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Re-Classifying Bridges with Unknown Foundations

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ABSTRACT

A practical, cost-effective and rational approach to re-classify bridges with unknown foundations is presented in this paper. The method is based on satisfying static equilibrium under appropriate loads for the existing bridge pier/bent conditions using three-dimensional, non-linear finite element analysis. The method is applicable to partially and fully-embedded piled-foundation sub-structures where physical measurements of the super-structure and top of the foundation elements (layout, type, and size) can be made. The computed pile embedment using the proposed method is remarkably in close agreement with the actual embedment for bridges referenced in this paper. The approach presented in this practice-oriented paper can provide confidence in assessing the "unknown foundation" bridges and will expedite the screening of these bridges to protect the public. The methodology can also be used to validate embedment determinations done by Non-Destructive Testing (NDT) methods in previous or current projects and to guide any future NDT.

INTRODUCTION

Since the early 1990's, the Florida Department of Transportation (FDOT) and other transportation agencies in the United States have evaluated the impact of scour on bridges. The efforts of such evaluation focused on assessing the stability of state and locally-owned bridges over tidal and non-tidal waterways with scourable beds and determining the risk of failure due to scour. In general, the bridges fall into three categories; namely, bridges with detailed construction records (Category A); bridges with partial construction records (Category B); and bridges without construction records (Category C). The scour evaluation (Hydraulic Analysis; Soil-Structure Evaluation; and Remedial Measures) of the various categories is basically the same once the sub-structure is defined. Assessment of the stability of Category A (i.e., known foundation) bridges is straightforward and many bridges in various states have been evaluated over the past sixteen years. As a result, hundreds of bridges have undergone monitoring, remedial measures or replacement.

Bridges with unknown foundations (i.e., Category B and C) are much more difficult to evaluate in an efficient manner. With the financial and budgetary constraints currently imposed on transportation agencies throughout the world, there is an urgent need for a practical, cost-effective, and rational approach. For Category B bridges, the inference and/or Back-Calculation (Reverse Engineering) methods initiated by the authors (Sayed 2005) after the FHWA Unknown Foundation Summit (FHWA 2005) are appropriate and are outlined in a recent paper (Sayed et al. 2009). Category C bridges are the most challenging. The Static/Back-Calculation (S/B-C) method presented herein is suggested as a means of re-classifying unknown foundation bridges to be "known" so that the scour evaluation can be carried out in the conventional way to assess the risk of failure (Stein and Sedmera 2006) due to the design storm events.

PROCEDURE

Background

The approach presented herein to re-classify bridges without construction records from being "unknown" to "known" is applicable to partially and fully-embedded pile groups where physical measurements of the super-structure and top of foundation elements (layout, type, and size) can be made. Table 1 presents the proposed approach of analysis for unknown foundation bridges.

Table 1. Proposed Methodology for Re-Classifying Unknown Foundation Bridges

Bridge Category	Availability of Records	Proposed Approach
B	Bridges with partial construction records	Inference Method and/or Back-Calculation (Reverse Engineering) Method
C	Bridges without construction records	Back-Calculation (Reverse Engineering) Method + Static/Back-Calculation Method

A detailed assessment of available bridge data (bridge inspection reports, site reconnaissance, etc.) is important in this process in order to develop an optimum and cost-effective analysis. A good geotechnical investigation program that incorporates Non-Destructive Testing (NDT), if required by the Owner, and addresses the scheduling of borings and NDT in an optimum manner is a key to minimizing the cost involved.

Static/Back-Calculation (S/B-C) Analysis

The focus of this paper is to address the use of Static Analysis for the existing bridge conditions to back-calculate the embedment of the piled-foundation system supporting the bridge. The question that needs to be asked is as follows: What is a reasonable estimate of minimum pile embedment that satisfies static equilibrium given the design and construction methods used at the time the bridge was built? The answer to this question can be established if one has accurate physical measurements of the components of the super-structure and top of the foundation elements (layout, type, and size). Such measurements enable the structural engineer via Back-Calculation (Reverse Engineering) to reasonably compute the service loads on the sub-structure. With a reasonable Factor of Safety for traditional Allowable Stress Design (ASD), or appropriate load and resistance factors for Load and Resistance Factor Design (LRFD), the engineer can establish the ultimate load for which the foundation elements were designed. Using this ultimate load and relevant information from the geotechnical investigations, the structure can then be modeled to arrive at a minimum embedment that satisfies static equilibrium for a typical bent or pier as shown in Figure 1.

