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Effect of Temperature Variation and Type of Embankment Soil on Integral Abutment Bridges in Sudan

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Abstract

The Integral-Abutment Bridge (IAB) concept was developed at least as far back as the 1930s to solve long-term structural problems that can occur with conventional bridge designs. Due to limited funding sources for bridge maintenance, it is desirable to establish strategies for eliminating joints as much as possible and converting/retrofitting bridges with troublesome joints to jointless design.

IABs or jointless bridges have many advantages over full height abutment or stub abutment bridges. They eliminate expansion joints in bridge superstructures. They also simplify design, detailing, and construction. In spite of many of these recognized benefits, the behavior of such structures is not yet fully understood, and nationally adopted design criteria are still lacking.

This paper presents results of finite element analysis of four IABs at Kassala State (Sudan), the four bridges are considered one of the first fully integral bridges designed and constructed in Sudan. The structural system adopted for these bridges is: RC walls on single row of piles at abutments and piers; hollow-core RC slab at deck. The temperature change is varied between 10°C and 50°C and three types of locally available soil are applied behind the abutments. The effects of varying temperature and embankment soil type in the deflection, maximum bending moments, and maximum shear forces are presented and discussed.

The effect of temperature change and bridge length in the bridge forces is also presented; Useful comments on the optimum IAB length to be locally adopted are suggested.

Keywords: Bridge total length; Embankment soil; Integral abutment bridges; Joint less bridges; Semi-integral bridge; Temperature variation

Introduction

Integral Abutment Bridges (IABs) possess a number of unique design details that make them desirable in many applications. These bridges are constructed without expansion joints, within the superstructure of the bridge, nor elastomeric bearings at the supports, i.e. the superstructure is constructed integrally with the abutments and piers [1,2].

IABs eliminate the use of moveable joints and the expensive maintenance or replacement costs that go with them. The overall design of IABs is simpler than that of their non-integral counterparts; the simplicity of these bridges allows for rapid construction. IABs have proven themselves in earthquakes and performance studies. The advantages of IABs make them the preferred choice for many design and construction engineers in Sudan and worldwide.

In addition to reducing first costs and future maintenance costs, integral abutments also provide for additional efficiencies in the overall structure design. IABs have numerous attributes and few limitations. Some of the most important attributes are summarized below [2]:

Simple Design

Where abutments and piers of a continuous bridges are each supported by a single row of piles attached to the superstructures, or where self-supporting piers are separated from the superstructure by movable bearings, an integral bridge may, for analysis and design purposes, be considered a continuous frame with a single horizontal member and two or more vertical members.

Rapid construction

Only one row of vertical piles is used, meaning fewer piles. The back wall can be cast simultaneously. Expansion joints and bearings are not needed; hence, the normal delays and the costs associated with bearings and joints installation, adjustment, and anchorages are eliminated. Few construction joints are required in the IABs, which results in rapid construction.

No cofferdams

Integral abutments are generally built with capped pile piers or drilled shaft piers that do not require cofferdams.

Simple beam seats

Preparation of load surface for beam seat can be simplified or eliminated in integral bridge construction.

Greater end span ratio ranges

IAB are more resistant to uplift since the integral abutment weight acts as a counterweight. Thus, a smaller end span to interior span ratio can be used without providing for expensive hold downs to expansion bearings.

Simplified widening and replacement

Integral bridges with straight capped pile substructures are convenient to widen and easy to replace. Their piling can be recapped and reused. There are no expansion joints to match and no difficult temperature setting to make. The IAB acts as a whole unit.

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Improved ride quality

Smooth jointless construction improves vehicular riding quality and diminishes vehicular impact stress levels.

Despite the significant advantages of integral bridges, there are some problems and uncertainties associated with them. These include the following [3]:

- Temperature-induced movements of the abutment cause settlement of the approach fill, resulting in a void near the abutment if the bridge has approach slabs.
- Secondary forces (due to shrinkage, creep, settlement, temperature and earth pressure) can cause cracks in concrete bridge abutments. This problem can be eliminated by using approach slabs.

