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ECONOMIC REVIEW OF VARIATION OF PRESTRESSED GIRDER LENGTH ON BRIDGE CONSTRUCTION PRACTICES

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ABSTRACT - In the last decade, long-span continuous beam bridges have been built to meet the need of the total bridge length requirements for obstacle avoidance. In almost 100 years of development of bridge construction coupled with the development of concrete technology, the maximum bridge length, which was originally about 20 m, currently has reached a length of 50 m or longer with the use of prestressed construction. The longer girder length will reduce the number of pillars, minimize the possibility of damage to the pillars due to local scouring or expand the coverage of the free area under the bridge. This study aimed to evaluate the economical aspect of the use of prestressed girders with length variations of 40 m, 50 m, and 60 m. The analytical calculations were carried out based on the applicable standards of bridge design. The results of the study indicated that the most economical configuration for a long span bridge (200m-400m) is the use of a prestressed girder length of 50 m with a girder cross-section height of 2.10 m. However for 480m bridge lengths, 60m PCI girder lengths tend to start out lower. It can be concluded that for a longer bridge span, a longer PCI girder is also required.

Keyword: Prestressed Concrete (PCI) Girder, Long-Span Bridge, Continuous Beam, Economical Configuration

1. INTRODUCTION

The rapid development of traffic volume especially in urban areas demands the expansion of road infrastructures, such as bridges and flyovers.

Precast concrete girders have gained increasing popularity in the last decade in bridge construction in Indonesia owing to its rapid construction and structural simplicity. Prestressed (PCI) girders are one concrete precast girder type that is most popular in the construction of bridge and flyover. In the case of long span beam structures, the span is divided into several lengths and is supported by pillars. Thus, the span of the girder will determine the number of pillars necessary to support them. The shorter span will need a larger number of pillars.

A study on the cost-effectiveness of bridge construction methods through the application of value engineering indicates the significant impact of pillars construction cost on the total cost of bridge construction [1]. The study indicates that the use of fewer pillars is preferable to reduce the total cost of bridges.

In developed countries, the use of long-span precast girders of up to 194 ft (59 m) [2] is a common practice. Owing to the development of prestressing techniques as well as concrete technology, the use of precast girders continues to increase in length. For instance, the Route 22 Bridge over the Kentucky River was initially built as a steel structure but was changed into a spliced, post-tensioned, precast concrete girder bridge that features a 325-ft-long (99 m) main span to become the longest span of this type in the United States [3]. Longer span is available but with the use of precast box girder.

In Indonesia, the development of precast concrete girders can be observed from the story Srandakan Bridge located in the Southern area of Jogjakarta. The first Srandakan bridge was built almost 100 years ago at about 1925. The 531 m long bridge was consisted of 59 of 9 m length steel girders and supported by in total of 58 pillars across the Progo River. When pillar stability disruption took place due to surrounding environmental degradation, the large number of pillars will obviously be in the risk of further damage and hence threaten the stability and safety of the bridge structures. Due to the continuous scouring effect of the river as a result of excessive sand mining exploration coupled with the increasing number as well as a load of traffic passing on the bridge, some of the pillars experienced a considerable level of a settlement. Some of the girders followed to move downward, although still supported by damaged pillars, that disrupted the bridge’s rideability and endanger the bridge's structural stability [4]. Since then, the bridge was out of service.

In 2005 the Srandakan Bridge II was built downstream to the old one. Similar to the old bridge, the 625.75 m long new bridge and was constructed as a series of the simply supported beam of a longer span. The new one consists of two spans using different girder lengths. The first span uses 14 girders with a length of 35 m and the second uses 3 girders with length 40.8 m. The total span of the bridge is supported by 16 pillars. For the structure of the Srandakan Bridge II, typical precast concrete girder of I shape or commonly called as Prestress Concrete I girder or often known as PCI girder was used [4]. It is interesting to note that some of the recent prestressed bridges constructions in Indonesia also used the same girder length of 40 m or even less.