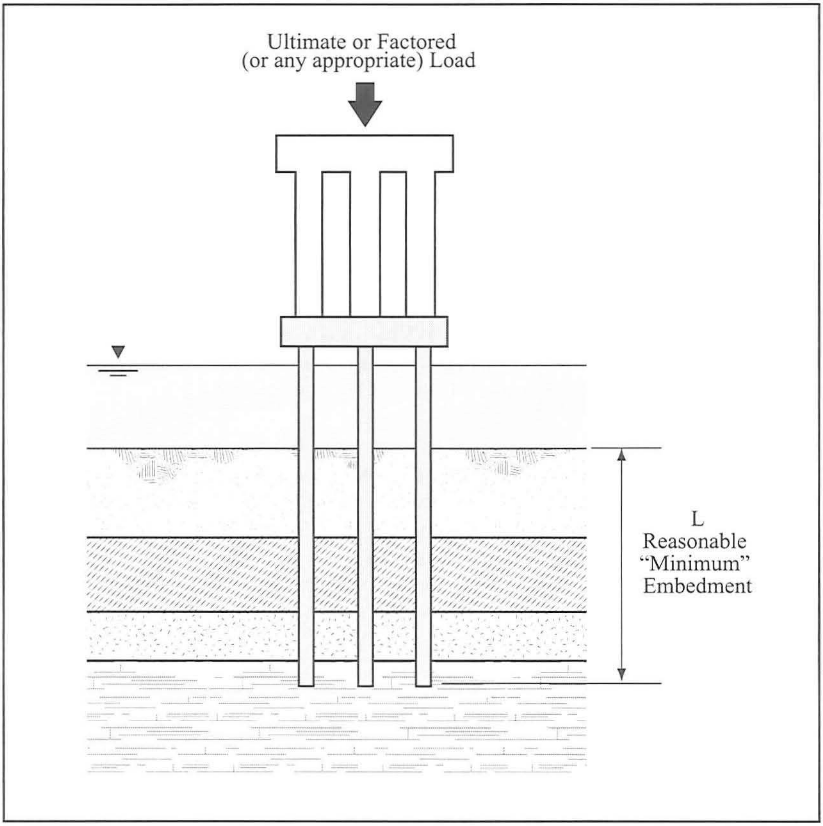


Figure 1. Typical bridge pier/bent over waterway

For older bridges, Allowable Stress Design (ASD) was commonly used. The Static/Back–Calculation Analysis is based on the following relationship:

$$(R)(FS) = \eta_g \Sigma Q_o \quad ; \quad Q_o = Q_o(L) \tag{1}$$

Where

R = Allowable load per pile bent or pile group;
FS = Factor of safety;
η_g = Pile group efficiency; and
Q_o = Ultimate pile capacity of single pile.
$Q_o(L)$ = Ultimate pile capacity of single pile expressed as a function of pile embedment (L); and
L = Reasonable "Minimum" embedment.

It should be noted that the smaller the Factor of Safety (FS), the shorter the embedment. Hence, the proposed method provides a conservative but realistic "current" embedment.

For the most recently designed and constructed bridges, Load and Resistance Factor Design (LRFD) was probably used. The basic equation is, in this case, expressed as:

$$\gamma_d R_{DL} + \gamma_L R_{LL} = \eta_g \Sigma \varphi Q_o \quad ; \quad Q_o = Q_o(L) \tag{2}$$

Where

γ_d and γ_L = Load factors for the dead and live load components;
R_{DL} and R_{LL} = Dead and live load components of the service load R; and
φ = Resistance (performance) factor.

For locally-owned bridges that are not designed for certain standard loading requirements, an appropriate load per pile would be required to use the S/B-C method as shown in the flowchart in Figure 2. The load posting of these bridges can be used in lieu of the more rigorous Back-Calculation (Reverse Engineering) to arrive at the load per bent/pile needed for using the S/B-C analysis.

