Construction was completed in 1969. The bridge replaced a three-arch bridge that was damaged by floods in 1966.

The red arrows in the line diagram show that the bridge has inclined supports and inclined tie-downs, features that are hidden by the abutment walls in the photo. It can be noted that the line diagram for this bridge has been used as the basis of *Fig. 1* in this paper.

The section depth varies parabolically from 7.00 m at the abutments to an extremely slender 2.50 m at midspan. The span to depth ratio is thus 23 at the abutments and an amazing 65 at midspan. There is a hinge at midspan. The bridge has been described by Zorzi as a three-hinge portal arch.

The cross section of the bridge is a single cell box girder whose deck width is 9.60 m, and whose roadway consists of two 3.50 m lanes and 1.30 m sidewalks.

The inclined supports reduce the main span from 163 m to 147.3 m (and not 135 m as given on the line diagram ie. 184.0–18.35–18.35 = 147.3 m). The 18.35 m long cantilever extensions are a ratio of 18.35/147.3 = 0.125 L of the 147.3 m reduced main span, which is again quite short.

The triangulated abutment portions were cast on falsework after which cantilever construction with form travelers was used to cast 3.50 m long segments. Each cantilever is prestressed longitudinally with 80 × 32 mm diameter Dywidag bars, and vertically with 28 mm diameter Dywidag bars spaced at 0.70 m. Each inclined tie-down is prestressed with 36 to 42 × 32 mm diameter Dywidag bars that carry the tie-down force from the cantilever extension to the common foundation that is shared with the inclined support. Here, the tie-down force is resisted by the self-weight of the bridge. Therefore, rock anchors (below the foundation) were only used during cantilever construction, and they were removed once the structure was made continuous.

Compression Forces Acting on These Bridges

It is interesting to note that bridges with inclined support reactions R / tie-down forces F, as given in *Figs. 3*–*5*, have the added advantage that the horizontal component of the support reaction / tie-down force adds compression to the bridge deck. The three diagrams in *Fig. 6* show the compression forces added to the deck for

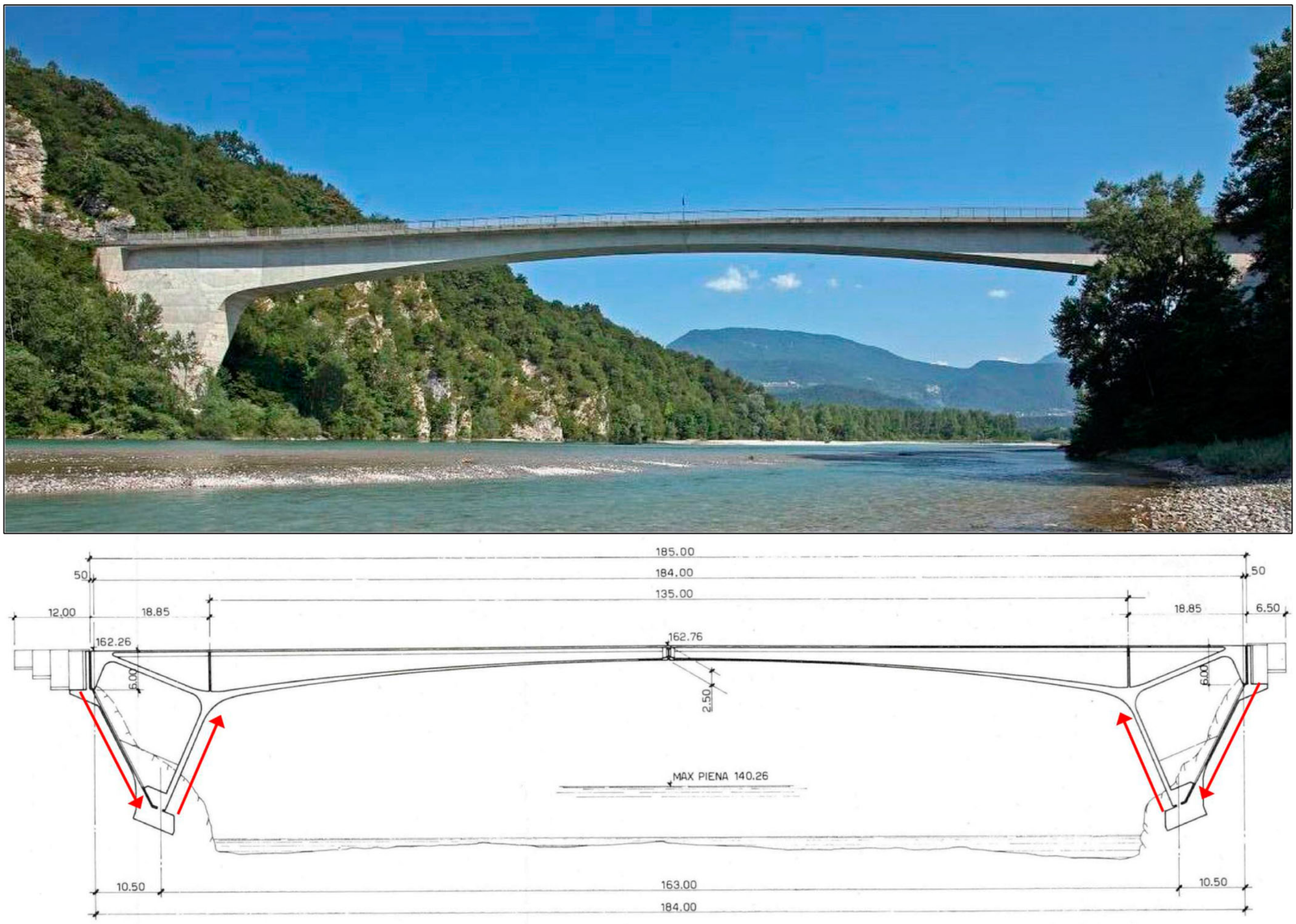

Fig. 5: Pinzano bridge (163 m span)

bridges of the Luzancy, Gänstor, and Pinzano type respectively.