For instance, the Bogem Bridge in Yogyakarta was constructed with 3 PCI girders of 23 m each. Similarly, the Causeway section of the Suramadu Bridge [5] as well as in the Terminal Flyover Gulf Lamong also uses of PCI girder length of 40 m [6]. The flyover at the segment of Cimanggis-Cibitung employs PCI girder 40 m length, while the Overpass bridge at STA 44+010 Tebing Tinggi – Parapat motorway also used 40,8 m girder length. Lately, one of the state own enterprises, PT Wijaya Karya [7] introduced the production of PCI girder of length up to 52 m. This means if there is a bridge whose longer span might use longer girder length to reduce the number of pillars. For instance, a bridge san of more than 100 m can be designed with only two upper structures of a continuous beam with 2 PCI girders and 1 pillar. Although the use of girder of a longer length might reduce the number of pillars, reduce the total cost of the bridge and hence minimize the potential occurrence of local scours on the pillars, it is interesting to discuss further the common construction practices in using PCI girder on why only PCI girder length of 40m was commonly used in practices.

Therefore, this research aimed to study the efficiencies of the use of PCI girder of various lengths, namely 40 m, 50m, and even up to 60 m. The parameters of the study were moments and cost of construction of bridge using PCI girders of various lengths, including pillar and foundation.

An accelerated method has been applied on a bridge construction in high earthquake area [8]. The experiment found that an inverted tee-cap beams can be superior for using precast concrete elements in the bridge superstructure. Thus, the cost of bridge can be optimized effectively, and the girder-to-cap joint area can be handled properly. For a short to medium span bridges, life cycle-cost analysis (LCCA) was an power tool to review the cost project. Extensive study of 57% Indiana NBI bridges on cost-effectively design have been studied by Leiva Maldonado and Bowman [9]. The investigation classified three groups of span length, and various type of superstructures including bulb tees, AASHTO prestressed beams, slab bridges, prestressed concrete box beams, steel beams, steel girders, folded plate girders and simply supported steel beam which were loaded by dead and continuous-live load. The addition of long-term costs using LCCA has been shown to generally minimize the cost-effectiveness gap between all alternatives over the same length of time. When unique site conditions are considered during the study, this reduction may be a significant factor. If complex site conditions are established, before selecting the best choice, several alternatives for each span length must be considered.

2. LITERATURE REVIEW

2.1 Beam Pre-Stressing Methods

Concrete has a disadvantage owing to the large self-weight that makes it inefficient for long-span structures. However, the introduction of the prestressing method in concrete structures has made it possible to employ a longer span of the concrete element. Pre-stressed concrete is concrete structures where large internal stresses and at certain distributions are given in such a way as to counter stresses due to external loads to the desired level [10]. The calculated stresses in prestressed concrete must take into account the following matters [11]:

1. Transfer conditions with initial prestressed force and limited load (dead load and construction load).
2. The initial calculation of prestressed force loss is usually set at 25% for the pre-tension system and 20% for the post-tension system.
3. In the service condition (service) has worked an effective prestressing force (calculated loss of prestressing force) and maximum load (dead load, live load, and other influences).

2.2 Loading Stage of Prestressed Concrete Beam

There are two methods for the process of stressing precast concrete, namely: the Pre-Tension Method, where prestressed steel is given a prestressed force before concrete is cast and Post-Tension Method, where cable channels or tendons called ducts are prepared in their tracks then concrete is cast and stressed at an appropriate age [11]. The construction of prestressed concrete should be considered at least two stages of loading, namely:

a) Transfer Phase: In the transfer condition, the workload is only self-weight, the weight of the workers and work equipment, while the live load or external load has not worked at all, so that at this stage the workload is minimal, while the prestressing force is at maximum work because it has not yet occurred losing prestressing force, and
b) Service stage: in this stage, Pre-stressed concrete has been used or functioned as a structural component so that external loads such as vehicle live loads, wind loads, earthquakes, etc. start working which causes prestressing force loss. The loss of prestressing force must be analyzed because it will reduce the prestressing force in the tendons.

2.3. Characteristics of Prestressed Concrete Beam

The height of the prestressed beam section ranges from 65 to 80 percent of the height of a normal concrete structure. Prestressed concrete structures require less concrete but need about 20 to 35 percent more steel reinforcement. It is mentioned by [12] that the use of high strength concrete girders offers excellent opportunities for extending the effectiveness of I girder for bridge structures. These provide greater savings when calculated for manufacturing per unit of precast in the long run. These savings are derived from fewer maintenance costs due to better concrete quality control. Less use of concrete results in smaller foundations due to the lower cumulative weight of the upper structure, so that there are savings from the use of less concrete. However, these savings must be paid back again due to the high price of high-quality materials demands for prestressed concrete. Although it is more economical in terms of the use of concrete, the prestressed system itself raises additional costs. Besides, the molds for prestressed concrete also becomes more complex, because the cross-section of prestressed concrete, in general, has a winged cross-section with several thin bodies [13].