The pile group efficiency, η_g, is computed from the following expression (Sayed and Bakeer 1992):

$$\eta_g = 1 - (1 - \acute{\eta}_s * K) * \rho \tag{3}$$

Where

$\acute{\eta}_s$ = Geometric efficiency;
K = Group interaction factor; and
ρ = Friction factor.

The S/B-C computation is carried out by using the three-dimensional, non-linear finite element program FB-MultiPier/FB-PIER (FDOT 2000) iteratively to arrive at the stability/instability embedment. The program considers both axial and lateral pile-soil interaction. Soil is characterized by user-defined parameters. The pile group efficiency and time-dependent soil parameters can be incorporated using the procedure outlined by Sayed and Bakeer (1992). The Static/Back-Calculation process is depicted in Figure 2.

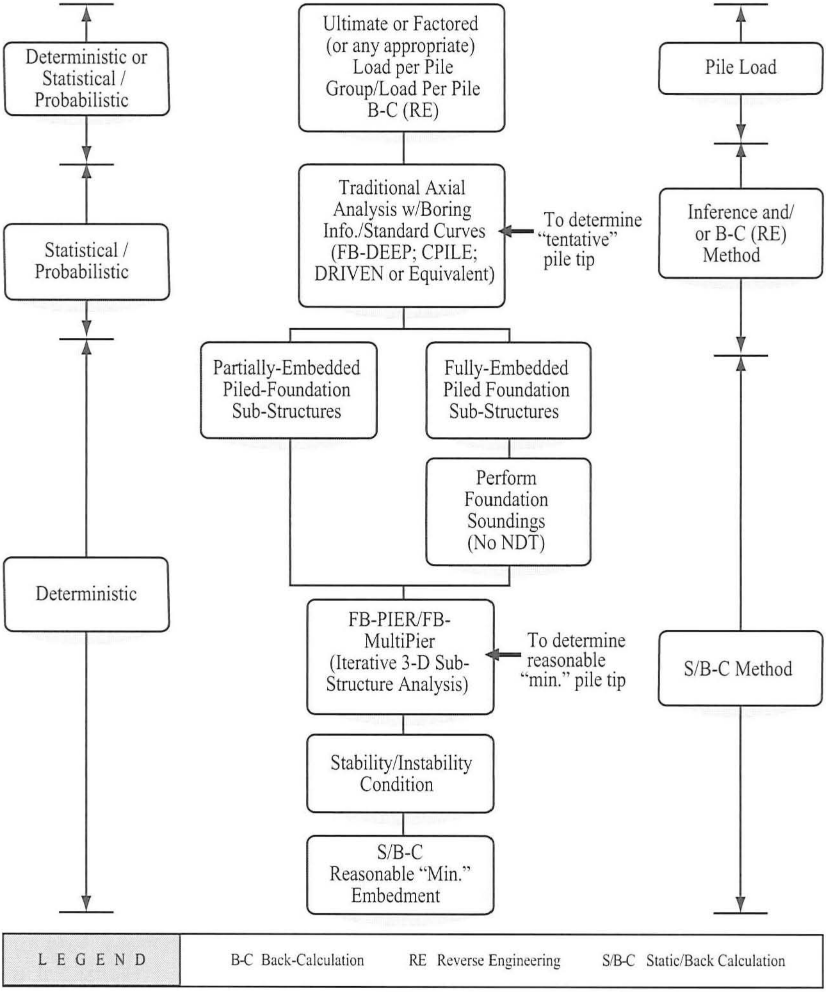


Figure 2. Static/Back-Calculation (S/B-C)

As discussed later in the paper, the proposed method agrees reasonably well with the actual embedment for the "known" foundation bridges used to illustrate the predictive capability of the S/B-C method. Results have shown the actual length is at least equal to the reasonable minimum embedment computed using the Static/Back-Calculation (S/B-C) method added to the known unsupported length. Thus, when implemented with sound engineering judgment, the S/B-C method can be used to analyze bridges with unknown foundations. Subsequent scour evaluations can then be performed using the S/B-C "reasonable minimum embedment" as the "known" foundation embedment. If a bridge is classified as low-risk based on the scour evaluation using the S/B-C "reasonable minimum embedment", it can be removed from the list of "unknown foundation" bridges. If it is found to be scour critical, further measures can be taken. Thus, the method provides a deterministic, conservative, and practical approach to unknown foundation bridges.