The horizontal dimensions for this example are shown in the figure, while the vertical dimension is such that the bridge has equilateral triangular elements at each end (60 degree angles). The cross section of the bridge is the same as that shown in *Fig. 7*.

The Luzancy type bridge has inclined supports and vertical tie-down forces. The combined vertical reaction of the self weight and tie-down force is 589 + 484 = 1073 kN. This creates a compression of 1240 kN in each of the inclined supports. The horizontal component of these reactions adds a compression of 620 kN to the deck. This bridge thus behaves like a three member arch (with respect to compression). The vertical tie-down force of 484 kN has no component in the horizontal direction and therefore has no effect on the compression.

The Gänstor type bridge has vertical supports and inclined tie-down forces. The vertical component of the 559 kN tie-down force is 484 kN, while the horizontal component is 280 kN. This adds a compression of 280 kN to the entire bridge deck.

The Pinzano type bridge has inclined supports and inclined tie-down forces. The compression forces for this bridge are the superposition of the compression forces of the Luzancy type and Gänstor type bridges. The resulting compression in the deck is 620 + 280 = 900 kN between the inclined supports and 280 kN for the remainder of the deck.

As far as structural efficiency is concerned, the Pinzano type bridge appears to be the most efficient, as the inclined supports reduce the main span length while introducing the greatest amount of compression into the deck. The Gänstor type bridge appears to be the least efficient in that the main span length is not reduced and the smallest amount of compression is introduced into the deck.

Despite all of these advantages of inclined supports / inclined tie-down forces, this paper will proceed with vertical supports / vertical tie-down forces, as it is believed in general that construction will be easier. However, if additional main span length or deck compression is desired, one of these three solutions may be used to achieve this result.

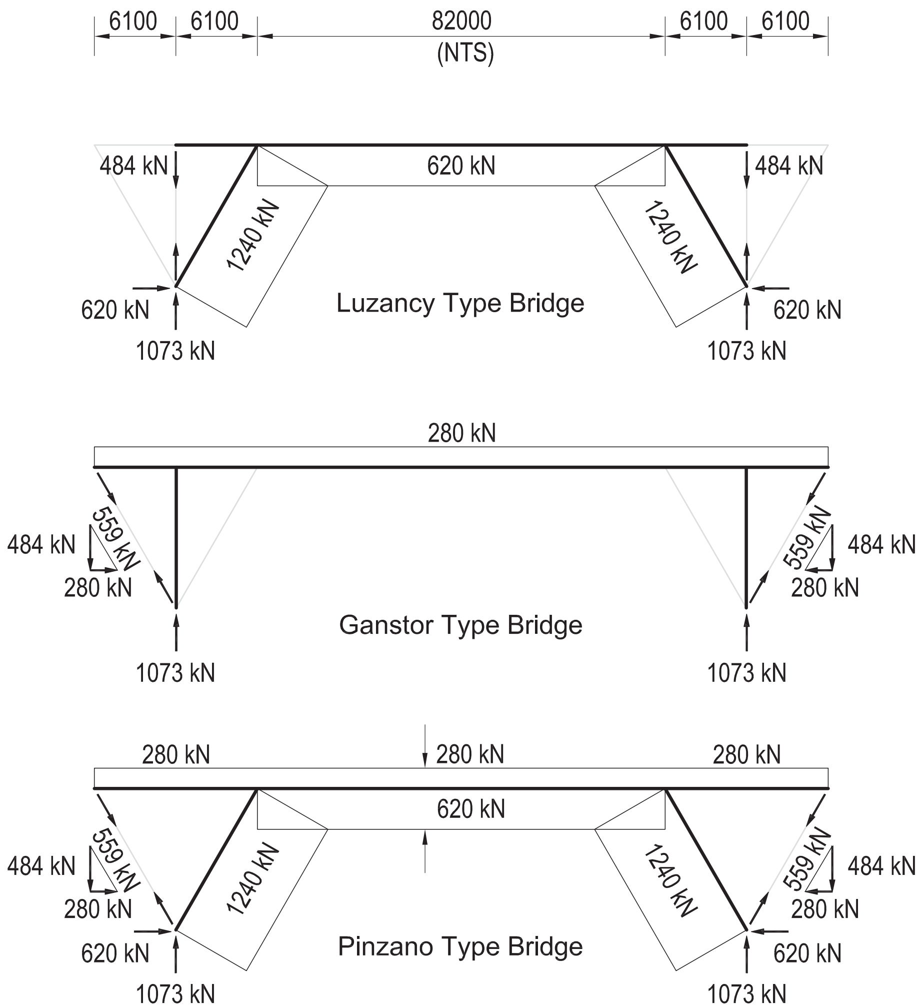

Fig. 6: Compression forces acting on three bridges

Design Example

Figure 7 shows the elevation and cross section for a proposed 82.00 m long variable depth cast-in-place segmental river crossing. The end cantilevers have a length of 13.67 m, which is a ratio of L/6 of the span length. (Shorter end cantilevers may be used, but the shear forces in them will be quite high and they will require vertical prestressing. The present example keeps the shear forces in the end cantilevers to within the same range as those for the main span.) The length of the bridge is 4/3 L or 109.34 m, which is significantly less than that of a three-span continuous bridge, which would be a minimum of 2 L to not have uplift at the ends, and most likely would be quite a bit longer (say 2.30 L = 0.65 + 1.00 + 0.65 L). The tie-down forces are applied at a distance of 0.60 m from the ends, giving an overall bridge length of 110.54 m.