Soil-structure interaction at IAB embankments

Although the IAB concept has proven to be economical in initial construction for a wide range of span lengths as well as technically successful in eliminating expansion joint/bearing problems, but is not problem-free overall in service. Because of the increased use of IABs, there is now greater awareness of and interest in their post-construction, in-service problems. Because of the continuity between superstructure and substructure of IABs, there is a significant interaction with surrounding soil and backfill behind abutments, especially during thermal expansion as the structure is pushed into the soil of the backfill (Figure 1). The soil is usually represented as an elastic-plastic material whose properties affect internal forces in the integral bridge [3,4]. Therefore, it is necessary to consider the influence of embankment soil in the integral bridge design. This is, apparently, seems one of the main problems in the analysis of IABs in practice.

Fundamentally, these problems are due to a complex soil-structure interaction mechanism involving relative movement between the bridge abutments and adjacent retained soil. Although these problems turnout to be primarily geotechnical in their cause, they can result in significant damage to structural components of the bridge. Overall, these post-construction problems, and the maintenance and/or remedial costs they generate, inflate the true life-cycle cost of an IAB.

As the bridge superstructure goes through its seasonal length changes, it causes the structurally connected abutments to move away from the soil they retain in the winter and into the soil during the summer. The mode of abutment movement is primarily rotation about their bottom although there is a component of translation (horizontal displacement) as well. The total horizontal displacements are greatest at the top of each abutment and can have a maximum magnitude of the order of several centimeters [1,4].

Case study: Four IABs in Sudan

Four IABs at Karakon – Hameshkoreib road in Kassala State at east of Sudan are presented in this paper as case study. Table 1 shows the bridges main data and Figures 2-4 illustrate the general views regarding Bridge #2; the other three bridges differ from Bridge #2 in the number of spans and total lengths.

Studying the effects of longitudinal bridge movement on the forces at the four subject bridges was a major focus of the paper. A bridge will expand and contract from seasonal and diurnal variations in temperature and will contract with concrete creep and shrinkage strains. Piers and abutments must be designed to accommodate this movement, and the superstructure must be capable of carrying the forces induced by the stiffness of the piers and abutments.

Materials and design data

The following sections present the material, geometric and design data adopted for the four bridges (Tables 2 and 3 and Figures 2-5).

Codes and standards

Loading and primary dimensions are estimated from BD 37/01 [5] and BD 42/96 [6]. Integral bridges should basically be designed using same limit state principles and design codes as any other bridge. Normally this will mean using the appropriate parts of BD 37/01 which does not refer specifically to integral bridges; the advice note: BA 42/96 [6] furnishes the specific extra requirements for integral bridges.

Live load

Highway load: (HA) or (HA)+(37.5) Units (HB) loads.

Live load at the wing walls is taken=10 kN/m^2.

Soil data

The soil profile at location of Bridge # 4 is shown in Figure 6; similarly soil profiles at the other three bridges are extracted from the soil reports and used in the analysis models.

Lateral earth pressure

Lateral earth pressure shall be assumed to be linearly proportional to the depth of the soil based on the active pressure coefficient K_a=(1-sin Ø)/(1+sin Ø), where Ø is the internal friction angle of the embankment soil.

Temperature effect is calculated assuming the following:

Thermal expansion, $\Delta_L = L \times T \times \alpha$ (1)

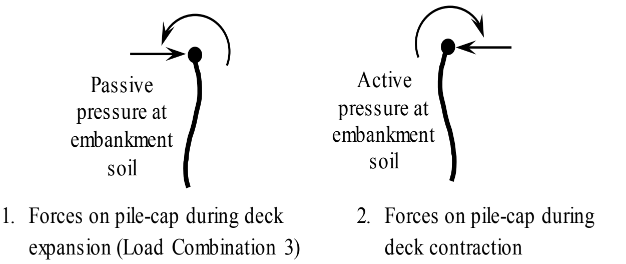


Figure 1: Abutment piles: deformed shape and forces at pile head.

Bridge	No. of spans	Span (m)	Width (m)	Total length (m)
Bridge #1	3	17.0	12.0	51.0
Bridge #2	2	16.0	12.0	32.0
Bridge #3	4	17.0	12.0	68.0
Bridge #4	5	17.0	12.0	85.0

Table 1: Main geometric data of four IABs.

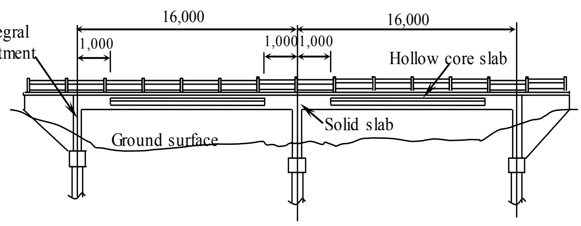


Figure 2: Elevation at Bridge #2.