PRACTICAL CONSIDERATIONS

General

Just as the engineer must consider the loading requirements for which a bridge would have been designed, he/she should be aware of the construction methods and specifications typically used at the time of construction. Piles do not always drive as predicted during design or as assumed based on the one or two borings which may be available for the S/B-C analysis. Without driving records, knowledge of construction practices can be critical in correctly using the S/B-C method. Since most of the authors' work has been for structures in Florida, examples of Florida Department of Transportation (FDOT) practices are presented.

FDOT Pre Mid-1990's

Before the mid-1990's, FDOT used a modified Engineering-News Record (ENR) formula to determine the blow count required to achieve design capacity. However, by FDOT Standard Specifications, piles were driven their full length to grade (cut-off elevation) and the driving criteria derived from the ENR formula was used only to assure a minimum capacity was achieved. If a pile was driven its full length without achieving the required blow count, an extension or splice was required. If the blow count was achieved before this, driving continued until the pile reached grade or the "maximum practical resistance" was obtained. Practical refusal was defined as a third of the penetration per blow provided by the required blow count from the bearing formula, maintained over 0.6 m (2 ft). Absolute refusal was defined as a tenth of this same penetration, maintained for 50 blows. Driving was stopped before full penetration only if practical or absolute refusal was achieved. Based on these requirements, it can be concluded that piles driven in accordance with FDOT Standard Specifications on these older bridges were almost always driven at least to the embedments predicted during design. Only in special cases, such as the occurrence of unexpected hard rock or very dense material, might they be shorter. Borings performed as the part of the bridge evaluation can often alleviate concerns that such rock or dense material was encountered.

FDOT Post Mid-1990's

Since the mid-1990's, FDOT has required all structures founded on piles to include dynamic load testing of test piles using Pile Driving Analyzer (PDA) equipment. Based on the results of driving these piles and subsequent CAPWAP analyses, production pile lengths and driving criteria are set. There is confidence that the piles are driven to a required driving resistance which includes a known Factor of Safety (or load and resistance factors), or to a minimum tip elevation, whichever is deeper. The minimum tip elevation is usually set by the structural engineer to ensure lateral stability, but can also be controlled by potential settlement, punching failure, etc. Scour is accounted for when applicable. Thus, if the structure was designed and constructed in accordance with FDOT procedures, one can be fairly certain that actual embedment is at least as deep as that calculated by the S/B-C method.

General Use of S/B-C Method

With knowledge of the circumstances under which a state or local bridge was constructed, the S/B-C method can be applied to all types of bridge structures founded on piles. As described in this paper, bridges constructed using FDOT Standard Specifications have been analyzed successfully. Non-FDOT bridges, whether in-state or out-of-state, can be analyzed similarly by adapting the methodology to account for the design and construction practices which were in use at the time the bridge was built.

