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Effect of the Superstructure Construction Method on the Cost and Duration of Bridge Projects in Sudan

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مُستخَلص:

السودان بلدٌ واسعٌ يتكون من ستة عشر ولاية يوجد فيها آلاف الكيلومترات من الممرات المائية والأودية ، جعلت الحاجة إلى تشييد الجسور كبيرة لأجل تحسين الإتصال والتنمية. هناك عدة جسور تم تشييدها في العقود الماضية في السودان من الخرسانة أو الفولاذ باستخدام عدة أنظمة من الجسور المعلقة والقوسية والجسور الجملونية والمستوية على كوابل وبطرق تشييد متعددة. إن اختيار أفضل طريقة لتشييد المنشأة العلوية للجسور تعتبر مهمة لنجاح مشاريع تشييد الجسور الذي يقاس عموماً بسرعة التشييد وقلة التكلفة المالية.

تُلخص هذه الورقة المعلومات الرئيسة للجسور الكبيرة في السودان من حيث المعلومات الهندسية الأساسية وطريقة التشييد وزمن التشييد والتكلفة المالية وتقدم مقارنة بين طرق تشييد الجسور الرئيسة بالسودان فيما يتعلق بتكلفة الجسر محسوبةً بالدولار الأمريكي لكل متر مربع ومعدل تشييده محسوباً بالمتر المربع لكل أسبوع. وتقدم الورقة أيضاً توصية بأفضل طرق لتشييد المنشأة العلوية في الجسور بالسودان والتي يتوقع أن تساهم في تحسين تكلفة وتقليل مدة تشييد الجسور.

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Abstract

Sudan, being a wide country consisting of sixteen states, in which thousands of kilometres of waterways and valleys are extended, bridges had become desperately needed for proper communication and development. There were many types of bridges in Sudan made of concrete, steel and composite sections showing various types of suspended, steel truss, arch and cable-stayed bridges which were constructed by different methods.

This paper summarizes the data of main bridges in Sudan; it shows the construction duration, cost, and type of the superstructure and presents comparison between bridges' superstructure construction method in terms of cost in US$ per m^2 of bridge plan area and production rate in m^2/week. The paper also recommends the most favourable bridge construction methods that are expected to contribute better into saving cost and construction time.

1. Introduction

Bridges are important components of highway networks which need to provide adequate safety and serviceability for the public. Commonly used modern bridge construction methods include Full-span Launching Method, Advancing Shoring Method, Balanced Cantilever Method, Incremental Launching Method, and Precast Segmental Method …etc. Wardhana and Hadipriono[1]concluded that 12 (7.6%) out of 157 bridge collapses excluding natural disasters and deterioration/obsolescence bridge failures in the United States between 1989 and 2000 were due to defective design and construction. Catastrophic bridge failures such as bridge collapses during construction incurred by the use of inappropriate construction methods can cause considerable loss in terms of time, money, damage and rework. Accordingly, selecting a desirable bridge construction technology is vital for the success of bridge projects.

Bridge superstructure construction methods involve prefabricated beams or segments which are erected on false-work, by gantry (span by span or balanced cantilever), or erected by crane. Cast in-situdecks involve post tensioned girders and slabs, balanced cantilevers, incremental launching and cast in-situ[2].

Some of the bridge site constraints affecting the selection of construction method and working activities are: land use, staging areas, navigation constraints, hydraulic conditions, flood plain information, flood level and discharge as well as the environmental considerations.

The construction Industry Institute [3] defined constructability as the optimum use of the construction knowledge and experience in planning, design, procurement and field operations to achieve the overall project objectives with minimum cost and construction time. Mohamed and Ismail [4]presented an innovative method of construction that has been used in Egypt for the first time to construct 6th October Bridge extension. They found that the unit cost decreases as the number of spans is increased for both stepping shuttering and incremental launching truss systems. Harris [5]also reported that the launching truss and the stepping shuttering systems are most appropriate for long bridges in the range of 300–600m, where the production rate for the stepping shuttering is about 300 m^2 of deck surface area per week for spans up to 40m.