The type I girder beam has been widely used in bridges and flyovers design because it is easy to work with and is suitable for most field conditions [14,15]. The weakness of the use of type I girder is its inability to carry the torque/ torsional load so it is not suitable to be applied on bends. In a study carried out on the effect of torsion on the stability of segmental concrete bridges [16], it was concluded that torsion has a significant effect on the structural behavior segmental girder beams. Moreover, torsion not only alters the failure load of the beam but also changes the type of failure mechanism. The shear and torsion chapter consists of a collection of complex, restrictive, empirical equations which, while leading to safe designs, lacks an understandable central philosophy [17]. Furthermore, type I girders with a combination of prestressed concrete materials are considered cannot be used for large spans owing to the heavy self-weight of the structures that it is no longer effective [11].

In this research, the bridge loading refers to Indonesian regulation [18] while the earthquake load review refers to [11]. Bridge design must refer to the boundary conditions required to achieve development targets, safety, and service aspects by taking into account the ease of inspection, economic factors, and aesthetics. The loading of the bridge will be selected based on technical and environmental factors.

Loss of prestressing is the reduction of force acting on the tendon in the initial stages of loading and may occur due to various reasons, such as those that occur during the stressing of steel tendon (jacking) or at a certain time after the completion process when already in function. In general, the loss of prestressing force can be classified as follows [11]: 1). Immediate loss (Immediate elastic losses): Loss of prestressed force that occurs directly after the concrete is prestressed. 2). long-term loss (time-dependent losses): long-term loss is the loss of prestressing force by time, which is caused by a. shrinkage concrete (shrinkage), b. concrete creep (creep), c. prestressed steel relaxation.

The allowable stresses on the prestressed beam must be controlled by magnitude as follows [19]:

1) Steel tension

a) allowable stress due to jacking force does not exceed

$$f_{pj} = 0.94 f_{py} \quad (1)$$

Which is not greater than the smallest value between 0,80f_{pu} and the maximum value suggested by the tendon manufacturers. f_{py} is specified yield strength of prestressing tendon. f_{pu} is the ultimate tensile strength of prestressing tendon.

b) Immediately after the transfer of the prestressed force, do not exceed

Tensile stress,

$$f_{eff} = 0.82 f_{py}, f_{eff} = 0.74 f_{pu} \quad (2)$$

c) post-pull tendon after pruning, not exceeding

$$f_{eff} = 0.70 f_{pu} \quad (3)$$

2). Concrete stress

a) Transfer conditions, do not exceed

Compression, $f_{at} = 0.60 f'_{ci}$ (4)

Compression, $f_{at} = 0.70 f'_{ci}$ (5)

(at the beam edge)

Tension, $f_{bt} = 0.25\sqrt{f'_{ci}}$ (6)

Tension, $f_{bt} = 0.50\sqrt{f'_{ci}}$ (7)

(at the beam edge)

If the tensile stress exceeds the values listed above, additional reinforcement must be provided (non-prestressed reinforcement or prestressed reinforcement) in the tensile area to withstand the total tensile stress of the concrete calculated with the assumption that the cross-section is not cracked.

b) Service conditions or workload, do not exceed:

Compression, $f_{as} = 0.45 f'_c$ (8)

(due to prestressed and fixed load)

Compression, $f_{as} = 0.60 f'_c$ (9)

(due to prestressing and total load, where the transient load works quite large)

Tension, $f_{bs} = 0.50\sqrt{f'_c}$ (10)

In the design of prestressed beams based on the ultimate limits state, the design of the moment of the capacity of the T beam (beams and slabs are considered monoliths) that considered two conditions, namely rectangular beam and T beams, in the design it is assumed that the tensile beams are in a cracked state. The cross-section is said to be a T beam if it has slab/flange conditions in a compression state, monolithic condition of slabs and beams, and a neutral axis is located on the cross-section of the body.

Total of moment

$$M_r = \phi\, M_n \geq M_u \quad (11)$$

with ϕ = 0.8

For the calculation of shear strength, referring to [15], basically concrete can accommodate shear stresses that occur in the cross-section, but often shear that occurs at the cross-section is much greater than the shear strength provided by concrete (V_c). If this condition takes place it is necessary to provide additional reinforcement in the form of shear reinforcement (V_s) to overcome the lack of stress that cannot be covered by the concrete shear strength.