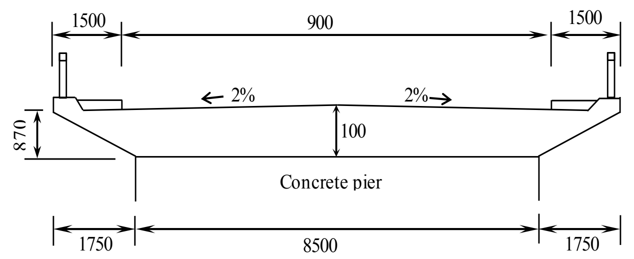


Figure 3: Cross section at solid part of the deck slab.

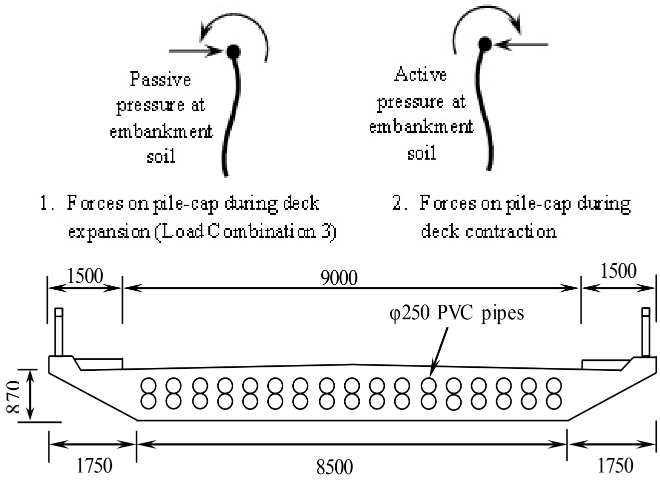


Figure 4: Cross section at hollow core part of the deck slab.

Where L=length of the bridge, ΔT=the temperature range between temperature at time of setting of bridge concrete to the maximum and minimum temperature extremes.

Max. Air temperature=65°C.

Min. Air temperature=10°C.

Temperature at time of setting assumed=25 °C.

Thermal coefficient of expansion, α=12×10^{-6} mm/mm/°C

The bridge deck Type 3, according to [7].

Effective temperature change, ΔT

The effective temperature is the temperature that governs the overall longitudinal movement of the bridge superstructure. Determination of the effective temperature is a complex problem influenced by shade temperature, solar radiation, wind speed, material properties, surface characteristics and section property [8].

The following equations are sometimes used to calculate the temperature change, [9]:

$$\Delta T = T_1 - T_2 + \frac{T_3 - T_1}{3} \tag{2}$$

Where,

T_1=air temperature at dawn on the hottest day,

T_2=air temperature at dawn on the coldest day,

T_3=Maximum air temperature on the hottest day,

However, temperature calculated using Equation 1 does not seem to be suitable for the case of IABs in Sudan since it gives too low temperature changes. Hence, in the absence of approved temperature contours in Sudan, the Authors used maximum and minimum temperatures corresponding to the nearest metrological station at Kassala Town (100 km to South from Bridge #2). Calculation of temperature effects are performed using the procedure shown in reference [7].

The effective temperature change also depends on the air temperature at concrete setting: assumed here=25°C. However, to illustrate the extended effect of temperature change on the forces exerted on the IABs the temperature change is varied between 10°C and 50°C.

Analysis steps

Longitudinal capacity:

Calculate the active earth pressure coefficient, K_a, needed to resist braking and traction forces, applying γ_m=0.5 to K_a. Check that sufficient horizontal capacity is available from the earth behind the abutment to resist the longitudinal forces, and check the magnitude of the horizontal movement required to mobilize the required earth pressure.

- Check horizontal movement.
- Check capacity of soil to resist horizontal forces.

Analysis of deck, piers, and abutments

The whole bridge structure is modeled and all bridge load combinations are applied. Linear elastic foundation model based on actual soil parameters is applied at piles and abutment wall.