Based on Mohamed and Ismail [4]findings, the construction progress rate for the stepping shuttering is 14% and 48% higher than that for the incremental launching truss and the traditional formwork systems, respectively. The principal advantage of the stepping shuttering system is the saving in false-work, especially for high decks. Constructability improvements are achieved in stepping method by eliminating delays in erecting and dismantling formwork for each bridge span, and it allows for higher construction progress rates compared with
other available systems.

2**. Objectives**:

This paper attempts to document for the construction methods used for bridges' superstructure in Sudan on way to assist in achieving higher performance, on future projects, regarding cost and construction time. Hence, data of recently constructed bridges is to be analysed to view optimum cost and construction time and to conclude on the most suitable bridge construction methods that can save cost and construction time.

The paper also aims at encouraging the owners and contractors to adopt using logical procedures to guide the selection of the most appropriate bridge superstructure construction method.

3. Bridge Construction Methods commonly used in Sudan:

Construction of bridges in Sudan started since the first decade of the past century. For strategic reasons and infrastructure development, the country, since 1991, conducted outstanding expansion in the road networks in terms of length, widening of carriageways, strengthening of old bridges and construction of many new bridges.

Sudan, as other countries, has adopted advanced structural technologies indicated by application of prestress, cable supported and suspended structures in bridge projects. The skilled human and technical resources will strongly affect to structure safety, cost and construction time. The successes in bridge projects will be reached if the project achieved quality, cost saving and completed in optimum time schedule. Therefore, selecting an appropriate bridge construction method is essential for the success of bridge construction projects.

Many construction systems have been applied to the construction of bridges in Sudan such as: launching, balanced cantilever, cable stayed, suspended and direct erection methods involving formwork and cranes mounted on barges.

The following Tables (1) to (6) summarize the basic data regarding the main old and recently constructed bridges in Sudan.

For the listed bridges note that:

i. The mentioned bridges cross either a main river or waterway.

ii. Bored pile foundations are used for all bridges.

iii. Pile cap for most bridges is located above water level. However, some pile caps were constructed under water level using sheet-piles and dewatering techniques.

iv. Pier columns and pile caps were constructed using false formwork and cast-in-situ reinforced concrete.

v. The cost of approaches is excluded for all bridges.

vi. The contactors of the listed bridges were either from Sudan, Egypt, China, Turkey, or Italy.

In light of the above it was noticed that the cost and duration of the listed bridges is highly affected by the bridge superstructure system.

Table (1): Khartoum State Main Bridges[6]:

No.	Bridge Name	Year of Completion	Bridge Superstructure System	Construction Method
1	Shambat Bridge	1960	Main spans: Prestressed Concrete (PsC) double cell box girders	Balanced Cantilever
			Side spans: Reinforced Concrete (RC) girder bridge.	Launching by gantry frame
2	Burri Bridge	1972	Main spans: PsC double cell box girders	Balanced Cantilever
			Side spans: RC girder bridge.	Launching by gantry frame
3	Salvation Bridge	1999	Main spans: cast-in-place PsC box-girders	Balanced cantilever
			Side spans: PsC girders,	Launching by gantry frame
4	Almanshia Bridge	2005	Main spans: cast-in-situ PsC box-girder	Balanced cantilever
			Side spans: PsC girders	Launching by gantry frame
5	Al MakNimir Bridge	2008	Main spans: Steel box-girders	Incremental launching.
			Middle two spans: Stayed by cables to steel box pylons.	Incremental launching.
6	Tuti-Khartoum Suspension Bridge	2009	Two towers: cast in-situ RC. Main span cables. Deck of composite sections.	Cables erected by catwalk. Deck by crane and barge
			Side spans: composite steel I-girders	Erected by crane
7	Al Halfaya Bridge	2010	Spans: Composite steel I-girders sections	Lifted by crane. Deck cast-in-situ RC.
8	Khor Samaha Bridge	2011	Pre-cast RC I-girders	Erected by crane
9	Al Dabasin Bridge	construction is on-going	Composite steel box and I-girders.	Erected by crane.
10	Tuti-Bahry Bridge	construction is on-going	Cable-stayed	Balanced Cantilever Method.

