Pier Optimization Using Support Condition and Pier Shape: Eyiste Balanced Cantilever Viaduct

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Abstract Balanced cantilever method (BCM) is becoming quite popular in the recent years as an efficient bridge construction technique in Turkey. There are numerous projects under construction or being planned. General Directorate of Highways (KGM) is the responsible government entity for the planning, construction and operation of these vehicular bridges.

Eyiste Viaduct is one of the remarkable examples of this method to be constructed in Konya, Turkey. The super structure has 9 spans with a maximum span of 170 m, totaling to a 1372 m in length: to be the longest balanced cantilever bridge in Turkey. Crossing a deep valley, the shortest pier is 32m, and the tallest pier is 155m in height.

For a long and tall balanced cantilever bridge, conventional balanced cantilever method with fixed deck/pier connection presents two problems: 1) Due to the height/rigidity difference between piers, almost all seismic force effects is attracted by the shortest pier; 2) Due to the longitudinal ~1200m fixed length, large forces are created both in the deck and the piers because of creep shrinkage and temperature (CST) effects. Moreover, the initial conventional design calls for box shaped 8mx8mx1.8m thick pier sections to resist the seismic forces. However, 8m wide pier surface creates critical wind forces for the 155m tall piers.

In order to create an economical design by solving these problems, various optimization options are evaluated. In the end, only the four tallest piers are cast monolithically with the deck, remaining supported on longitudinally sliding bearings, providing flexibility and reducing seismic effects. In addition, pier shapes are revised as the double wall section to reduce wind surface and to provide similar pier stiffness in transverse direction. Finally, these modifications provided an aesthetic, innovative and economic solution for the Eyiste Viaduct. Similar case studies around the world will also be presented.

1 Introduction

Balanced cantilever method is one of the most popular bridge construction methods around the world due to its major advantages. The concept of this technique is based on erecting the bridge deck without scaffolding, segment by segment. Balanced cantilever method (BCM) is effectively used to pass relatively large spans in the range of 80 to 200 m. It is preferred to build structures over rivers or deep and rugged valleys without needing access from the ground. Since the early 1960's, there are many examples of this method used all over the world.

In Turkey, one of the very first examples are the Yeni Kömürhan Viaduct (1986) in Adıyaman with 104 m main span, and the İmrahor Viaduct (1999) in Ankara with 115m main span length, both operating and serving to vehicular traffic today. In recent years, General Directorate of Highways (KGM), which is the responsible government entity for the planning, construction and operation of these vehicular bridges, has started to use this technique more frequently.

There are many balanced cantilever bridge projects under construction. Amasya Şehzadeler Viaduct with 160 m main span is one of these viaducts that is close to completion. Eyiste Viaduct is one of the remarkable examples of this method to be constructed in Konya, Turkey. The superstructure has 9 spans with a maximum span of 170 m, totaling to a 1,372 m in length, which will be the longest balanced cantilever bridge in Turkey. The viaduct crosses a deep valley; the shortest pier height is 32m and the tallest pier height is 155m. The elevation of the viaduct is shown in below figure.

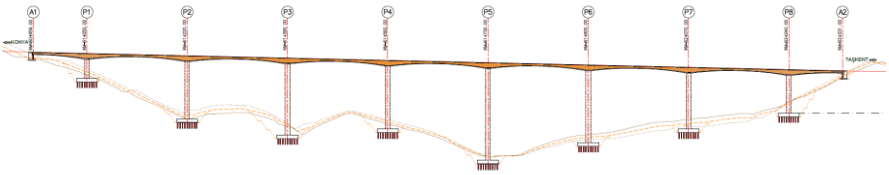


Figure 1. Eyiste Viaduct Elevation View

Table 1. Eyiste Viaduct –General Data

Owner	KGM
Designer	Inpro Mühendislik
Span Arrangement	91m + 7x170m + 91m = 1372m
Superstructure Width	12.5 m
No of Traffic lanes	2 lanes

2 Balanced Cantilever Method

In Cast in situ balanced cantilever method, generally the piers and the abutments are constructed first. Then, from one or more pier heads, deck segments are cast one by one, symmetrically and in a balanced fashion. To construct deck segments, a special moveable formwork equipment called formwork traveler is used. By using formwork traveler, the construction speed is increased, and segment geometry can easily be changed. It is possible to design and build with constant depth or linear, parabolic variations on bridge geometry.

