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COMPARATIVE STUDY OF SLAB OVER PSC I GIRDER AND SEGMENTAL PSC BOX GIRDER SUPERSTRUCTURES FOR METRO VIADUCTS: A COST AND STRUCTURAL EFFICIENCY PERSPECTIVE

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ABSTRACT

This Study comprehensively compares Segmental PSC Box girders and Precast PSC I-girders with in-situ slab for metro viaducts, across 19m to 31m spans. Their structural performance and economic feasibility were analyzed to determine the most cost-effective superstructure for varying span lengths. Both types were optimized for material use and serviceability, with consistent material properties. Optimal material usage (concrete, reinforcement, HT steel) were quantified and charted by varying depths. Using practical construction rates, the optimum costs and material quantities for each span was compared to guide bridge engineers in selecting optimal span arrangements. Further graphs illustrate how optimum depths, material quantities, and deflections relate to span.

The study indicated that, if economy is the criterion of selection of a span arrangement, then beam and slab deck can be adopted upto a span of 22 m and thereafter, the box girder is a cheaper alternative. On the other hand, if the limitation of the depth is the criterion, then slab over PSC I- girder deck is the choice, but then the economy has to be sacrificed. Moreover, the central deflections are relatively high in the case of slab over PSC I- girder superstructure which makes it less preferable, if riding comfort is a criterion. The Box girder is a better alternative which gives lower deflections with good riding comfort and better serviceability.

Keyword: Metro Systems, Viaducts, Prestressed Concrete**,** Box Girders, Precast I- Girders.

INTRODUCTION

This paper evaluates the economic viability of two prominent simply supported prestressed concrete superstructures for metro viaducts. We compare superstructures with segmental PSC box girders and composite RCC slab over precast I-girders across 19m to 31m spans, by analyzing, designing them to their optimum material requirement and then comparing their cost implications to identify the most cost-effective option for each span. Our study considered material usage, construction, and long-term maintenance. The results of the study enable the engineers in deciding a particular type of superstructure and span arrangement that could result in a minimum overall cost considering the limitations of substructure, availability of specialized erection, scaffolding, shuttering and pre-casting for completion of metro project within the assigned times lines. The results of study will also contribute to the optimization of superstructure bridge design, promoting the development of efficient, sustainable, and cost-effective metro infrastructure.

LITERATURE REVIEW

Global studies on metro viaduct superstructures consistently highlight that prestressed concrete (PSC) box girders and precast PSC I-girders with in-situ slabs each offer distinct advantages, with the optimal choice largely dependent on span length and project specifics. Box girders, known for superior torsional stiffness and aesthetic appeal, are generally more efficient and economical for longer spans, curved alignments, and wider decks, despite their potentially more complex formwork (unless precast segmental). Conversely, precast I-girders with composite slabs often prove more material-efficient and easier to erect for shorter to medium spans and straighter sections due to simpler formwork. The ultimate decision is guided by a comprehensive economic analysis encompassing material, construction, and long-term maintenance costs, alongside structural performance, site constraints, and aesthetic considerations.

V.N.L.S.A.P. Aishwarya, I. Yamini Srevalli, and M. Neelakantam (2021) found that for a 40m span, 4-lane major road bridge, I-girders are more economical than box girders due to requiring less concrete, reinforcing steel, and prestressing steel. This material efficiency leads to a lighter superstructure, reducing dead loads on piers and abutments. Consequently, substructure elements like foundations and pier columns can be smaller and less massive, leading to a more cost-effective overall bridge structure while still meeting all IRC standards.

Precast Concrete Construction Technologies have been instrumental in addressing challenges in Indian Metro viaduct structures. Mahesh Tandon (2020) highlighted how the dramatic rise of metro systems, as a primary mode of urban public transport, has significantly contributed to pollution reduction and improved quality of life amidst India's rapidly growing urban vehicle population and expanding cities. Mr. Tandon emphasized that for structural engineers, metro projects offer significant opportunities to develop skills and devise innovative solutions for large-scale urban construction. Crucially, he noted that early design stage decisions are vital for a project's success, impacting construction speed and quality, environmental footprint, aesthetic appeal, and overall cost-effectiveness Structural engineering considerations for elevated viaducts in Indian metro rail systems have been a key focus.

Mohammad Ammar and Prof. Vijay Kumar Meshram (2021) highlighted the growing importance of metro systems in India due to rapid population growth and the demand for efficient mass transit. Their study emphasized the advantages of prestressed concrete elements in superstructure design for achieving optimal material use and enhancing aesthetics, which is crucial for public acceptance in urban settings. The paper specifically presented a typical design for a 24-meter span viaduct using a pretensioned I-girder with a cast-in-situ deck slab, illustrating practical applications and structural behavior insights. This work further underscored the benefits of using precast superstructure elements in elevated viaducts, noting improved construction ease, enhanced quality control, increased safety, faster project completion, and reduced on-site disruptions due to off-site fabrication under controlled conditions.