Table (2): Geometric and Construction Data of Khartoum State Main Bridges[6]:

No.	Bridge Name	Length (m)	Width (m)	Construction Time (months)	Total Cost (US$)	Cost/m^2 (US$)
1	Shambat Bridge	1057	22.6	30	5,219,000	218
2	Burri Bridge	767	23.0	26	10,032,000	569
3	Salvation Bridge	757	22.7	24	32,000,000	1,857
4	Alamnshia Bridge	340	20.5	24	13,000,000	1,784
5	Al MakNimir Bridge	642	22.0	18	23,325,200	1,652
6	Tuti–Khartoum Bridge	310	20.0	18	16,500,000	2,661
7	Al Halfaya Bridge	910	27.0	20	40,000,000	1,628
8	Khor Samaha Bridge	90	27.5	3	03,931,200	1,588
9	Al Dabasin Bridge	1670	18.5	24	33,989,000	1,100
10	Tuti-Bahry Bridge	600	24.0	36	41,500,000	2,882

Table (3): Main Bridges in other States of Sudan[6]:

No.	Bridge Name	Year of Completion	Bridge Superstructure System	Construction Method
1	Atbara Bridge	2004	Pre-cast RC I-girders	Erected by Crane
2	Merowe Bridge	2007	6 spans, PsC T- girders	Launched by gantry
			3 spans PsC Box- girders cast insitu	Balanced cantilever
3	Shendi Bridge	2008	17 spans, Precast T-girders, and Box-girders.	Lifted by wires from barge.
4	Aldamer Bridge	2009	40m long PsC T-girders	Moved on rails and launched by gantry
5	Dongola Bridge	2009	40m long PsC T-girders	moved on rails and launched by gantry
6	Al Dabba Bridge	2010	40m long PsC T-girders	moved on rails and launched by gantry
7	Rufaa Bridge	2010	Main spans: cast in-situ concrete box girder,	Balanced cantilever
			Approach spans: cast in place	By formwork
8	Alflueim Bridge	2011	Main spans: cast in-situ concrete box girder,	Balanced cantilever
			Approach spans: cast in place	By formwork
9	Sinnar Bridge	Construction is on-going	PsC box-girders.	Balanced Cantilever

Table (4): Geometric and Construction Data of Main Bridges in other States of Sudan[6]:

No.	Bridge Name	Length (m)	Width (m)	Construction Time (months)	Total Cost (US$)	Cost/m^2 (US$)
1	Atbara Bridge	440	18	15	12,650,000	1,597
2	Merowe Bridge	396	20.5	30	13,000,000	1,601
3	Shendi Bridge	660	20.5	27	24,400,000	1,803
4	Aldamer Bridge	858	20.5	24	27,600,000	1,569
5	Dongola Bridge	694	20.6	24	23,700,000	1,628
6	Al Dabba Bridge	366	20.6	14	18,000,000	2,399
7	Rufaa Bridge	354	11	24	13,000,000	3,338
8	Aldddueim Bridge	990	11	32	34,000,000	3,122
9a	Sinnar Highway Bridge	310	18.4	36	24,675,824	4,326
9b	Sinnar Railway Bridge	450	7		21,430,975	6,803

4. Comparison Regarding Cost and Production Rate:

Based on the above mentioned bridge data, comparison can be made using the construction cost and duration. Data of the main bridges constructed in Sudan during the period 1999 to 2011 incorporated with their construction methods, duration and the cost per square meter and of production rate are summarized in Table (5).

In Table (5), note that the production per week is a "comprehensive measure" calculated as follows:

Production rate = (Length of bridge × its width)/construction time in weeks.