The abutments shown are founded on driven piles, but they can also be on spread footings or drilled shafts (depending on the soil conditions). The tie-downs are rock/soil anchors, and the force in the tie-downs can be specified as some percent of the fixity force as discussed in *Fig. 2*.

The bridge has two 3.66 m traffic lanes and two 3.05 m shoulders, giving a clear roadway width of 13.42 m and an overall width of 14.33 m. The bridge depth is 4.10 m at the abutments (and the ends) and 2.05 m at midspan, which gives span to depth ratios of 20 and 40 respectively. Key dimensions of the box girder cross section are shown in the figure.

Figure 8 shows the segment layout and construction sequence for this cast-in-place segmental bridge. The bridge consists of 17.77 m long end portions that are cast on falsework, seven 5.00 m long cantilever segments on each side, and a 5.00 m long closure segment. There are 0.60 m thick diaphragms at the abutment and tie-down locations. The abutment diaphragms transfer the bearing reactions

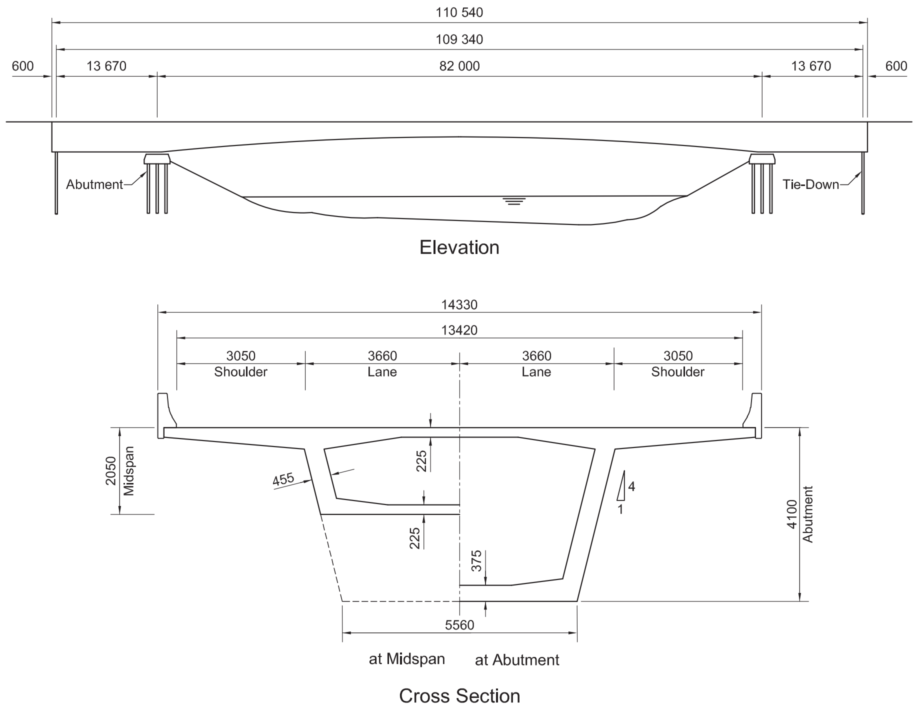

Fig. 7: Design example (units: mm)

from the webs, while the tie-down diaphragms transfer the rock/soil anchor forces distributed across the width of the box girder to the webs.

The construction sequence consists of casting the end segments on falsework and then activating the tie-downs. Form travelers are then used to cantilever out segment by segment until midspan is reached, whereupon the closure segment is cast. The form traveler has been assumed to weigh 45 tonnes (50 tons). Top cantilever tendons are stressed as each segment is erected, while bottom continuity tendons are stressed after continuity is established. The articulation is such that the pot bearings at both abutments are locked against longitudinal movement during construction, and one of the bearings is freed after closure, so as not to lock-in stresses in the main span. (An alternative design might be to have the superstructure monolithic with the abutments—this may be a more efficient design—but many of the generalizations made here would be difficult to describe as this design would be more site specific).

Figure 9 shows three bending moment diagrams for this bridge. The first shows that a tie-down force of 9817 kN acting over an arm of 13.67 m creates a negative moment of 134 200 kN-m. This negative moment shifts the self-weight positive moment of 143 200 kN-m down to 9000 kN-m, while also shifting the negative moment down to 159 200 kN-m.

The second diagram shows the positive moments at midspan and the negative moments at the abutments for superimposed dead load (barriers and overlay) and live load (AASHTO HS25 and HL93 loading). The third diagram shows that the combination of self weight, superimposed dead load, and HL93 live load gives positive and negative design moments of 71 100 kN-m and 177 100 kN-m respectively.