Despite numerous studies on metro rail superstructures, a gap remains in explicitly comparing optimum cost to span lengths, which is crucial for optimal superstructure selection. While researchers have examined different types individually and some have conducted comparative analyses of various options, no prior work directly correlates the cost of metro rail superstructures with specific span lengths. This indicates a need for further research to provide valuable insights for selecting the most economically viable superstructure given a particular span.

RESULT AND DISCUSSION

This section presents a detailed analysis of Segmental box girder superstructure and PSC-I-girder designs across various span lengths specifically 19 m, 22 m, 25 m, 28 m, and 31 m. The results are illustrated through a series of graphs that depict the relationship between span length and key design parameters. These include: overall cost, total reinforcement quantity, high-tensile steel requirement, concrete volume, and structural deflection. Each graph highlights how these parameters vary with increasing depth of each span, providing insights into both structural performance and economic implications. The analysis aids in identifying optimal span ranges by balancing material consumption, structural efficiency, and cost-effectiveness. It also provides valuable data for decision-making in preliminary design stages, especially in selecting span lengths that offer the best trade-off between performance and construction economy.

Segmental PSC Box girders: -

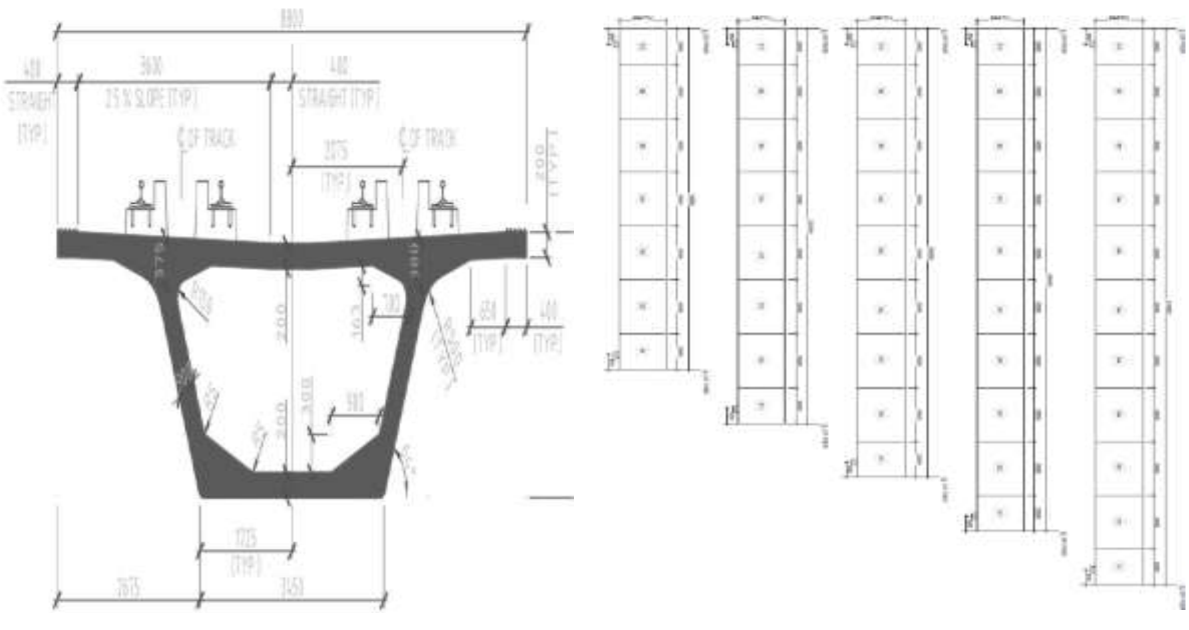

Fig 1: -Typical Cross section of PSC segmental box girder and Arrangement of segments S1 to S4 for spans 19m to 31m

Fig 2:-Image of line model of PSC segmental box girder in STAAD Pro.

Table 1:- Summary of results for PSC segmental box girder,(typical for 31 m span).

Depth in m	Concrete. Quantity in cum	Reinforcement. Quantity. in MT.	HT Steel Quantity. in MT	Cost Rs. in Lakhs	DEFLECTION (mm)
2.1	166.077	5.218	8.353	29.47	0.072
2.2	168.679	5.289	7.986	29.18	0.090
2.3	171.286	5.361	7.657	28.94	0.111
2.4	173.898	5.433	7.360	28.76	0.133
2.5	176.515	5.505	7.091	28.61	0.156
2.6	179.137	5.578	6.846	28.5	0.178
2.7	181.764	5.650	6.623	28.43	0.199
2.8	184.395	5.722	6.418	28.38	0.219
2.9	187.030	5.795	6.229	28.36	0.238
3	189.670	5.867	6.055	28.36	0.255
3.1	192.313	5.940	5.894	28.38	0.271
3.2	194.960	6.012	5.745	28.42	0.286
3.3	197.610	6.085	5.606	28.48	0.299
3.4	200.263	6.157	5.476	28.55	0.311
3.5	202.920	6.230	5.356	28.63	0.322
3.6	205.579	6.303	5.242	28.72	0.332
3.7	208.241	6.376	5.136	28.83	0.341
3.8	210.905	6.448	5.037	28.94	0.349
3.9	213.571	6.521	4.943	29.07	0.356
4	216.240	6.594	4.855	29.2	0.362