Table (5): Cost and Production Rate

No.	Bridge Name	Year of Completion	Construction Method	Cost/m^2 (US$)	Production Rate (m^2/week)
1	Salvation Bridge	1999	Balanced Cantilever	1,857	167.1
2	Atbara Bridge	2004	Erected by Crane	1,597	123.2
3	Alamnshia Bridge	2005	Balanced Cantilever	1,784	67.8
4	Merowe Bridge	2007	Launched by gantry	1,601	63.1
5	Shendi Bridge	2008	Lifted by wires from barge	1,803	116.9
6	Al MakNimir Bridge	2008	Incremental launching.	1,652	183.1
7	Tuti–Khartoum Bridge	2009	Crane and barge	2,661	80.4
8	Aldamer Bridge	2009	Launched by gantry	1,569	171.0
9	Dongola Bridge	2009	Launched by gantry	1,628	139.0
10	Al Dabba Bridge	2010	Launched by gantry	2,399	125.7
11	Rufaa Bridge	2010	Balanced Cantilever	3,338	37.9
12	Al Halfaya Bridge	2010	Erected by Crane	1,628	286.7
13	Khor Samaha Bridge	2011	Erected by Crane	1,588	192.5
14	Aldueim Bridge	2011	Balanced Cantilever	3,122	79.4

The following notes and findings are obtained from Table (5):

i. Bridges No. 1, 6, 8, 12, and 13 show relatively less cost and high production rate.

ii. Production rate of Bridge No. 4 was slightly affected by accident during construction: flood washed-out the temporary service bridge.

iii. Bridge No. 7 (suspension bridge) is a special bridge type which is meant to be a land-mark at Khartoum city-centre, hence, the cost and duration is seriously affected.

iv. The high cost and low production rate of Bridges No. 11 and 14 is owing to the narrow width of the bridges and to the contractor being working on both bridges simultaneously.

v. Incremental Launching Method for composite bridges and Launching by gantry for prestressed concrete T-girders are acceptable construction methods for bridge superstructure.

vi. Construction by crane mounted on barge for composite steel I-girder bridge seems to be acceptable solution (Note that for Alhalfaya Bridge: cost = 1,628 US$/m^2; production rate = 286.7 m^2/week).

Table (6) present the average cost and production rates for 10 of the 14 bridges; excluding Bridges No. 4, 7, 11 and 14 because of the above reasons:

Table (6): Average Cost and Production Rate:

Bridge No.	Construction Method	Average Cost/m^2 (US$)	Average Production Rate (m^2/week)
1 and 3	Balanced Cantilever	1,821	117.5
6	Incremental Launching	1,652	183.1
8, 9 and 10	Launching by Gantry	1,865	145.2
2, 5, 12 and 13	Erection by Crane or Wires	1,654	179.8

5. Check of Application of Fuzzy Analytical Hierarchy Process (FAHP):

The Analytical Hierarchy Process (AHP) method has been widely used for solving multi-criteria decision-making problems[4], [7]. The Authors applied FAHP similar to Nang [8]into local bridge project in Sudan: Cable-stayed Tuti-Bahri Bridge Project, Bridge No. 10 in Table (1).

The results were successfully applied and adopted for selection of the most appropriate bridge superstructure construction method among the two methods outlined hereafter:

i. Incremental Launching: with construction sequence as follows:
   1. Construct piers of the towers.
   2. Introduce temporary intermediate piers.
   3. Erect deck segments by incremental launching.
   4. Construct the upper part of the towers.
   5. Erect the cables.
   6. Remove temporary piers

ii. Balanced Cantilever: with construction sequence as follows:
   1. Construct the towers.
   2. Introduce cables.
   3. Erect deck segments, two segments: each on one side of the towers.

The suggested procedure will be recalled here, in short, for convenience. The proposed approach employs triangular and trapezoidal fuzzy numbers and the α-cut concept to deal with the imprecision inherent to the process of subjective judgment[9] see Figure (1): triangle LNR and trapezoid LMOR.