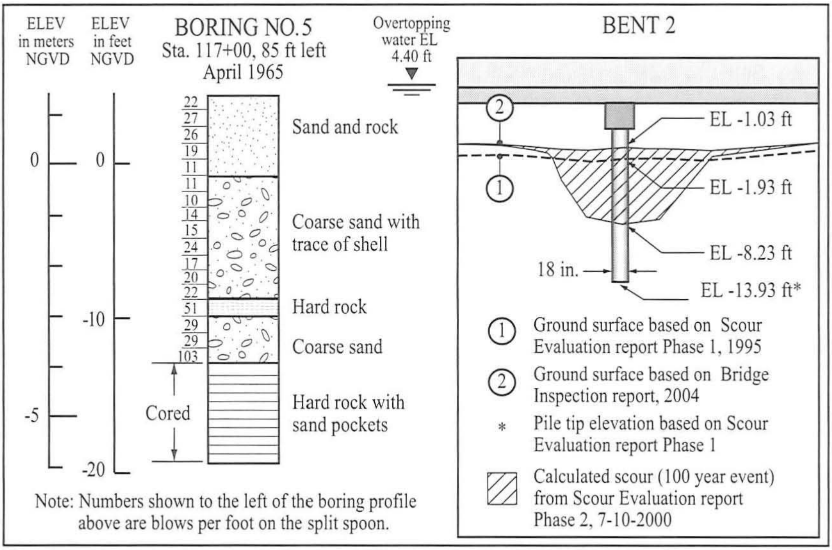
PREDICTIVE CAPABILITY OF S/B-C METHOD

General

The usefulness and predictive capability of the Static/Back-Calculation (S/B–C) analysis presented in this paper are demonstrated by several case studies of bridges with known foundations, one of which is detailed below. In these case studies, the structural loads and geotechnical parameters were considered "known"; the foundation was "unknown". The analysis was carried out using the non-linear, finite element program FB-MultiPier/FB-PIER V4 (FDOT 2000) to determine the pile embedment at which static equilibrium is first encountered. This reasonable minimum embedment was then combined with the known unsupported length and compared to the actual known foundation. In the analysis, piles were modeled assuming no material deficiencies or section property losses and pile creep effects were not considered. The deflected shape (P-delta effects), and possible pile cracked section properties were incorporated and the pile-cap connection was assumed pinned.

Case Study

Bridge Number 030064, US-41 over Outback Canal, Collier County, Florida, is the subject of the case study presented in detail in this section. The bridge was constructed in 1966 and has undergone no repairs or rehabilitation. The bridge structure is approximately 13.6 m (45 ft.) long, consisting of two 6.8 m (22.3 ft.) spans with a superstructure composed of 343 mm (13½ in.) thick simple span cast-in-place slabs. The intermediate pile bent has five 455 mm (18 in.) square prestressed concrete piles with an unsupported length of 1.2 m (3.8 ft.). The soil boring at the bridge bent is shown in Figure 3. Partial geotechnical parameters used in the analysis are provided in Table 2 and more details are given in the report by Ayres and GCI (2007). The total load was computed to be 1775 KN (399 kips) per pile bent or 355 KN (80 kips) per pile. The model geometry was based on the 1965 Bridge Plans. The Static/Back-Calculation (S/B-C) as depicted in Figure 2 and formulated in Equations (1) and (3) was carried-out.



Note: Numbers shown to the left of the boring profile above are blows per foot on the split spoon.

Figure 3. Report of SPT Boring for Bridge 030064

Table 2. Geotechnical Parameters for FB-MultiPier/FB-PIER V4 Model Bridge No. 030064, US-41 over Outback Canal, Collier County, Florida

SOIL BORING DATA									
Layer No.		1		2		3		4	
Soil Description		Coarse Sand w/trace of Shell		Hard Rock		Coarse Sand		Hard Rock	
Average SPT-N (Blows Per Foot)		17		51		29		100	
Thickness	Feet	6.7		0.9		3.5		6.5	
	Inch	80.0		10.8		42.0		78.0	
Elevation Range (NGVD)	Feet	-1.93 to -8.6		-8.6 to -9.5		-9.5 to -13.0		-13.0 to -19.5	
	Inch	-23.2 to -103.2		-103.2 to -114.0		-114.0 to -156.0		-156.0 to -234.0	
SOIL/ROCK LAYER PROPERTIES									
Geotechnical Parameters		Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Friction Angle (φ) (degrees)		32°	32°	---	---	34°	34°	---	---
Soil Modulus k (kci)		0.06	0.06	0.8	0.8	0.06	0.06	0.8	0.8
Total Unit Weight (γ) (kci) (10^{-5})		6.7	6.7	6.9	6.9	6.9	6.9	7.0	7.0
Undrained Shear Strength (C_u) (ksi) (10^{-3})		---	---	40.0	40.0	---	---	56.0	56.0
Major Principal Strain at 50% (ε_{50})		---	---	0.004	0.004	---	---	0.004	0.004
Avg. Undrained Shear Strength (C_{avg}) (ksi) (10^{-3})		---	---	40.0	40.0	---	---	56.0	56.0
US-SI CONVERSION FACTORS									
1 in = 25.4 mm				1 kci = 2.71 x 10^{-4} Kn/mm^3					
1 Kip = 4.45 kN				1 ksi = 6.89 x 10^{-3} kN/mm^2					

A Factor of Safety of 2.5 was applied to the axial load for ASD Method. The analysis converged at a pile length of 5.2 m (17 ft.) but failed to converge at a pile length of 4.8 m (16 ft.). Actual average pile length for this bridge bent is 4.9 m (16.1 ft.).