Actually, two different tie-down forces have been considered in this design. The first is a tie-down force of 9817 kN which gives the bridge a small reserve of positive moment under self weight (as shown in *Fig. 9*), while the second is a tie-down force of 11 450 kN which gives the bridge a small reserve of positive moment under permanent load (self weight and superimposed dead load). (These tie-down forces represent 120% and 140% fixity.) A reserve is necessary so as to not have a stress reversal at midspan when the transient live load acts on the bridge.

This second tie-down force gives positive and negative design moments of 48 800 kN-m and 199 500 kN-m respectively. This is actually more favorable, as this negative moment is essentially the same as the 199 900 kN-m that occurs during cantilever construction (with the 45 tonne form traveler), while the positive moment is reduced. However, as the shear forces in the cantilever extensions are becoming larger, and the net result of this second solution is a minimal reduction in the bottom continuity tendons, the first solution is maintained.

The prestressing tendon layout is shown in *Fig. 10*. There are 16 cantilever tendons (two for each segment) that are stressed as each segment is erected, and 9 continuity tendons (anchored in pairs at five segments) that are stressed after continuity is established and carry the service loads. Each tendon consists of 15 × 15 mm diameter strands (although a few of the cantilever tendons have only 12 strands in a 15 strand anchorage).

One end of each cantilever tendon is anchored at the face of a segment after it is cast, while the other end is anchored at the ends near the tie-down diaphragms. Here, twelve tendons are anchored at the top, while four tendons drape down and are anchored in the webs (so as not to have tension at the bottom of the section). The continuity tendons are anchored in bottom slab anchor blocks.

The tie-downs consist of a row of rock/soil anchors across the width of the box girder. Each rock/soil anchor is a high strength steel tendon with a stressing head at one end, and a transfer device at the other end to allow force transfer to the rock or soil.

It is imperative that these rock/soil anchors be adequately protected to prevent corrosion. The integrity of the bridge relies on these rock/soil anchors to provide a prescribed force, and even the partial loss of some of this force might prove disastrous and cause the bridge to collapse.

The rock/soil anchors need to be installed and grouted correctly using the latest technology. They should have multiple levels of protection in the same way as stay-cables have multiple levels of protection. Also, provision should be made during design to accommodate future contingency tie-downs that may be installed and stressed at any time during the life of the structure. This would be similar to future external post-tensioning tendons on segmental bridges that are designed to have their anchorage / deviation devices installed during construction.