1) Nominal shear strength (Vn)

$$V_n = V_c + V_s \quad (12)$$

2) Plan shear limit strength (Vr)

$$V_r = \phi * V_n \geq V_u \quad (13)$$

with ϕ = 0.7

For the calculation of torsion strength, based on [15], the effect of the torsion may be ignored if the moment of torsion (T_u) is less than the critical torsion moment (T_{cr}).

I. Critical torsion moment (T_{cr})

$$T_{cr} = 0.083\lambda\sqrt{f_c'}\left(\frac{A_{cp}^2}{p_{cp}}\right)\sqrt{1+\frac{f_{cp}}{0.33\lambda\sqrt{f_c'}}} \quad (14)$$

II. Torque Resistance Moment (T_r)

If $T_u > T_{cr}$, the cross-sectional design must be based on the moment of torque resistance

$$T_r = \phi\, T_n \geq T_u \quad (15)$$

where T_n calculated by

$$T_n = \frac{2A_o A_t f_{yt}}{s}\cot\theta \quad (16)$$

with ϕ= 0.7

3. METHODOLOGY OF RESEARCH

In this research, the focus of the study is to review the use of various PCI girder length of 40m, 50m and 60m length, to be applied to bridges that have a total bridge span of 200 m, 300 m, 400 m, and 480 m. Each of the long span bridges was divided into several structural configurations as presented in Figures 2, 4, 6, and 8. Each structural configuration was compared one to another in terms of strength (moment capacity), total efficiency (price) of PCI girder, pillars, and foundations. In this study, the Landak II Bridge data in Pontianak, West Kalimantan were used in the form of material, soil, and loading data. The analysis is manual using Microsoft Excel software and refers to the applicable Indonesian National Standard. To calculate the upper-structure and sub-structure prices, based on the unit price prevailing in the city of Pontianak as of September 2019 [7].

4. RESULT AND DISCUSSION

The material properties used for the PCI girders of bridge construction with a length of 40 m, 50 m, and 60 m are as follows: Concrete quality of the prestressed concrete girders K-800, compressive strength f'_c = 67.69 MPa, Modulus of elasticity of concrete, E_c = 44220.94 MPa, Poisson ratio v = 0.20, shear modulus, G = 11.392.56 MPa, and unit weight of reinforced concrete W_c= 25 kN/m^3. Material for prestressed steel, strands type, Stress-relieved 7 wire strands (ASTM A416) grade 270 with melting stress strands, f_{py}= 1580 MPa. Tensile strength of strands, f_{pu} = 1860 MPa, nominal diameter d =14.29 mm, effective area of each strand (75% nominal area) A_{st} = 120.29 mm^2, nominal rupture load each strand, P_{bs} = 230.00 kN, number of strand, na = 25, ideal diameter of strand duck, d_i = 85 mm, rupture load one strand, P_{b1} = 5290 kN, Elasticity Modulus of strands, E_s = 200000 MPa. Steel for non-prestressed purposes: steel grade BJ–55, minimum tensile stress, f_u = 550 MPa, minimum yield stress, f_y = 410 MPa, Elasticity Modulus of steel, E_s = 200 GPa. The unit weight of Asphalt, $W_{asphalt}$ = 22 kN/m^3.

The detail dimension of the I girder span of 40 m and 50 m were taken in accordance with the prestressed I beam produced by PT. Wijaya Karya, Tbk. as stated in the Product Bridge Brochure, 1st Edition, 2012. Figure 1 shows the cross-section of the prestressed I girder. For prestressed beam dimensions with a span of 60 m using a modified cross-sectional dimension with a height of 2.55 m, the detail dimension is presented in Tabel 1.

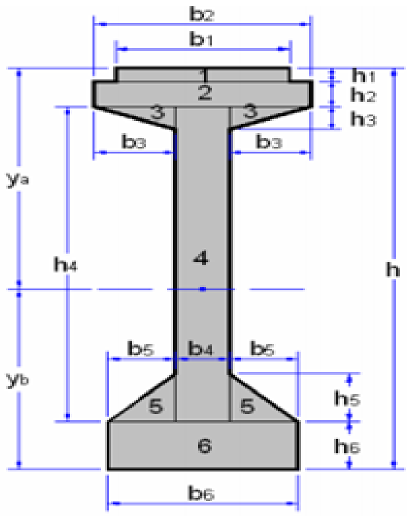

Fig. 1 Cross-section PCI girder [15]

The height of the cross-section of the PCI girder bridges increases proportionally to the increase in the girder's length. It is a technical consequence since the longer the girder length will result in a greater moment resistance and hence need larger moment inertia and capacity. The best way to increase the stiffness and strength of the beam is by increasing the height.