Figure 2. BCM during cantilever construction [1]

During the construction process, generally one side of the deck is cast earlier than the other side. After concrete reaches the predetermined strength, cantilever posttensioning tendons, which are located at top portion of the deck slab are stressed, and the formwork equipment is moved to form the next segment. This typical cycle continues until the closing segment is cast. After closing segment construction, to provide the continuous frame behavior, continuity tendons that are located at bottom slab of the deck are stressed. Finally, the superimposed dead loads like asphalt, sidewalks, barriers, etc. are built, and the bridge is completed.

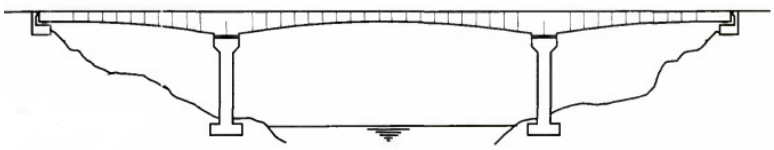


Figure 3. BCM completed [1]

Due to the nature of the conventional balanced cantilever construction method with fixed pier and deck connection, deck has to be continuous without any expansion joints. Especially in longer bridges, this continuous length causes extra forces and stresses on both the piers and the deck, due to the temperature, creep and shrinkage effects.

3 Eyiste Viaduct

Eyiste Viaduct located in Konya, passes over a deep and long valley. Deck is 12.5 m wide and carries two traffic lanes. Deck is chosen as single cell box girder with parabolic height change form pier to mid span. The deck height at midspan is 4m and at the pier head is 10m. The initial design calls for box shaped pier sections (8x8x1.8m thick), all of which are cast monolithically to the deck. The typical cross-sections are given in Figure 4. The Viaduct has 9 spans (91+7x170+91) totaling to 1,372m in length, with relatively short (32m) and tall piers (155m).

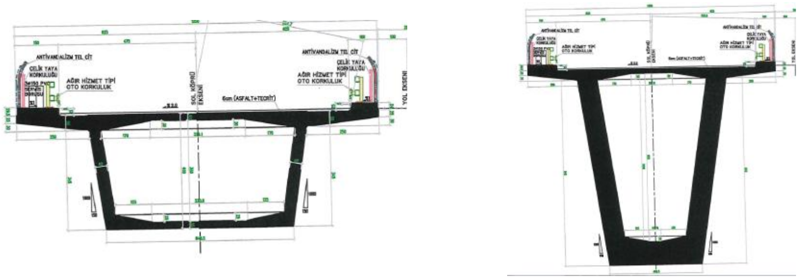


Figure 4. Eyiste Viaduct typical deck cross-sections

The long fixed deck length (more than 1,200m) and varying pier heights presented two important problems in the initial viaduct design. Firstly, the short piers are stiffer, hence almost all the seismic force effects is attracted by the shortest pier. Secondly, due to the long fixed deck length, temperature, creep and shrinkage forces at side piers and at the deck are created. Moreover, to resist these large forces, initial design calls for box shaped 8x8x1.8m thick sections for all piers. However, 8m wide pier surface creates critical wind forces for the taller piers in transverse direction.

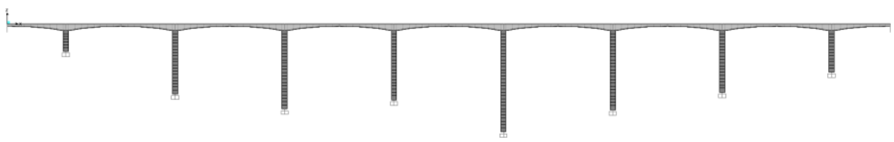


Figure 5. Eyiste Viaduct model with initial sections.