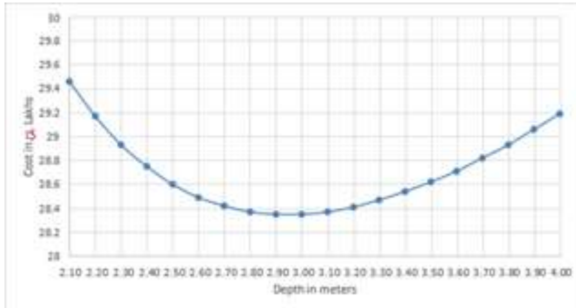

Fig 3 Variation of cost with depth for PSC segmental box girder of 31 m span

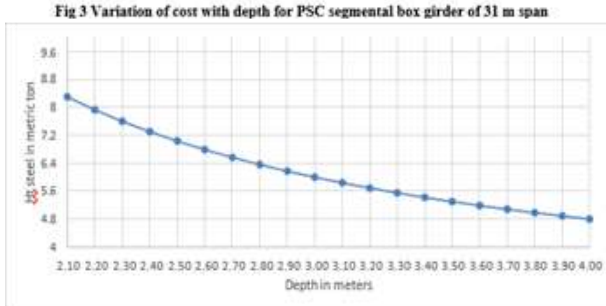

Fig 4 Variation of HT steel quantity with depth for PSC segmental box girder for 31 m span

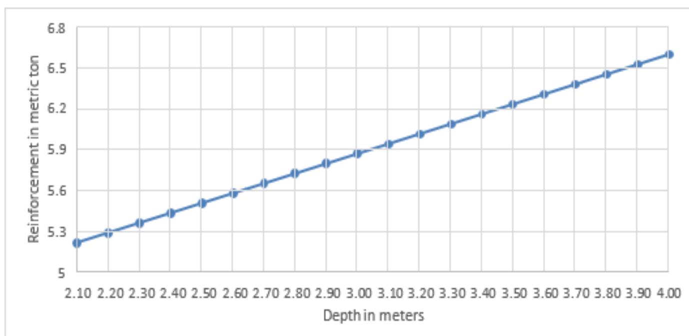

Fig 5 Variation of reinforcement quantity with depth for PSC segmental box girder for 31 m span

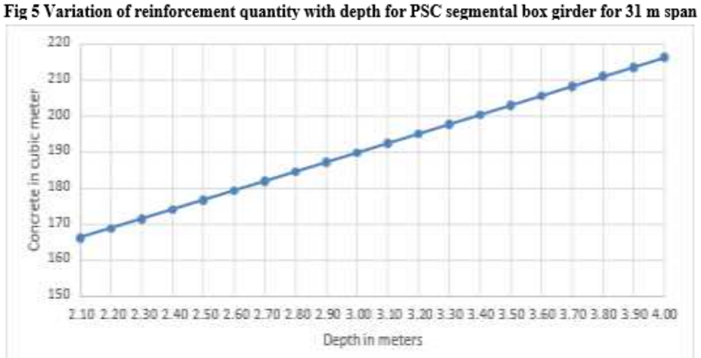

Fig 6 Variation of concrete quantity with depth for PSC segmental box girder for 31 m span

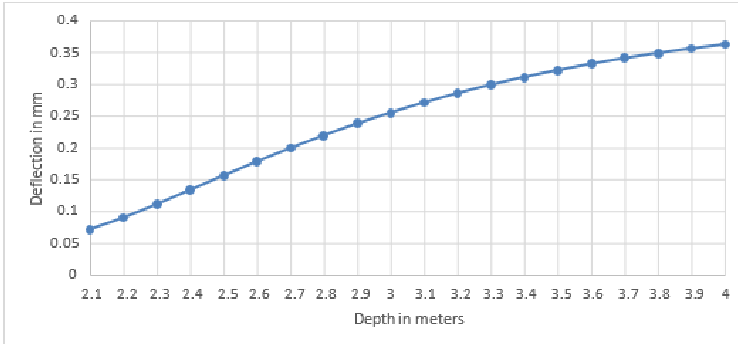

Fig 7 Variation of deflection with depth for PSC segmental box girder for 31 m span

The concrete, reinforcement and HT Steel quantities were similarly calculated for the segmental box girders of spans 19m, 22m, 25m, and 28m also. The results were tabulated and graphs prepared. This comprehensive effort involved detailed analysis and calculations, ultimately producing a full suite of results presented in both tabular and graphical formats.