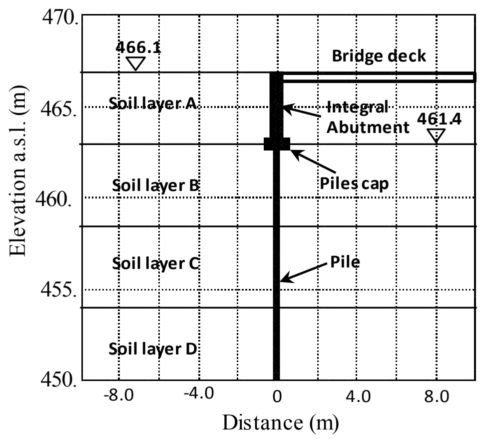
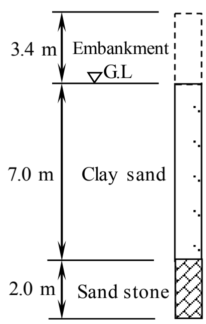


Figure 5: Soil layers used in the model.



	SPT (N)	γ (kN/m^3)	Ø (°)	E (kN/m^2)	UCS (MPa)
3.4 m Embankment	-	19	35	50,000	-
	-	19	33	50,000	-
7.0 m Clay sand	29	19	35	58,000	-
	>50	19	0	100,000	-
2.0 m Sand stone	>100	19	0	100,000	32,600

Figure 6: Soil profile at Bridge # 4.

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The abutment piles are designed such that their diameters are much smaller than abutment wall thickness to insure negligible restraint to rotation (pinned ends) at abutment/pile interface. Hogging due to creep is therefore also unrestrained, but can be ignored.

Maximum thermal expansion and Load Combination 3 are applied [6,7] where maximum earth pressure on abutment walls is based on K^* calculated as if expansion is unrestrained, ($K^*=K_0+(d/0.03\mathrm{H})^{0.6}K_p$, where d=longitudinal defection at top of abutment, K_0, K_p=coefficients of at rest and passive earth pressure, respectively, [clause 3.5.5 in [6]]

Maximum thermal contraction, together with minimum bridge loads and active earth pressures are applied as loads. The effects of long term creep and positive differential temperature loading are included.

Load Combination 3 is applied to deck expansion, considering passive earth pressure and rotation at pile heads, i.e. Piles are designed for bending. Thermal movement, creep rotation and rotation due to differential temperature loads are applied to pile heads, resulting in reverse bending in piles.

Results of Analysis

The interaction of abutment wall and piles with soil layers are modeled using finite elements concepts. The results of longitudinal defection, bending moment and shear force at abutment/deck joint for the four bridges are presented in Figures 7-9, respectively.

It is worthwhile mentioning that for the 4 bridges the negative moment and shear force at abutment governed the design. Design sagging moments within spans and negative moments at piers are governed by Load Combination 3 (permanent loads, primary live loads, and those arising from restraint due to the effects of temperature change)

In this paper three types of soil are tried at embankments behind the abutments, Table 2 shows the physical properties of the embankment soils.

Effect of temperature and bridge total length

Although it was advised to adopt IABs up to 60 meters, [6] many countries experiences much longer IABs [1,3]. In this study the longest IAB is 85 m long. Also note that 3 of the 4 subject bridges have same span but differ in total length, the effect of temperature change showed 9.6% average increase in negative bending moment, at abutment/deck joint, due to 10°C increase in temperature change e.g. in Bridge #4 (85 m long). Figure 10 presents the effect of temperature and bridge total length the maximum negative moment at top of abutment walls of the 4 bridges.

It is noticed from Figure 10 that for IABs longer than 65 m the forces at abutment/deck slab joint start to increase rapidly at temperature change=50°C (the temperature change normally experiences in Sudan) resulting in non-economical cross sections; this probably explains the advice of given in [6]. Therefore, it is recommended at present time to adopt alternative bridge setup e.g. semi-integral bridges for bridges with total length exceeding 100 m.

However, the literature review and field inspections indicate that the maximum lengths of integral abutment bridges have not been reached [3,10]. Jointless bridges over 180 meters in total length have been built and have performed satisfactorily in USA.

Conclusions

The following conclusions are drawn from this paper:

- Changing the soil properties behind the abutment and around the piles does not affect significantly the performance of deck slab in terms of bending moment, shear force and horizontal deflection.
- The bending moment, shear force, and deflection in deck slab tend to increase linearly with increase in temperature.
- As expected, the variation in soil type at embankment behind the abutment wall has negligible effect in the deformation and forces at wall to deck joint (Table 4).
- The restraint provided by abutment wall backfill is usually considered ineffective in reducing the free thermal expansion of the superstructure this is attributed to the fact that the superstructure to abutment in the direction the bridge is high, and the reactive soil pressure at top of abutment wall is often considered low.