Table 1 Section Beam Properties

No	PCI girder length					
	40 m		50 m		60 m	
	b_i (m)	h_i (m)	b_j (m)	h_j (m)	b_k (m)	h_k (m)
1	0.60	0.08	0.60	0.08	0.70	0.05
2	0.80	0.12	0.80	0.12	0.80	0.15
3	0.30	0.12	0.30	0.12	0.30	0.12
4	0.20	1.25	0.20	1.65	0.20	2.05
5	0.25	0.25	0.25	0.25	0.30	0.25
6	0.70	0.25	0.70	0.25	0.80	0.30
Total height h (m)	1.70		2.10		2.55	

Strength control was carried out by comparing the forces acting on the structure resulting from the design load and the capacity of structural elements determined based on the dimensions and quality of the material used. The design loads were calculated according to the loading specification and requirements for bridge design. Table 2 and Table 3 show the results of structural analysis and the strength capacity of the girder based on its cross-section capacity analysis. These results show that the strength resistance resulted from the load acting on the beam is lower than the strength capacity of the girders, and hence the structures are safe. Besides, the torsion moment occurring in the bridge structures that might affect the bridge stability is below the torsion capacity [16].

Table 2 The Moment And Shear Results Of Loading Under Ultimate Conditions

Review	Length of PCI girder		
	40 m	50 m	60 m
Bending Moment (kNm)	15458.3	24343.3	36737.7
Torsion Moment (kNm)	1142.8	1109.5	1074.3
Shear Force (kN)	1483.0	1882.9	2383.7

Table 3 Nominal Bending and Torsion Capacity

Capacity	Length of PCI girder		
	40 m	50 m	60 m
Bending Moment (kNm)	17112.9	24979.2	38849.8
Torsion Moment (kNm)	4403.4	4815.8	5230.4
Shear Force (kN)	2627.2	3873.4	4780.9

Based on the calculation of upper and lower bridge structures, the total cost for each bridge span was determined. The rate of increase of the bridge price is slightly higher with the increase in the length of PCI girder, especially when the length of the PCI girder is more than 50 m.

Table 4 Price Upper and Sub-Structure of Bridge.

Parameter	Length of PCI girder (m)		
	40	50	60
Upper Structure			
USD	60,080	75,037	102,844
Sub Structure			
USD	80,194	81,249	82,847
Total			
USD	140,274	156,286	185,691

There is 4 bridge span considered in the simulation, namely 200m, 300m, 400m, and 480m where all these variations adopt similar typical structures, and only differ in the girder length and hence the number of pillars. Each configuration was set as such to consider any possible arrangement of various girders length in the bridge construction practices. Fig. 2, 4, 6, and 8 show that for the similar span of the bridge, the shorter girder length requires more pillars. The addition of a pillar certainly increases the construction cost. The price comparison of each configuration for a certain bridge span is presented.

Fig. 3 indicates that for a certain bridge span, various configurations of the girder span will yield a variety of prices that not necessary to have a certain pattern.

4.1 Configuration and Prices of 200 m Span Bridge.

Configuration 1 (5 PCI girder @ 40 m)

Configuration 2 (4 PCI girder @ 50 m)

Configuration 3 (2 PCI girder @ 40 m and 2 @ 60 m)