Predicted vs. Actual Length

Results of the various case studies showed a good correlation between predicted pile lengths from the S/B-C analysis and actual average pile lengths. This comparison is graphically summarized in Figure 4.

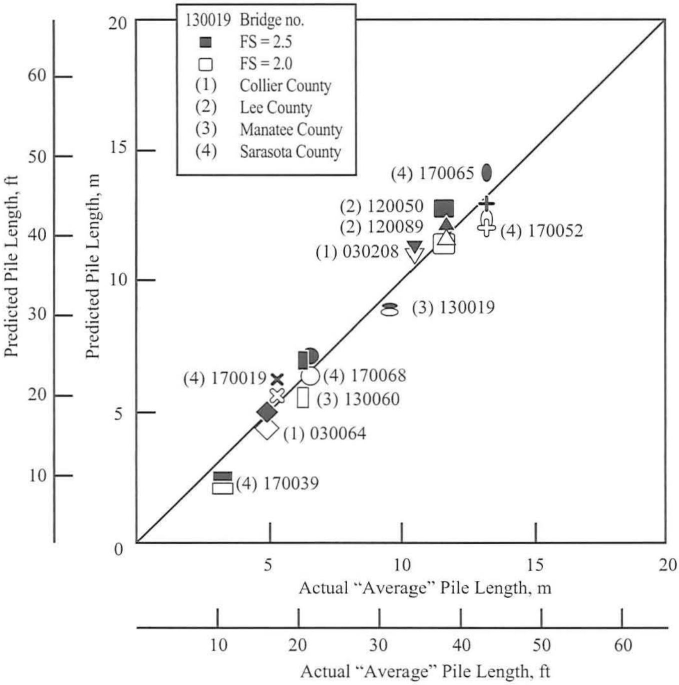


Figure 4. S/B-C Predicted vs. Actual Pile Length

VALIDATION OF NON-DESTRUCTIVE TESTING (NDT)

The S/B-C method can also be used to validate embedment determinations done by NDT methods in previous or current projects. For "high priority" unknown foundation bridges, the S/B-C reasonable minimum embedment can be used along with the embedment required for stability considering the scour to plan and guide any future NDT that may be required by the owner. In general, the S/B-C method can reduce the extent of costly NDT that may be done in the future and presents an alternative to positive discovery of bridge foundations.

SUMMARY AND CONCLUSIONS

Since the mid 1990's, the Static/Back-Calculation (S/B-C) method has been adopted and developed by the authors as a calibration tool for the geotechnical/structural model in the Soil-Structure scour evaluation for several hundred bridges with known foundations in the State of Florida. With the confidence gained from these analyses, the S/B-C method is proposed as a means to re-classify unknown foundation bridges from "unknown" to "known" by determining the reasonable minimum embedment. The method is a practical, cost-effective, and deterministic approach and can reduce or eliminate the use of costly Non-Destructive Testing (NDT). It is based on satisfying static equilibrium under appropriate load for the existing bridge pier/bent conditions using three-dimensional, non-linear finite element analysis. The approach is applicable to partially and fully-embedded (i.e., buried pile cap) sub-structures. Basic geotechnical data, structural loads (ASD, LRFD, or any appropriate load), geometry of the sub-structure (i.e., pile group layout and pile type and size), and knowledge of construction practices and methodologies are all needed to successfully utilize the method. Once the re-classification to "known" from "unknown" is done using the Static/Back-Calculation method, the scour evaluation (Hydraulic Analysis; Soil-Structure Evaluation; and Remedial Measures, if needed) is subsequently done in the conventional manner. The S/B-C method is a powerful tool that removes a major stumbling block in the path of the scour evaluation program for unknown foundation bridges. It alleviates the potential impact of budget cuts experienced by various agencies around the country and accelerates the screening of these bridges in a rational and timely manner to protect the public.

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