These outputs effectively encapsulate the findings for these specific span configurations.

Slab over PSC I girder: -

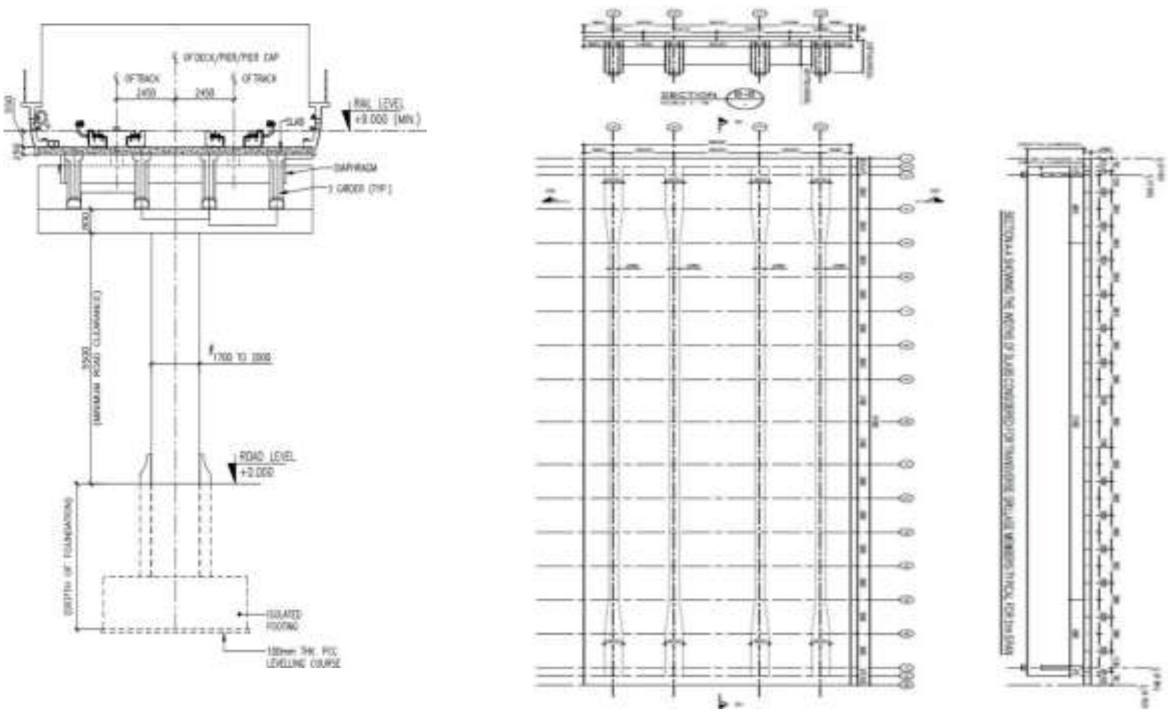

Fig 8: -Image of PSC-I-girder of and idealization for grillage members for 31 m span.

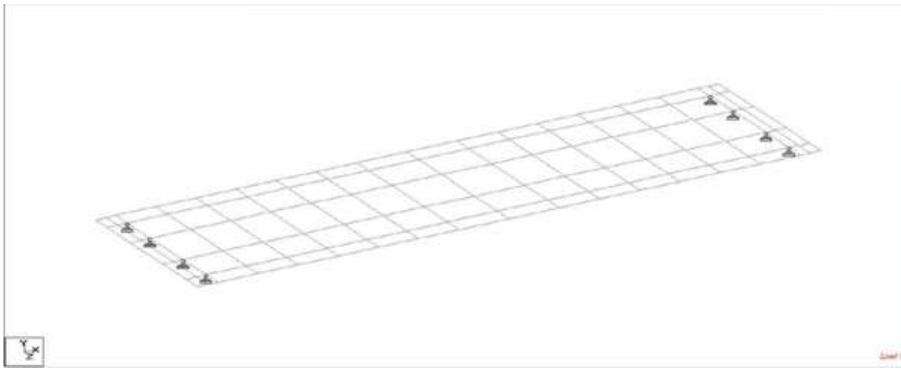

Fig 9:- Image of grillage of Slab over PSC-I-girder superstructure in STAAD Pro.

Table 2:- Summary of results for PSC-I-girder (typical for 31 m span).