Fig. 2 The 200 m span bridge configuration

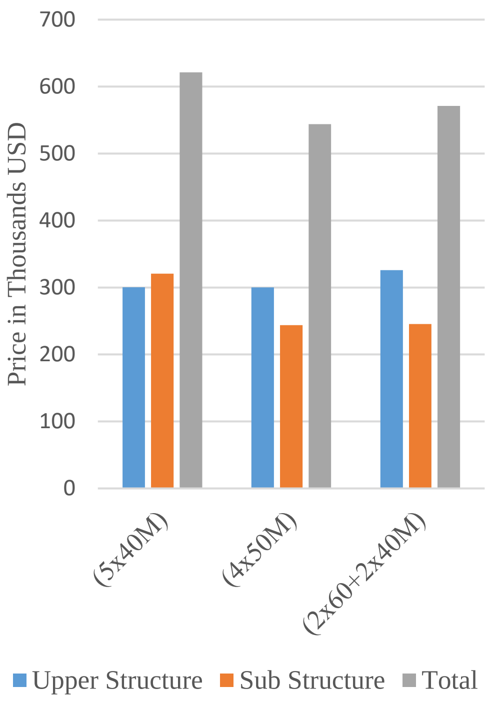

Fig. 3 Prices of 200 m Span Bridge

The use of 40m girder length gives the highest cost that might be attributed to the increase of the lower structure. Combination of girder different length that is somewhat larger give reasonably lower cost than girder length of 40m. The figure also indicates that the girder length of only 50 m gives the most economical price.

4.2 Configuration and Prices of 300 m Span Bridge

Configuration 1 (6 PCI girder @ 40 m and 1 @ 60 m)

Configuration 2 (6 PCI girder @ 50 m)

Configuration 3 (5 PCI girder @ 60 m)

Configuration 4 (3 PCI girder @ 40 m and 3 @ 60 m)

Fig. 4 The 300m Span Bridge Configuration

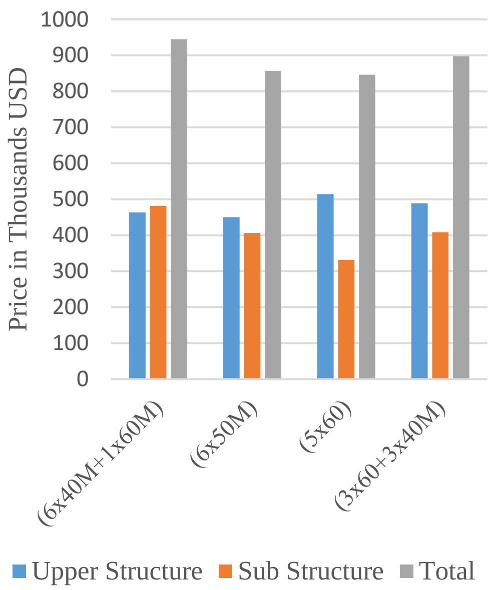

Fig. 5 Prices of 300 m Span Bridge

Similar findings were found in the bridge span of 300m (Fig. 5), where the use of a combination of different girder lengths and the use of longer girder length tends to give a more economical construction price. The shortest girder length of 40 m giver the highest construction cost and the use of girder length of 50m and its combination tends to give a much more reasonable price. Meanwhile, the use of the girder length of 50m only seems to give the lowest price.

4.3 Configuration and Price of 400 m Span Bridge.

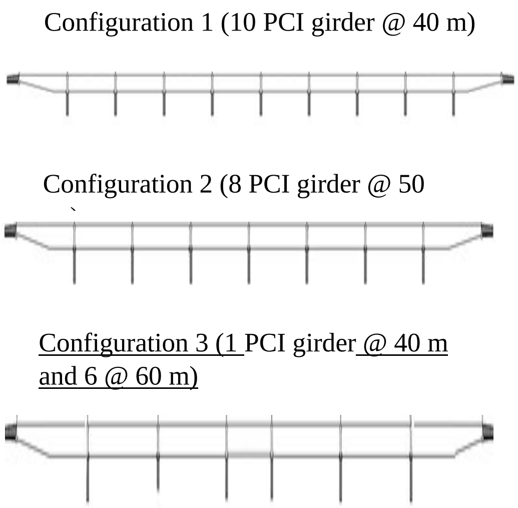

Fig. 6 The 400 m span bridge configuration

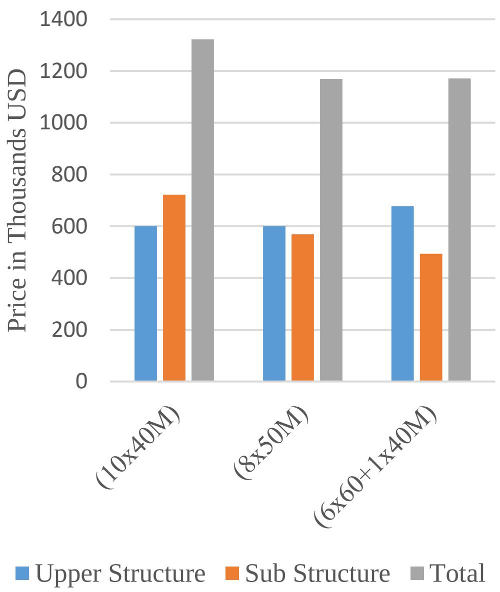

Fig.7 Prices of 400 m Span Bridge

Fig. 7 shows the results of simulation of various girder length configuration for 400m bridge span. Similar to the previous finding, the shorter girder length will need more pillar that contributes to the increase in the construction price. Meanwhile, the use of the girder length of 50m solely shows the minimal possible price.