The viaduct is modelled as a 3d frame in CsiBridge and analyzed under vertical and lateral forces. AASHTO 2002 load combination definitions are used. For seismic load case, maximum spectral response coefficient is selected as 0.2g per AASHTO 2002. In the modal analysis, longitudinal vibration period is found as 1.99s. Due to the difference in rigidity, shortest pier is the critical one under longitudinal seismic force and the longest pier is the critical under transversal wind combination. Using these reactions in the initial design, foundation and piles are designed and sized accordingly. As a result of this preliminary design, it is decided that the viaduct design has to be optimized.

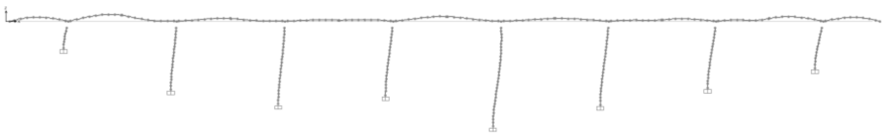


Figure 5. Eyiste Viaduct deformed shape under longitudinal seismic force.

4 Optimization Study

In order to find an economical solution, similar cases around the world and various optimization options are evaluated.

For this purpose, Tulle Viaduct (2003) with 180 m maximum span and 150 m maximum pier height, and the Sioule Viaduct (2005) with 193 m span length and 135m pier height, are reviewed. In these cases, to reduce the time dependent effects like the creep/shrinkage and temperature, free sliding bearing are used in the longitudinal direction.

Figure 6. Tulle Viaduct (2003), France [2].

During construction, all piers are connected to the deck structure using high-strength Freyssibars (Figure 6). After the cantilever construction is completed, bars are released and sliding bearings are installed in the longitudinal direction. Only a few piers that are required for longitudinal stiffness – usually the taller mid piers – are cast monolithic with the deck structure. Sliding bearings reduces the fixed deck length and let the deck move freely under CST and seismic effects, longitudinally. Using less stiff piers increases the vibration period and reduces total seismic force in the longitudinal direction.

In the transverse direction, all piers are restrained to the deck. To avoid the rigidity difference, pier shapes are designed accordingly: fixed mid piers start with solid section at the base and transforms to a less stiff double wall section (wall length in longitudinal direction); and the side piers are designed as single wall section (wall length in transverse direction) to resist the transversal seismic forces. Using these different pier shapes, almost uniform stiffness in transverse direction at all piers are achieved. In addition, using double wall shaped elements at tall piers helped reduce the pier surface area and consequently reduce the wind force effects.

In the 3d analytical computer model, short pier deck connections are modified as free to move in longitudinal direction. Four tall piers in the middle deck portion remained with fixed connections in longitudinal direction, to reduce seismic forces (by increasing the period) and limit the displacement at the same time. Then, to provide a uniform load distribution in the transverse direction pier shapes are modified as explained above. About 95 meter from the deck level, all piers are defined as double wall section, except the shortest one. Wall section is chosen as 10x1.5m with a spacing of 5.75 m in between. Lower portion of the piers are chosen as relatively rigid box section (10x13x1.5m). Also, using the double wall section provided an aerodynamic effect and smaller wind surface area. Elevation view of the model after the modifications can be seen in Figure 7.

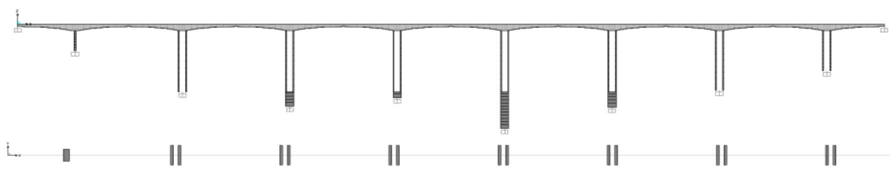


Figure 7. Eyiste Viaduct modified model.