Depth in m	Concrete. Quantity in cum	Reinforcement. Quantity. in MT.	HT Steel Quantity. in MT	Cost Rs. in Lakhs	DEFLECTION (mm)
1.9	152.394	3.765	34.978	67.294	5.027
2	156.454	3.892	24.848	52.512	8.342
2.10	160.514	4.019	18.185	42.932	14.876
2.20	164.574	4.146	13.442	36.231	14.233
2.30	168.634	4.273	9.885	31.309	12.465
2.40	172.694	4.400	8.360	29.435	10.988
2.50	176.754	4.527	8.087	29.440	9.741
2.60	180.814	4.654	7.843	29.487	8.683
2.70	184.874	4.781	7.621	29.568	7.773
2.80	188.934	4.908	7.421	29.682	6.991
2.90	192.994	5.035	7.238	29.821	6.311
3.00	197.054	5.162	7.072	29.985	5.718
3.10	201.110	5.289	6.919	30.170	5.198
3.20	205.170	5.416	6.779	30.374	4.740
3.30	209.230	5.543	6.650	30.594	4.333
3.40	213.290	5.670	6.531	30.830	3.972
3.50	217.350	5.797	6.422	31.079	3.650
3.60	221.410	5.924	6.320	31.340	3.361
3.70	225.470	6.051	6.225	31.612	3.102
3.80	229.530	6.178	6.137	31.893	2.867
3.90	233.590	6.305	6.055	32.184	2.656
4.00	237.650	6.432	5.979	32.483	2.463

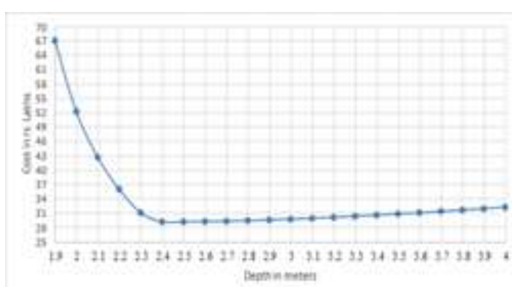

Fig 10 Variation of cost with depth for PSC-I-girder for 31 m span

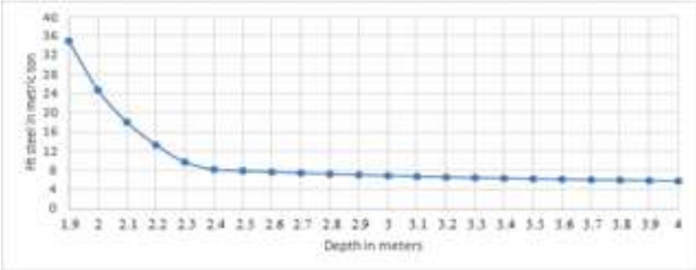

Fig 11 Variation of HT steel quantity with depth for PSC-I-girder for 31 m span

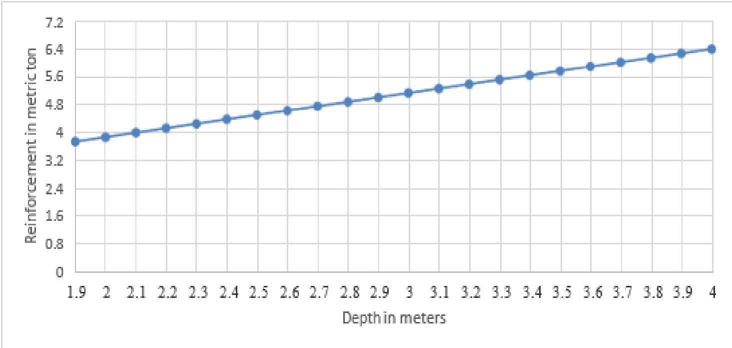

Fig 12 Variation of reinforcement quantity with depth for PSC-I- girder for 31 m span

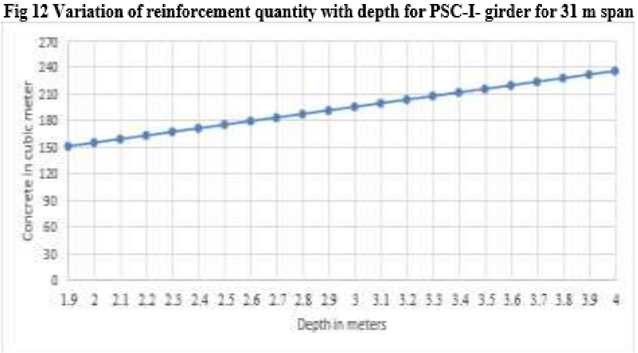

Fig 13 Variation of concrete quantity with depth for PSC-I- girder for 31 m span

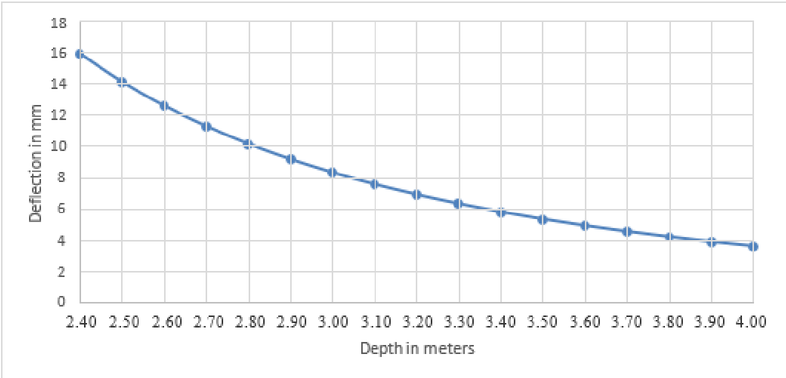

Fig 14 Variation of deflection with depth for PSC-I- girder for 31 m span

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The concrete, reinforcement and HT Steel quantities were similarly calculated for the PSC I -girders of spans 19m, 22m, 25m and 28m also. The results were tabulated and graphs prepared. Detailed analysis and calculations were carried out to obtain results which were presented in both tabular and graphical formats. These outputs provide the findings for these specific span configurations.

