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Authors(s)	Laefer, Debra F., Truong-Hong, Linh, Le, Khanh Ba
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REDUCTION OF LATERAL LOADS IN ABUTMENTS USING GROUND ANCHORS

Linh Truong-Hong, B.Eng, C.Eng, PhD, Postdoctoral Researcher, Digital Media Center, Dublin Institute Technology, Room 2002, Aungier St., Dublin 2, Ireland. Email: linh.truonghong@dit.ie

Debra F. Laefer, B.Eng, C.Eng, PhD, M.ASCE, Tenured Lecturer, Lead PI, Urban Modelling Group, School of Civil, Structural and Environmental Engineering, University College Dublin, Newstead G25, Belfield, Dublin 4, Ireland. Email: debra.laefer@ucd.ie, corresponding author

Khanh Ba Le, B.Eng, C.Eng, PhD, Senior Lecturer, Head of Division of Bridge and Highway Engineering, Faculty of Civil Engineering, Ho Chi Minh City University of Technology, B6 Hall, 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh city, Vietnam. Email: lbkhanh@hcmut.edu.vn

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ABSTRACT:

In bridge design, economically addressing large, lateral earth pressures on bridge abutments is a major challenge. Traditional approaches employ enlargement of the abutment components to resist these pressures. This approach results in higher construction costs. As an alternative, this paper proposes a formal approach using ground anchors to resist lateral soil pressure on bridge abutments. The ground anchors are designed herein to minimize lateral forces at the pile cap base. Design examples for high stem abutments (heights 6-8 m) are conducted for a simple 33 m long concrete bridge span, with 2-3 traffic lanes. The abutments are supported by driven, reinforced concrete piles. As lateral forces at the pile cap are significantly reduced, only one row of piles is needed. When compared to common abutment design, the proposed approach halved the number of required piles and decreased the required abutment volume by 37%.

NOTATIONS:

D_b - effective fixed anchor diameter

H - lateral force along the longitudinal direction at the base of the pile cap due to all loadings in the abutment without ground anchors

H_{base} - lateral force along the longitudinal direction at the base of the pile cap

K_1 - earth pressure coefficient

L_b - bond length of the strand

M - moment around the transverse direction of the bridge at the pile cape base due to all loadings in the abutment without ground anchors

M_{base} - moment rotating around the transverse direction of the bridge at the base of the pile cap

n - number of the ground anchors

n_{cal} - number of ground anchors calculate

n_{select} - number of ground anchors select

s_u - undrained shear strength

T_h - horizontal load of a ground anchor

T - working load of a ground anchor

T_u - ultimate load capacity of a ground anchor

Δy - lateral displacement of a pile along the longitudinal direction of the bridge

Δz - vertical displacement of a pile

Z_{anchor} - distance from a centre of gravity of ground anchors to the pile cap base

α - anchor's angle of inclination below the horizontal

ε_{50} - value of strains at one-half the maximum principal stress

ε_{100} - value of strains at the maximum principal stress

ϕ - friction angle

θ_{xx} - rotation of a pile around the transverse direction of the bridge

σ'_v - average effective overburden pressure adjacent to the fixed length

Keywords: anchors and anchorages, bridges, soil/structure interaction

REDUCTION OF LATERAL LOADS IN ABUTMENTS USING GROUND ANCHORS

Linh Truong-Hong, Debra F. Laefer, Khanh Ba Le

INTRODUCTION

Overpass bridges in urban regions often require high vertical clearances. This, coupled with limited construction right-of-ways, precludes slopes between the abutment face and roadway edge. The resulting bridge abutments are subjected to large lateral loads due to high backfills. In such cases, the traditional solution requires a large stem abutment and associated group of piles with a high lateral capacity to resist failure (e.g. sliding, overturning, and bearing failure) (Chen and Duan, 2000). To avoid large lateral loads acting on the abutment and its foundation, additional structural components must be integrated into the abutment system to resist the lateral pressure. This paper investigates an alternative and more economical approach through the incorporation of ground anchors.