In the computer model, all piers are rigidly connected to the deck during construction. In service, ultimate and extreme event cases, sliding and fixed bearing conditions are defined, as shown in Figure 8.

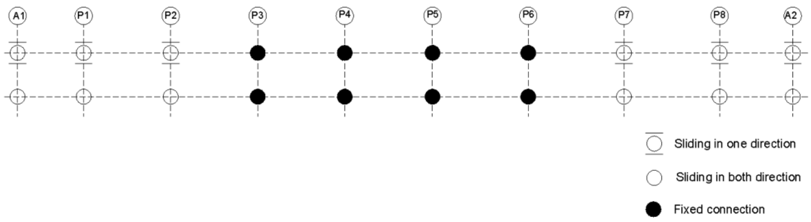


Figure 8. Eyiste Viaduct modified bearing conditions

The longitudinal vibration mode is found as 16.6s (Figure 9). As a result, total seismic force is decreased and the displacement in longitudinal direction is increased in acceptable limits.

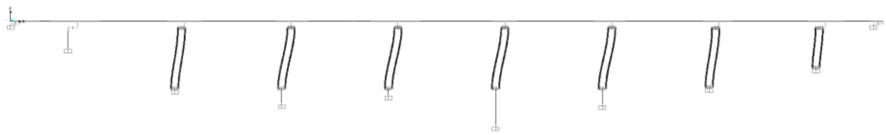


Figure 9. Eyiste deformed shape in longitudinal seismic force of modified model

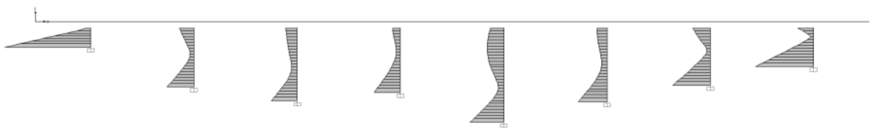
5 Comparison of Results

Modifications on the initial design brings many advantages to the project. Using sliding bearings at side piers has made the structure less stiff and increased the longitudinal vibration period reducing total seismic force effects. Comparison of this force difference in each direction is summarized in Table 2. Using this force, pier cross-sections are optimized. As a result, foundation dimensions and the number of piles needed reduced. These changes in the amount of material needed has reduced the total cost of the project. The base forces under seismic effects are given in Table 2.

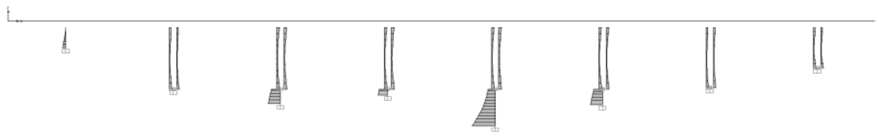
Table 2. Seismic base reaction comparison

INITIAL DESIGN					
OutputCase	**CaseType**	**StepType**	**GlobalFX**	**GlobalFY**	**GlobalFZ**
			kN	kN	kN
EX	LinRespSpec	Max	117,449	0	9,107
EY	LinRespSpec	Max	0	47,260	1
MODIFIED MODEL					
EX	LinRespSpec	Max	15,862	0	883
EY	LinRespSpec	Max	0	34,885	0

As it is seen in Table 2, the total seismic force in longitudinal direction (X) is decreased remarkably (ratio:0.14). In the transverse direction (Y), the seismic base force is also reduced (ratio:0.74), however wind force effects govern the design in transverse direction. Moment distribution on piers is also changed drastically, which can be seen in Figure 10. In the initial design (Fig.10a) shortest column (P1) attracts about 1,412,630 kNm moment and the tallest pier (P5) attracts about 555,695 kNm. In the modified model, maximum moment on P1 is 50,133 kNm (ratio:0.04) and the maximum moment on P5 is 365,295 kNm (ratio:0.65).