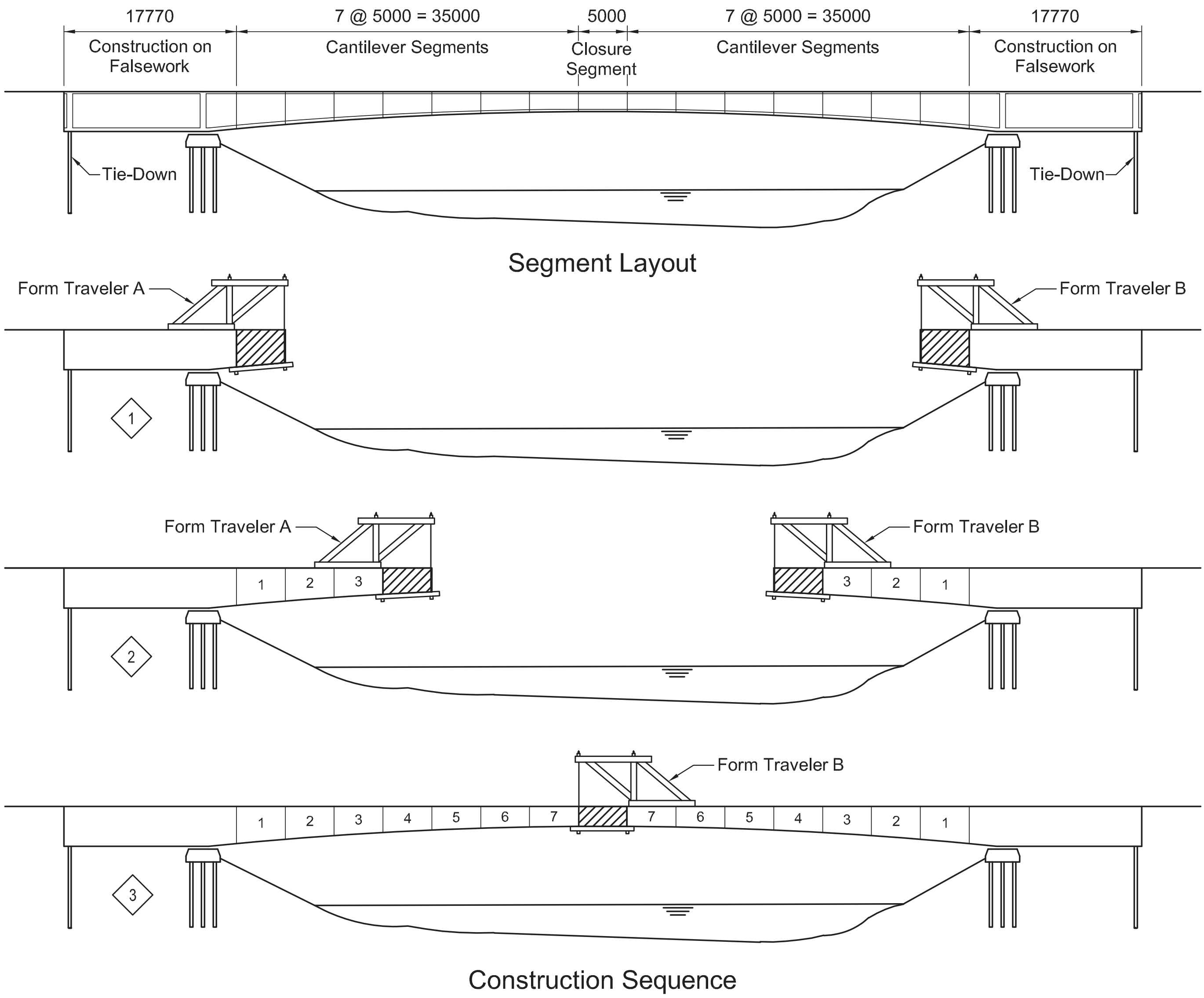

Fig. 8: Segment layout and construction sequence

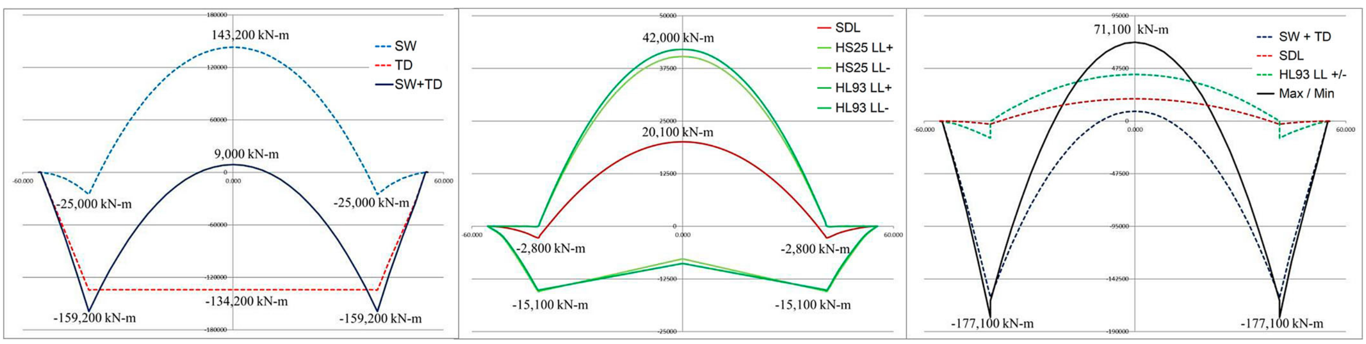

Fig. 9: Bending moment diagrams

Finally, just as health monitoring systems are being used for stay-cables and post-tensioning tendons, it may be prudent to consider something similar for tie-downs. Ensuring the durability of the tie-downs is a very important and serious subject, that may give significant opportunities for additional research and technical papers in this area.

Selected Applications

Four different bridge types that can readily be designed and constructed using the method described here are shown in *Fig. 11*. These bridges have the same span lengths and deck dimensions as the design example.

The steel I-girder bridge has five girders with a spacing of 2.90 m. The girder depth varies from 4.56 m at the abutments to 1.64 m at midspan, which gives span to depth ratios of 18 and 50 respectively. A similar steel box girder bridge with the same girder depths would have two box girders with a 3.60 m wide bottom flange and a space of 3.60 m between the girders.