The comprehensive analysis yielded crucial insights into the optimal design parameters for both superstructure types. Specifically, the investigation successfully identified the optimum depths for the various structural components. Correspondingly, a detailed quantification of essential materials, including concrete, reinforcement, and high-tensile (HT) steel, was meticulously performed. These material quantities, alongside the derived optimum costs, are thoroughly summarized and presented in dedicated tables for the slab over PSC I-girder and PSC segmental box girder superstructures, respectively. These tabulated results offer a clear and concise overview of the most efficient design configurations

Span in (m)	Optimum Depth in m	Optimum cost	HT Steel Quantity. in MT	Reinforcement. Quantity. in MT.	Concrete. Quantity in cum	Deflection (mm)
19	1.7	14.167	3.58	2.189	90.802	7.776
22	1.9	17.52	4.529	2.708	110.418	9.308
25	2.1	21.155	5.575	3.270	131.282	10.839
28	2.3	25.141	6.771	3.876	153.394	12.465
31	2.4	29.435	8.36	4.400	172.694	15.917

Table 3: -Summary of Optimum costs at optimum depths and corresponding material quantities of PSC I Girder superstructure

Span in (m)	Optimum Depth in m	Optimum cost	HT Steel Quantity. in MT	Reinforcement. Quantity. in MT.	Concrete. Quantity in cum	Deflection (mm)
19	1.9	14.54	2.66	3.15	104.256	0.6002
22	2.2	17.65	3.343	3.796	124.665	0.569
25	2.4	21.02	4.278	4.413	143.868	0.532
28	2.6	24.5	5.242	5.055	163.77	0.368
31	2.9	28.36	6.229	5.794	187.03	0.2377

Table 4: - Summary of Optimum costs at optimum depths and corresponding material quantities of Segmental PSC Box Girder superstructure.

Variation of Optimum Depth with Span: -

From the tabulation of results obtained throughout the span range under study, for any particular span under consideration,

- The PSC I girder superstructure has a comparatively lower depth.
- The PSC segmental Box girder superstructure has relatively higher optimum depth.
- The rate of variation of optimum depth with span in case of beam and slab and box girder superstructures is in the range of 0.07 to 0.09 m and 0.09 to 0.1 m per meter length of span respectively.

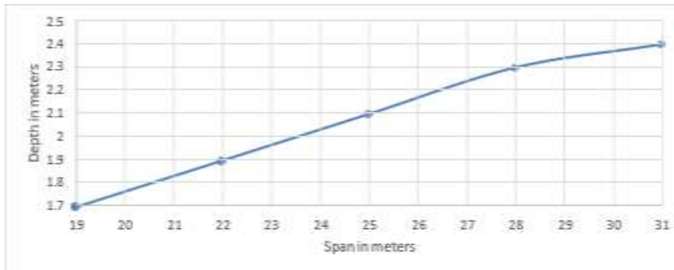

Fig 15 Variation of Optimum depths with span of PSC I Girder superstructure

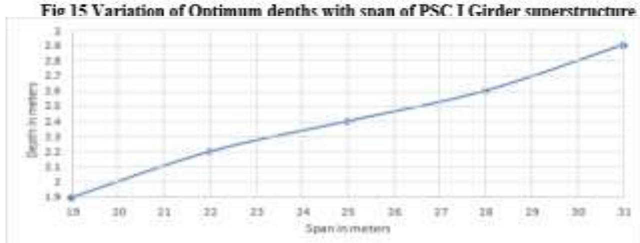

Fig 16 Variation of Optimum depths with span of Segmental PSC Box Girder superstructure

Variation of Concrete Quantity with Span:

It is observed from the tabulation of results obtained that throughout the span range under study, for any particular span under consideration,

- The Slab over beam superstructure requires relatively less concrete quantity.
- The box girder superstructure requires relatively higher concrete quantity.
- The rate of variation of concrete quantity with span in case of beam and slab and box girder superstructures is 5.473cum to 6.03cum and 4.778 cum to 5.548 cum respectively.