(a)



(b)

Figure 10. Eyiste Viaduct longitudinal seismic force moment distribution (a initial design; b, modified model)

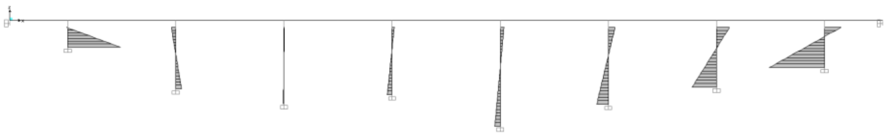
The reduced stiffness and increased period has an adverse effect on displacements. In the longitudinal direction, the stiffness is provided by four tall piers. Hence, the average displacement in longitudinal direction is increased from 13cm to 75cm, and in the transversal direction maximum displacement is reduced from 61cm to 54cm.

(a)

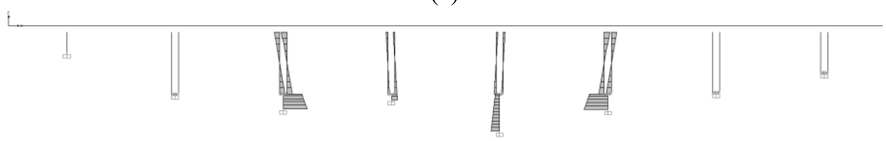
(b)

Figure 11. Eyiste Viaduct transversal seismic deformed shapes (a. initial design; b. modified model)

Changing fixed connection to sliding bearings also changed the moment diagrams due to temperature effects. ±20 C^0 uniform temperature change is applied in both models, and the results are shown in Figure 12. In the modified model, friction between bearing and the deck is ignored and moment values are output at only in fixed piers. In the initial design, the shortest pier (P1) attracts 831,867 kNm, and the tallest pier P5 attracts about 84,428 kNm moment due to CST effects. In the modified model, naturally, pier P1 and the other piers with sliding bearings attracts no moment due to CST, but pier P5 attracts about 4,500 kNm of moment. Displacements due to CST effects in the initial model is about 5.2 cm, whereas in the modified model the farthest points displaces about 13.7cm due to CST.



(a)



(b)

Figure 12. Eyiste Viaduct pier moment diagrams due to uniform temperature change (a. initial design; b. modified model)

Comparison of material quantities for the foundations of piers P1 and P5, before and after optimization are summarized in Table 3.

Table 3. Quantity comparison for foundations

Foundation		Initial Design	Modified Design	% Difference
P1	Concrete (m^3)	8,640	3,200	-63
	Rebar (t)	979	352	-64
	# of Piles	90	50	-44
P5	Concrete (m^3)	8,640	6,720	-22
	Rebar (t)	1904	840	-56
	# of Piles	90	70	-22

6 Conclusions

This paper presents the findings of the optimization study for the Eyiste Viaduct, which is planned to be constructed in Konya, Turkey. The initial, conventional design of the Eyiste Viaduct is presented. Due to the long fixed deck length and pier stiffness difference, large pier sections are required. Sioule and Tulle

Viaducts, which are constructed and in operation in France, are reviewed. It is seen that similar geometrical properties do exist in these bridges. Various trial and error runs are applied to the initial design of the Eyiste Viaduct, until an optimized geometry and bill of quantities are achieved. Changing the deck pier connection type at side spans with sliding bearings helped to increase the vibration period and reduce the seismic forces. Pier geometry is changed in order to provide uniform stiffness in both directions, and in order to reduce the wind effects in transversal direction. Finally, the quantity comparison between the initial and the modified design is presented. It is seen that the modifications on the initial design provided an aesthetic, innovative and economic solution for the Eyiste Viaduct.

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2. Photos credit to Jacques Mossot (www.structurae.net)