Both of these bridges are built by first erecting the 30.67 m long abutment

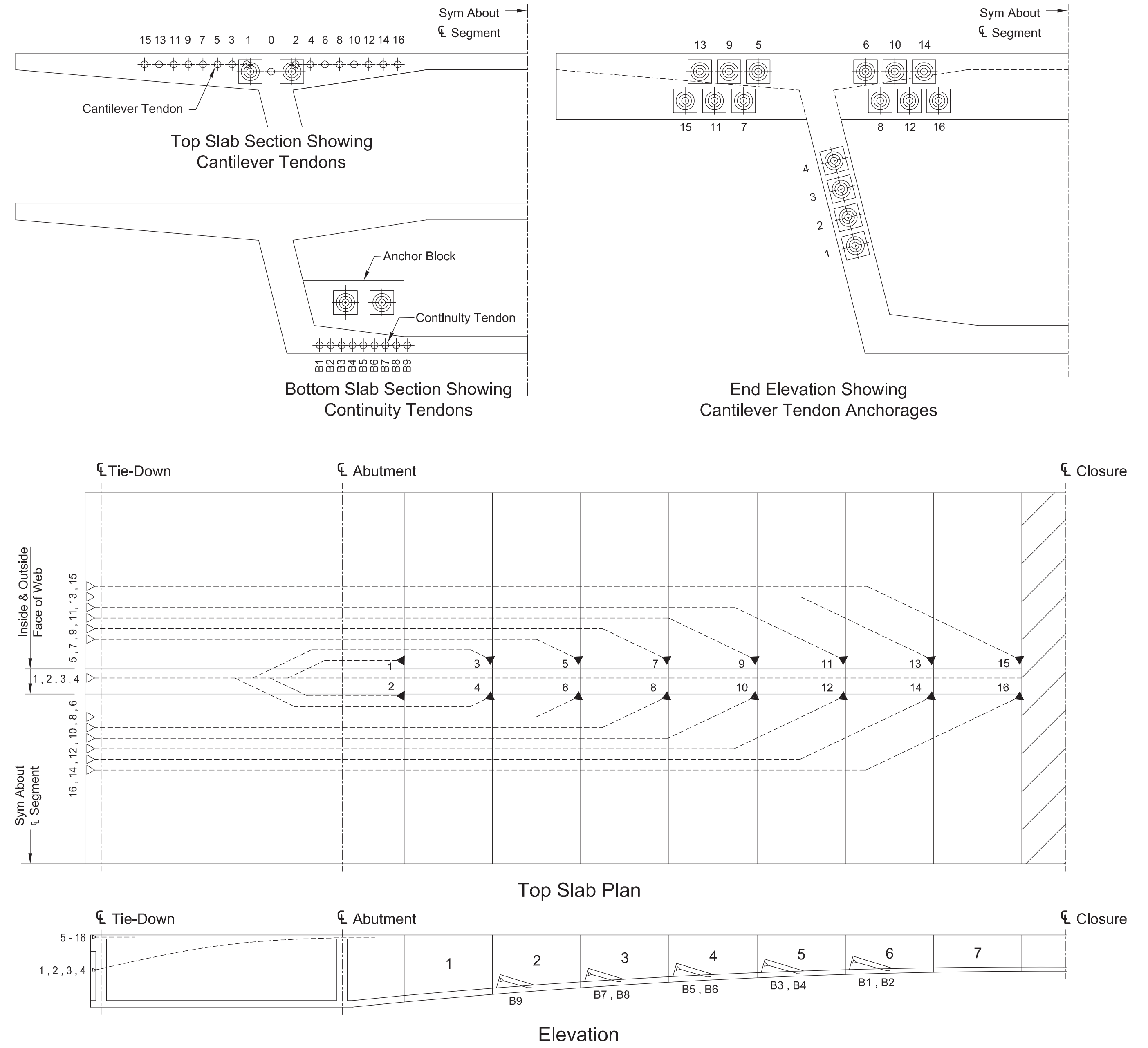

Fig. 10: Prestressing tendon layout

portions that have their tie-downs activated, and then dropping in the 49.20 m long main span portion of each girder. The deck is cast after all of the steel has been erected.

The precast spliced I-girder bridge has five girders with a spacing of 2.90 m. The girder depth varies from 4.56 m at the abutments to 2.28 m at midspan, giving span to depth ratios of 18 and 36 respectively.

Each of the five 110.54 m long girders is cast in three pieces, a "standard" constant depth 45.70 m long drop-in girder, and two "specialty made" variable depth 31.82 m long haunched girders (constant depth at the end and variable depth in the main span).

The haunched girders are erected first, after which the tie-downs are activated. The drop-in girder is then supported from hangers until the 0.60 m long closure pours are made at each end and the post-tensioning tendons are installed and stressed.

The drop-in and haunched girders are pretensioned, and the entire girder length is post-tensioned in two stages. The first is after the girders are continuous, while the second is after the deck is placed.

The cast-in-place concrete box girder bridge is similar to the cast-in-place segmental bridge, but has two cells instead of one cell. The girder depths are the same, varying from 4.10 m at the abutments to 2.05 m at midspan, again giving span to depth ratios of 20 and 40. This bridge has the same weight as the cast-in-place segmental bridge, since it has three 305 mm webs rather than two 455 mm webs.

This bridge is constructed entirely on falsework (with access openings as required). After the post-tensioning tendons have been stressed, the falsework is removed. By virtue of the extensive falsework required, application of this bridge type will most likely be limited to road crossings and not river crossings.

The precast segmental box girder bridge is similar to the cast-in-place segmental bridge given in the design example, with the only significant difference

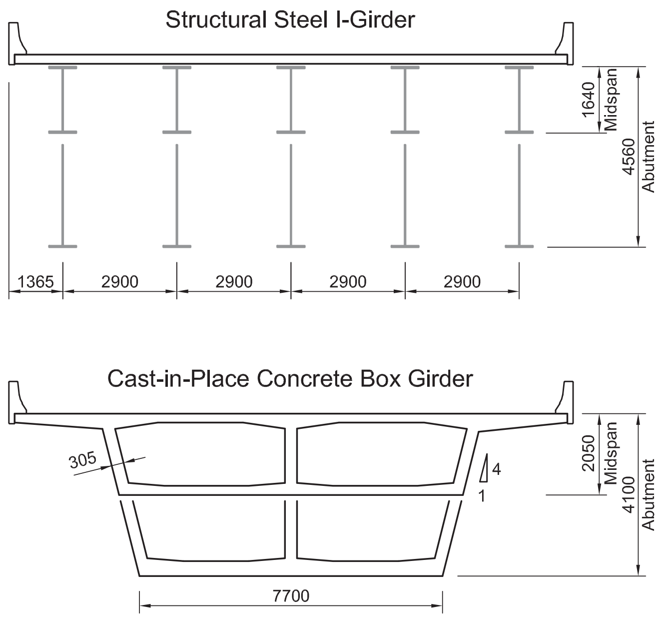

Fig. 11: Selected applications (units: mm)

being the segment layout. Rather than having seven 5.00 m long cast-in-place segments, this bridge would have fifteen 2.68 m long precast segments, in order to keep the maximum segment weight to under 68 tonnes (75 tons).

Abutment Treatments

Figure 12 shows two types of abutments that can be used to hide the cantilever extensions, and enhance the visual qualities of haunched single span bridges. Abutment type 1 has its wingwalls at the location of the box girder webs, while abutment type 2 has its wingwalls at the location of the barriers. Abutment type 1 is shown for a river crossing, whereas abutment type 2 is shown for a roadway crossing, but these are interchangeable depending on the site conditions.