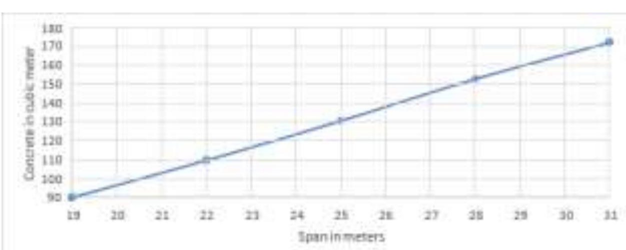

Fig 17. Variation of Concrete quantity at Optimum cost with span of PSC I Girder superstructure

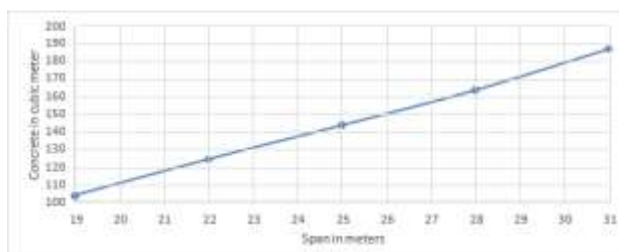

Fig 18 Variation of Concrete quantity at Optimum cost with span of Segmental PSC Box Girder superstructure

Variation of Reinforcement Quantity with Span: -

It is seen from the tabulation of results obtained that throughout the span range under study, for any particular span under consideration,

- The beam and slab deck requires relatively less reinforcement quantity.

- The Box girder deck requires relatively more reinforcement quantity.
- The average ` quantity with span for beam and slab and box girder superstructures varies from 0.115 to 0.14 MT and 0.16 to 0.18 MT per meter length of span respectively.

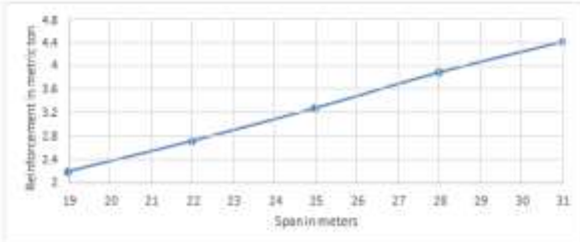

Fig 19 Variation of Reinforcement quantity at Optimum cost with span of PSC I Girder superstructure

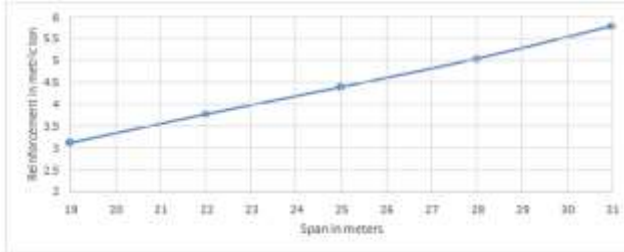

Fig 20 Variation of Reinforcement quantity at Optimum cost with span of Segmental PSC Box Girder superstructure

Variation of High Tensile Steel Quantity with Span: -

t is seen from the tabulation of results obtained that throughout the span range under study, for any particular span under consideration,

- The beam and slab deck requires relatively more HT steel quantity.
- The box girder deck requires relatively less HT steel quantity.
- The rate of variation of HT steel quantity with span in case of beam and slab and box girder superstructures is 0.188 to 0.269 MT and 0.14 to 0.2 MT per meter length of span respectively.

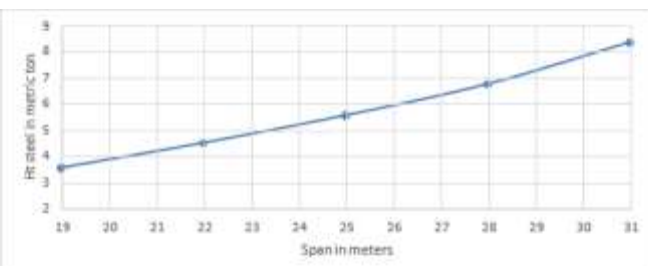

Fig 21 Variation of HT steel quantity at Optimum cost with span of PSC I Girder superstructure

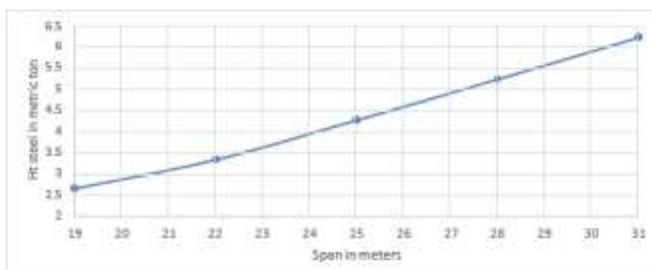

Fig 22 Variation of HT steel quantity at Optimum cost with span of Segmental PSC Box Girder superstructure

Variation of central deflection with Span: -

It is seen from the tabulation of results obtained that throughout the span range under study, for any particular span under consideration,

- The beam and slab deck has deflection more than PSC box girder
- The box girder has minimum deflection. This is owing to the fact that Box girder superstructure is stiffer element compared to that of slab over PSC I girder superstructure.
- The rate of variation of central deflection with span in case of beam and slab and box girder superstructures is 0.40 mm to
  0.51 and 0.031mm to 0.00764.1 mm per meter length of span respectively.