In Figure (1): The vertical axis represents values of α-cut; L, X_{aM} and R being the left, middle and right fuzzy numbers for the triangular α-cut, respectively; L, X_{aL}, X_{aR} and R being the two left and two right fuzzy numbers for trapezoidal α-cut. For more information see also the note under Table (7) and Reference [8].

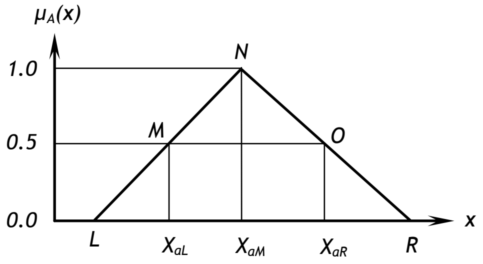

Fig. (1): Triangular and trapezoidal fuzzy intervals under α - cut

A case study that evaluates bridge construction methods is checked by the Authors to illustrate the use of Nang model:

i. Two expert engineers, specialized in bridge construction, were asked to identify possible factors that could affect the final decision through several survey questionnaires. The criteria used in the hierarchy were obtained and checked through the discussion process using Delphi approach[7]. Table (7) illustrates the judgments and the fuzzy numbers adopted in the process.

ii. Five main criteria for judgment on the selection of either of the two construction methods were adopted, namely: Quality, Cost, Safety, Duration, and Shape. The main criteria were further subdivided into sub-criteria as follows: Quality was characterized by durability and suitability; Cost was divided into construction cost and damage cost; Safety was associated with traffic conflict and site condition; Duration was divided into weather condition and constructability that affects productivity; Shape was divided into landscape, geometry, and environmental preservation.

iii. Once the hierarchy was established, the opinion of the two experts is used for direct pair-wise comparison and judgment. An example of experts' opinion with respect to the overall goal is shown in Tables (8) and (9). The overall goal being: "*Selection of the most appropriate bridge construction method for Tuti-Bahri Bridge*".

Table (7): Fuzzy importance scale*:

Judgment	Abbreviation	Explanation	Fuzzy number[8]
Very Unimportant	VU	A criterion is strongly inferior to another	(0, 0, 1, 2)
Less Important	LI	A criterion is slightly inferior to another	(1, 2.5, 4)
Equally Important	EI	Two criteria contribute equally to the object	(3, 5, 7)
More Important	MI	Judgment slightly favor one criterion over another	(6, 7.5, 9)
Very Important	VI	Judgment strongly favor one criterion over another	(8, 9, 10, 10)

** Note that the fuzzy number for "Very Unimportant" and "Very Important" judgments are represented by half trapezoidal membership functions; whereas the remaining other 3 levels are characterized by symmetric triangular membership functions. The fuzzy numbers shown in Table (7) are suggested by Nang [8] and accepted, after being checked by the Authors.*

Table (8): Evaluation results of the main criterion with respect to the overall goal:

Pair-wise criteria	Opinion of expert #1	Opinion of expert #2
Quality versus Cost	VI	MI
Quality versus Safety	EI	VI
Quality versus Duration	VI	VI
Quality versus Shape	VI	EI
Cost versus Safety	LI	MI
Cost versus Duration	LI	VI
Cost versus Shape	MI	MI
Safety versus Duration	VI	MI
Safety versus Shape	VI	EI
Duration versus Shape	MI	MI

Table (9): Evaluation results of the sub-criteria regarding the main criteria

Pair-wise criteria	Opinion of expert #1	Opinion of expert #2
Durability versus Suitability	EI	VI
Damage cost versus Construction cost	MI	MI
Traffic conflict versus Site condition	MI	EI
Constructability versus Weather condition	MI	VI
Landscape versus Geometry	EI	LI
Landscape versus Environmental preservation	LI	EI
Geometry versus Environmental preservation	LI	MI

iv. The final alternative weight can be derived by summing up all the weights; the total and average weights for Incremental Launching Method and Balanced Cantilever Method are shown in the last two rows of Table (10) for $\alpha = 0$, 0.5 and 1.0.