4.4 Configuration and Prices of 480 m Span Bridge

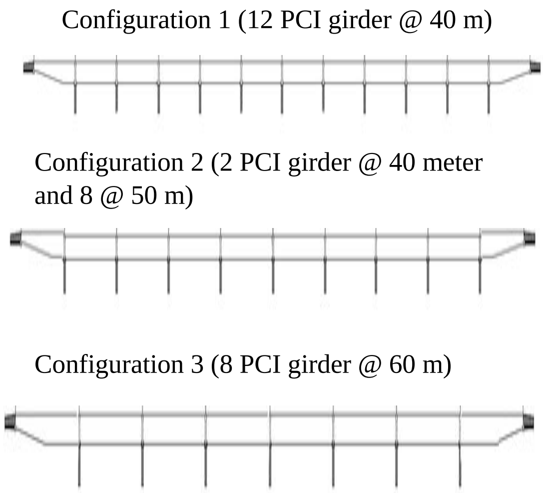

Fig. 8 The 480 m Spans Bridges Configuration

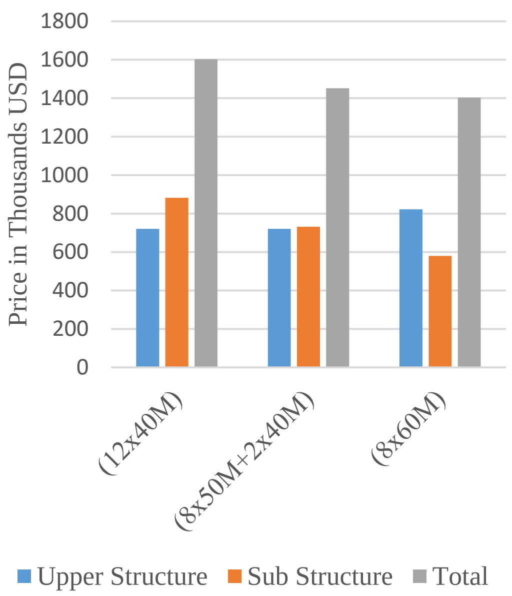

Fig. 9 Prices of 400 m Span Bridge

Observation of Fig. 9 shows the consistency of the finding, that the use of the shortest girder length of 40 m yields the possible most expensive construction price in comparison to the longer girder length and its combination. But, in this configuration, the use of a longer girder length of 60m tends to give a little bit lower construction price to that of 50m girder length.

For bridge spans of 200m, 300m and 400m, in various combinations of girder lengths it is confirmed that the 50 m PCI girder length produces the lowest prices or almost the same prices with 60 m PCI girder. Furthermore for 480m bridge lengths, 60 m PCI girder lengths tend to start out lower. It can be concluded that for a longer bridge span, a longer PCI girder is also required. In this simulation shows the significant influence of the substructure in determining the price of the structure. The price of the substructure appears to increase higher as the span of the bridge becomes longer. This is not to mention the various river conditions and challenges that may arise in development which may result in higher costs.

5. CONCLUSION

From the results of the design and analysis that have been carried out in this study several conclusions can be drawn:

1. The number of pillars supporting girders plays a dominant role in determining the economical value of bridge construction.
2. The use of shorter girder length may result in higher construction prices due to the greater sub structures cost increase.
3. For continuous beam bridges with a total span of 200 m, 300 m, and 400 m, the most economical value is obtained by using a configuration with the length of PCI girder @ 50 meters.
4. By obtaining the most economic value in a configuration that uses a length PCI girder @ 50 m, this proves that the production of the most optimal PCI girder is up to a length of 50 m in accordance with the Bridge Product Brochure, 1st Edition, 2012 owned by PT. Wijaya Karya, Tbk.
5. Furthermore for 480m bridge lengths, 60m PCI girder lengths tend to start out lower. It can be concluded that for a longer bridge span, a longer PCI girder is also required.

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