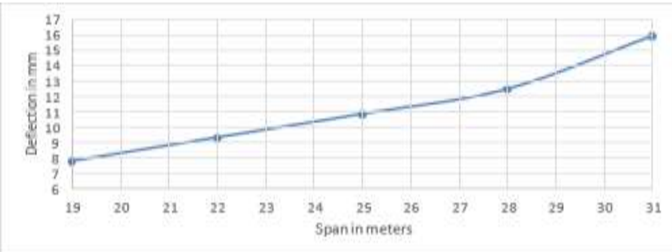

Fig 23 Variation of Central deflection (mm) at Optimum cost with span of PSC I Girder superstructure

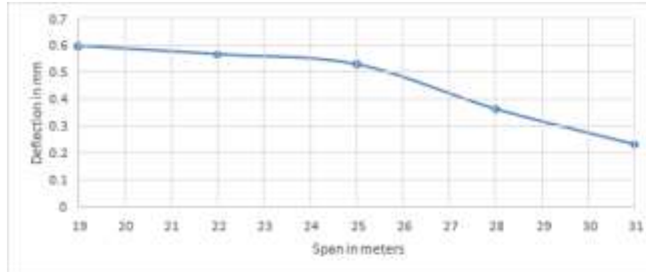

Fig 24 Variation of Central deflection (mm) at Optimum cost with span of Segmental PSC Box Girder superstructure

Variation of Cost with Span: -

It is seen from the tabulation of results obtained that throughout the span range under study, for any particular span under consideration

- The slab over I girder superstructure is relatively less costly upto span of 22 m and thereafter the Segmental PSC Box girder is relatively less costly upto spans of 31m.
- The rate of variation of optimum Cost with span in case of beam and slab and box girder superstructures is Rs. 0.745 to 0.949 lakhs and 0.765 to 0.915 lakhs per meter length of span respectively. Though the box girder has an efficient cross section than others, yet the cables have to be placed in the soffit slab and hence any variation required in the cable eccentricity in order to stress the top or bottom fibers to their optimum value has to be brought out in variation of depth of the section which results in simultaneous increase of concrete and reinforcement steel quantities.
- The costs evaluated in the graphs are for a particular rate i.e., Rs.8000/cum for concrete, Rs.70000/MT for reinforcement and Rs.1,50,000/cum for HT steel, all inclusive. If the rates at a particular place are different from those considered in the study, the graph for the cost have to be redrawn using the quantities presented in the other graphs (and tables) and then the cost analysis for that particular place has to be made.

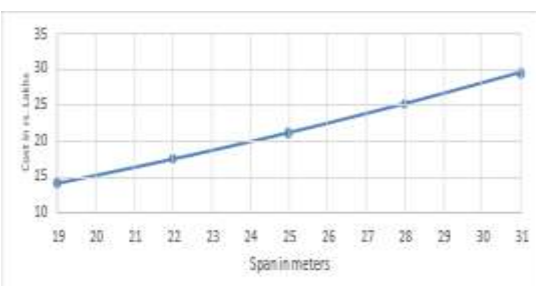

Fig 25 Variation of optimum Costs (in Rs. Lakhs) with span of PSC I Girder superstructure

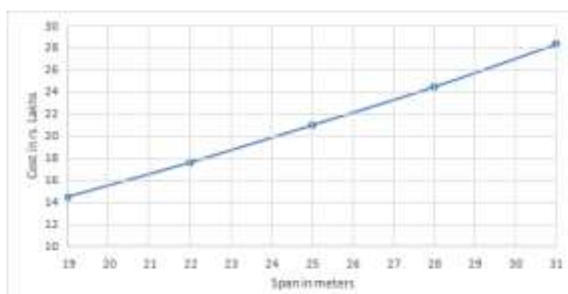

Fig 26 Variation of optimum Costs (in Rs. Lakhs) with span of Segmental PSC Box Girder superstructure

CONCLUSIONS

- If economy is the criterion of selection of a span arrangement, then beam and slab deck can be adopted upto a span of 22 m and thereafter, the box girder is a cheaper alternative.
- On the other hand, if the limitation of the depth is the criterion, then slab over PSC I girder deck is the choice, but then the economy has to be sacrificed. Moreover, the central deflections are relatively high in the case of slab over PSC I girder superstructure which makes it less preferable if riding comfort is a criterion. The Box girder is a better alternative which gives lower deflections with good riding comfort

and better serviceability.

- The deck level of any metro bridge is provided based on the platform level fixed at stations, which in turn, is fixed based on its clearance to road traffic provided for the station structure below its concourse level. Reduction of rail level between the stations is not desirable as provision of vertical gradients significantly affects the speed of train, increase in train traction energy and construction costs. Hence keeping minimal depth of superstructure to maintain the required clearance underneath the metro bridge for road traffic, is not a concern. In light of the above, the depth of superstructure can be kept at it's optimum that results in economy.

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