With respect to the three famous historical bridges discussed here, the Luzancy Bridge has a type 2 abutment where the superstructure frames into masked abutments, while the Gänstor Bridge and Pinzano Bridge have type 1 abutments, where the superstructure and abutment wingwall appear as a single surface in elevation. Also, whereas the supports / tie-downs are hidden for Gänstor Bridge and Pinzano Bridge, they are clearly visible for the Luzancy Bridge.

Conclusions

This paper has presented a systematic method for the design of haunched single span bridges.

This design method uses short cantilever extensions with tie-downs, and discusses the use of various combinations of vertical / inclined support reactions and tie-down forces. Various degrees of fixity provided by the tie-down forces are also discussed.

Historical reference has been made to three very famous bridges with respect to vertical / inclined support reactions and tie-down forces. Additional compression forces added to the deck for each of these three types of bridges has been discussed.

A complete design example for a cast-in-place segmental bridge has been presented. The length of the cantilever extensions (to transmit the shear forces) and the degree of fixity (to carry negative and positive moment) have been discussed.

The design of the prestressing is very efficient, as the cantilever tendons provided to construct the bridge are more than adequate to carry the negative service load moments, and the requirement for bottom continuity tendons is greatly reduced.

Selected applications of the method to other bridge types have been

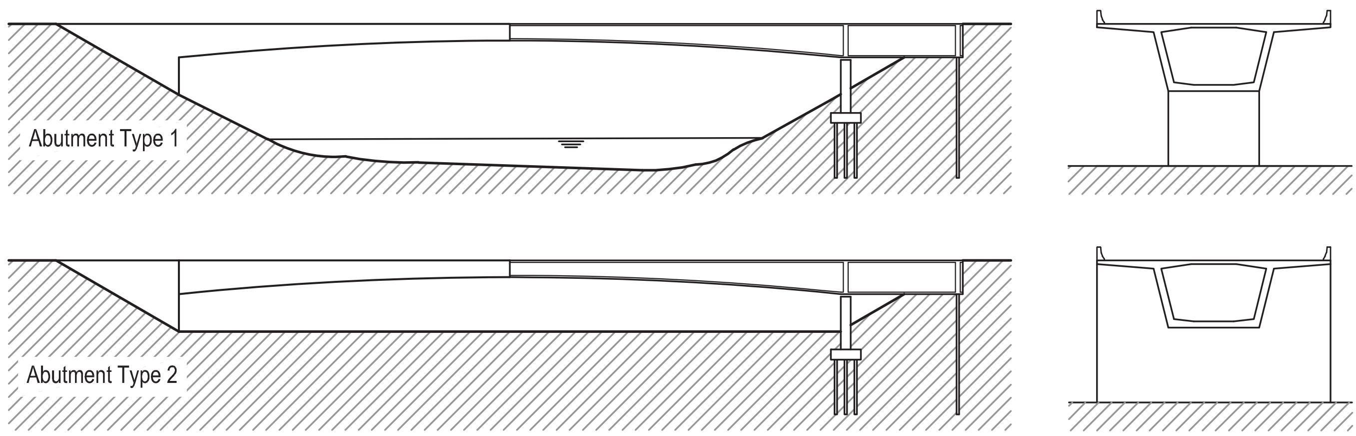

Fig. 12: Abutment treatments

discussed. Suitable abutment treatments for the application of the method to river crossings and road crossings have been presented.

Finally, an explanation of the behavior of Eugène Freyssinet's very famous and often misunderstood Luzancy Bridge has been presented.

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Appendix A: Some Notes on the Luzancy Bridge

The Luzancy Bridge[1–5] designed by Eugène Freyssinet (*Figure 3*) over the Marne River in France is a very special bridge. It is the first precast segmental bridge ever built. The bridge was post-tensioned in all three directions, and flat jacks were activated at the abutments to increase the level of compression in the bridge (and these flat jacks were reactivated later to counteract any unforeseen losses due to creep or abutment movement).

There has been some confusion about the structural behavior of this bridge, first because of the appearance of an upper compression strut in addition to the lower compression strut (inclined support), and second because of the appearance of a void above this upper compression strut in the line diagram (but not in the photo).

Let us discuss the void first. Careful inspection of the line diagram (by blowing it up) reveals that this is somewhat of an optical illusion. The upper opening appears only because there is no prestressing (or any other feature that needs to be shown or labeled) at this location. In fact, the right side at this location reveals a 20 mm segment joint, which is similar to the segment joints between all the other segments.

Now let us look at the upper compression strut. It is because the upper inclined element extends past the web of the box girder that additional lines outline this element in the line diagram and can be seen in the photo. What appears to be an upper compression strut is in fact the bottom flange of the cantilever extension, where the tie-down force creates negative moment with tension at the top and compression at the bottom (at this bottom flange).

To summarize, what appears as an upper compression strut is simply the bottom flange of the cantilever extension, and there is no void above this bottom flange. These two features may have contributed to the lack of understanding of this bridge and bridge type through the years. The definitive biography of Eugène Freyssinet has been written by Ordonez,[3] and many other works have been based on this material. With respect to the Luzancy Bridge, Ordonez has written:

The slimness of the beams is possible thanks to the end cantilevers formed by a triangular cell, whose two inclined elements work in compression and the vertical prestressed one works in tension (Pl. 323). The cantilever produces an oblique thrust which acts on the existing pillars some three meters below ground (Plates 315 and 316). The triangular cell is supported on the pillar by a Freyssinet hinge and several flat jacks, placed so as to regulate the thrust upon the pillars and thus the compression in the concrete. The jacks also enable the shrinkage losses and the eventual movements of the pillars to be compensated for.