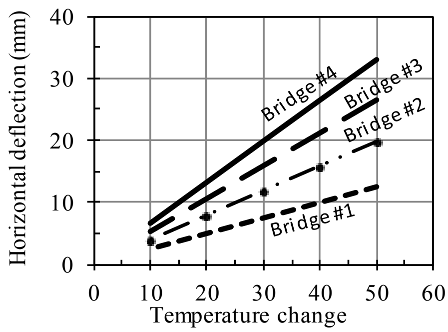

Figure 7: Effect of temperature change in the horizontal deflection at top of abutment.

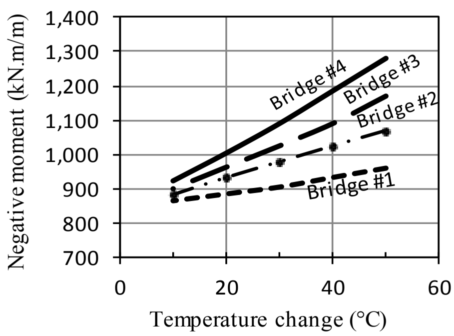

Figure 8: Effect of temperature change in the moment at abutment/deck joint.

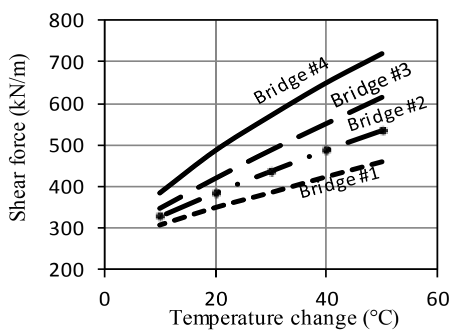

Figure 9: Effect of temperature change in the shear force at abutment/deck joint.

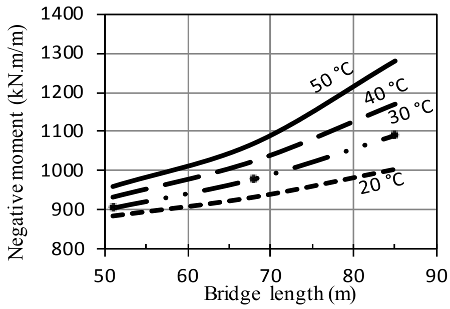

Figure 10: Effect of temperature and bridge length in the moment at abutment/deck joint.

Unit	Moment of initial, *I* (m⁴/m)	Modules of elasticity *E*, (kN/m²)	Rigidity *EI*, (kN/m²)
Abutment wall	0.018	1.40×10^7	2.52×10^5
Pile cap	0.630	1.40×10^7	2.28×10^6
Pile (equivalent for 1m)	0.003	1.40×10^7	2.52×10^4

Table 2: Abutment properties.

Soil layer	Soil type		Unit weight, γ_s (kN/m³)	Modules of elasticity, *E* (kN/m²)	Angle of friction, φ (°)
A	Embankment	soil 1: Fine sand	18.0	40,000	25
		soil 2: Gravely sand	19.0	50,000	35
		soil 3: Gravel	18.0	100,000	0
B	Sand		18.0	50,000	25
C	Sandy clay		18.0	58,000	29
D	Sand stone		19.0	100,000	0

Table 3: Soil properties.

Type of embankment soil	Analysis Results at Abutment/desk joint		
	Moment (kN.m/m)	Shear (kN/m)	Horizontal deflection (mm)
soil 1: Fine sand	1185	554	26.48
soil 2: Gravely sand	1185	543	26.42
soil 3: Gravel	1185	560	26.45

Table 4: Analysis results: Effects of embankment soil, Bridge #4, temperature change=40°C.

- The bending moment and deflection in deck slab increases linearly with increase in temperature.
- For countries experiencing high temperature changes, like Sudan, and until further verifications are reached, the maximum total length of IAB shall be carefully controlled. It is recommended at present time to adopt alternative bridge setup e.g. semi-integral bridges for bridges with total length exceeding 100 m.

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