From Table (10) it is clear that the Balanced Cantilever Method (weight = 0.526) is more appropriate alternative than Incremental Launching Method (weight = 0.448) for the adopted case study.

It is worthwhile mentioning that the Balanced Cantilever is the method adopted by the contractor and approved by the owner for the case study bridge. Construction is on-going, expected to end in 2014.

Table (10): Overall weights of the alternatives (for the two experts)

Sub-criteria	Construction method					
	Incremental launching			Balanced cantilever		
α =	0.0	0.5	1.0	0.0	0.5	1.0
Durability	0.081	0.080	0.084	0.134	0.134	0.135
Suitability	0.039	0.035	0.047	0.056	0.053	0.029
Damage cost	0.037	0.037	0.037	0.064	0.063	0.064
Construction cost	0.020	0.020	0.020	0.036	0.036	0.036
Traffic conflict	0.068	0.068	0.068	0.068	0.068	0.068
Site condition	0.065	0.064	0.065	0.039	0.040	0.039
Constructability	0.065	0.064	0.057	0.038	0.035	0.040
Weather condition	0.017	0.017	0.018	0.023	0.022	0.024
Landscape	0.017	0.017	0.017	0.017	0.017	0.017
Geometry	0.020	0.019	0.019	0.025	0.034	0.033
Environmental Preservation	0.020	0.021	0.025	0.028	0.025	0.028
Sum of Weights	0.449	0.442	0.453	0.537	0.527	0.513
Average Weights	0.448			0.526		

6. Conclusions:

The following conclusions have been drawn from this study:

i. Selection process of the superstructure construction method requires high knowledge and experience based on the information on the erection point, surrounding conditions, main characteristics of the bridge, erection machinery and material, which is usually performed based on the objective and subjective judgments of experts in the related bridge site.

ii. The Incremental Launching Method for composite bridge used in AlmakNimir Bridge and the launching system by gantry for prestressed concrete girders used in Aldamer Bridge, are acceptable and suitable methods for superstructure erection.

iii. Involving of crane and barge for erection of substructure usedin Alhalfaya Bridge can be considered as the most efficient method, and suitable for saving cost and construction time.

iv. Selection the most appropriate bridge construction method among others methods can be performed based on experts' opinion using FAHP models.

v. Using FAHP model in the selection of a most appropriate bridge construction method indicate that the balanced cantilever method is more suitable for the erection of the new Cable-stayed Bridge connecting Tuti Island to Bahri Town in Khartoum State.

vi. At normal conditions, construction cost of bridges in Sudan varies between 2,399 and 1,628 US$/m^2 while production rate is between 286.7 and 67.8 m^2/week.

7. Definition of Important Terms (تعريف المصطلحات المهمة)

Table (11): Definition of Terms

Term(المصطلح)	Definition (التعريف)
Balanced cantilever	كابولي متوازن
Box-Girders	روافد مقطعها صندوقي الشكل
Bridge superstructure	المنشأة العلوية التي تشييد فوق دعامات الجسر
Cable-stayed bridge	الجسور المستقرة على كوابل
Cast-in-situ concrete	خرسانة مصبوبة في الموقع
Cat-walk	ممر ضيق من الحبال المعلقة
Fuzzy Analytical Hierarchy Process	المعالجة بالتحليل الترتيبي العشوائي
I-Girders	روافد مقطعها يشبه الحرف I
Incremental launching	التركيب بالتدريج: دفع بلاطة السطح في مراحل
Prestressed concrete (PsC)	خرسانة سابقة الإجهاد
Reinforced concrete (RC)	خرسانة مسلحة
Span	بحر: المسافة بين دعامات الجسر
Suspension bridge	الجسور المعلقة، مثل جسر توتي-الخرطوم
T-Girders	روافد مقطعها يشبه الحرف T

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