Everything stated in this explanation is true, but it is hardly a clear explanation of the structural behavior, and nor should it be expected to be. Ordonez has written the only extensive volume on the life of Eugène Freyssinet, and it cannot also be a structural analysis textbook.

Freyssinet also used this solution for the Underground Basilica at Lourdes[10] (Figure A1). The structure was conceived by him in only fifteen minutes, and constructed from 1956 to 1958. It consists of 29 portal frames with tie-downs and can accommodate 20 000 people.

Figure A1 clearly shows the inclined supports and almost vertical tie-downs. The 12 cantilever tendons, 8 continuity tendons, and 3 tie-down tendons are also clearly shown and labeled. Each tendon consists of 12 prestressing wires each having a diameter of 7 mm.

The short cantilever extensions are extended further to the perimeter of the enclosed structure, where the 12 cantilever tendons are anchored. These carry the negative moment, while the 8 continuity tendons at midspan carry the positive moment. The dead end anchorage loops for 4 cantilever tendons can also be seen.

It should be noted that Freyssinet invented a new type of structural form with the Luzancy Bridge, Marne Bridges, and Lourdes Basilica; that is to say, a haunched single span bridge (or structure) having short cantilever extensions with tie-downs at the ends (and that form is precisely what this paper is about).

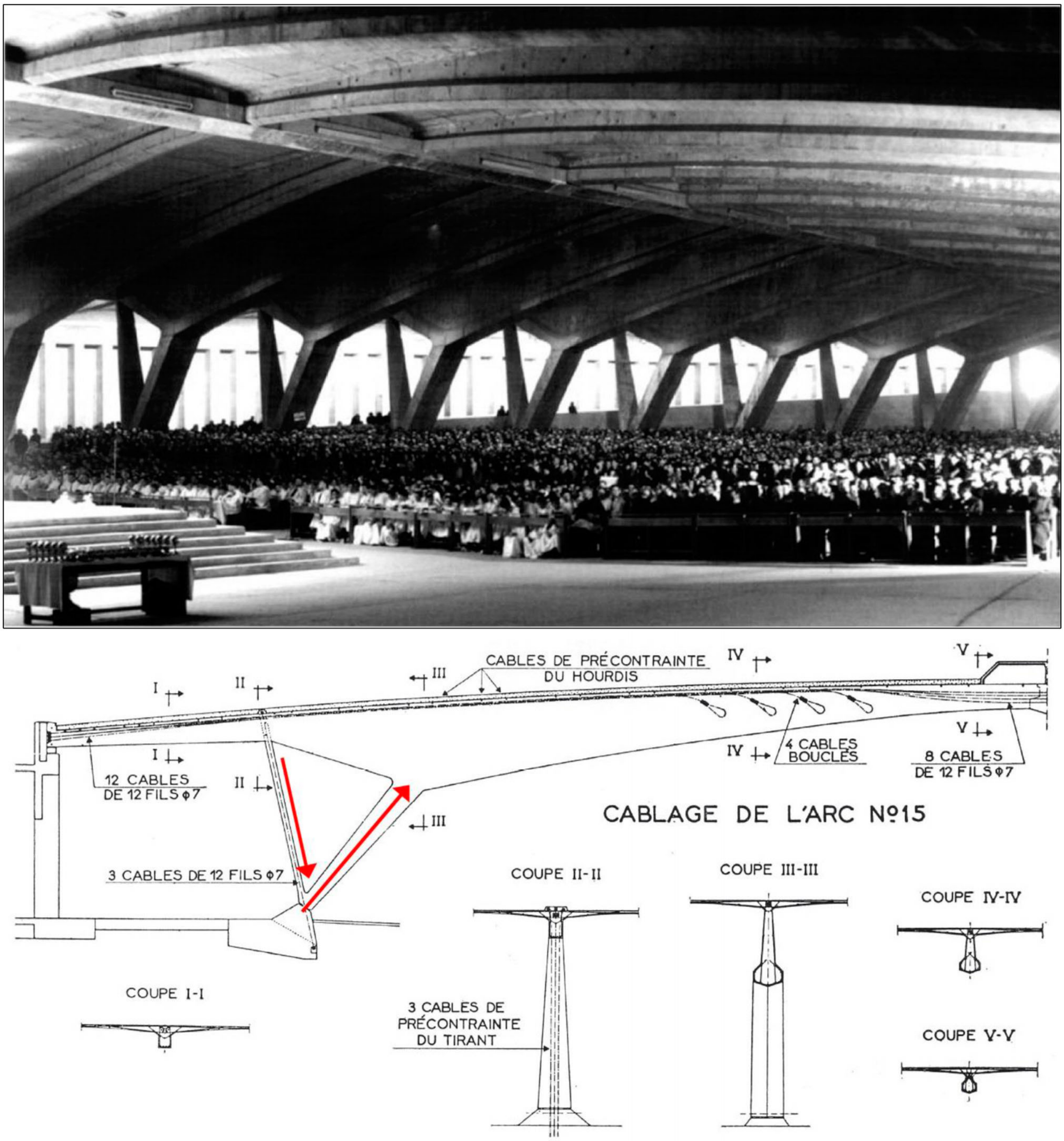

Figure A1. Underground Basilica at Lourdes.