BACKGROUND

A bridge abutment provides vertical support for bridge superstructures at the end of the bridge. There are those classified as a monolithic type (also called an integral abutment) where the abutment and superstructure behave in tandem as a single structure. Others are of a stem seat type where the superstructure and the abutment act separately. Recently, integral abutments have gained popularity to increase seismic capacity (Burke, 1993) and avoid the high costs associated with installation, maintenance and rehabilitation of expansion joints (Arockiasamy et al., 2004); the others however still continued to be constructed, especially in developing countries, as they are simple to design and construct.

One approach of the former is in the use of a mechanically stabilized earth (MSE) system for the abutment. The MSE walls act as facing walls subjected to lateral loads from earth pressure and surcharge loads, which the abutment foundations carry only the applied loads from the bridge (Zevgolis and Bourdeau, 2007), as was done in the I-95 Bridge in Trenton, New Jersey (Khodair and Hassiotis, 2005). The nearly 5.2 m high MSE wall included an integral abutment (0.9 m wide x 2.88 m deep with a 1.2 m deep pile cap) supported by 19 steel piles HP360x152 (Figure 1a). Similarly, the Founders/Meadows parkway bridge on Colorado State Highway 86 included an MSE abutment wall placed directly on top of a geogrid-reinforced segmental retaining wall, which provided 7 m of vertical clearance (Abu-Hejleh, 2000). The abutment had a 0.76 m stem wall and a 3.81 m x 0.61 m shallow footing, and the 5.9 m high MSE wall was located 3.1 m in front of the centreline of the bridge abutment wall. Using MSE bridge abutments could eliminate the need for deep foundations, however excessive localized lateral stresses can occur at the bridge/embankment transition, which would require additional maintenance costs (Zevgolis and Bourdeau, 2007). Furthermore, bridge abutments must exhibit long-term, high performance to ensure that only small differential settlements develop to avoid damaging the superstructures. The MSE walls have yet to be proven so settlement resistant over multiple decades.

In later approaches, ground anchors or soil nails can be used to resist the lateral soil pressure (FHWA, 1999). To date, this has been done in an ad hoc manner. An example is Bridge 325 Abington on the Edinburgh/Carline Railway line, in which 8 ground anchors were tested with loads varying from 127.5-196.0kN (CINTEC, 2009). Also at the Lake Parkway project in Milwaukee, Wisconsin, where railway bridge abutments were designed with a traditional abutment but with a cut-off wall. In that case, the abutment pile carried the vertical loads, and the ground anchors with soldier beams supported the lateral earth pressure [Figure 1b] (Anderson, 1998). This allowed an abutment thickness reduction from 1.5 m to 1.15 m. In most cases, ground anchors have been used to reinforce existing abutments. The design approach to incorporate them in new bridge abutments is not well established. To address this, a design approach is proposed below.

OBJECTIVES AND METHODOLOGY

The objective of this work is to investigate the beneficial impact of incorporating ground anchors into bridge abutment design to resist lateral soil pressures. This research should be considered a preliminary step to codifying a proposed approach. This study will evaluate the pile responses and required abutment geometry by comparing those quantities in the proposed approach to those in a traditional approach, where the abutment and its foundations must resist all lateral earth pressures.

In an overpass bridge, the closed end abutment with a high stem wall is often used to satisfy vertical clearance requirements. In this case, the high backfill causes large lateral pressures to applied on the abutment and its foundation. In order to reduce lateral earth pressures, ground anchors with pre-stressed strands are proposed in designing the abutment. Notably, this study only investigates the lateral pile response rather than the design of the entire abutment (e.g. abutment components or ground anchors). In Vietnam, new bridge abutments (usually of the stem seat type) are designed according to AASHTO (2004). This is the general context for the design procedure. Although the specification is recommended to use several load combinations for various limit states in abutment design, in this study, the lateral pile response is only evaluated under extreme loads applied on the abutment from a load combination for Service I limit state, involving nominal values of all loads that relate to normal operational bridge usage.

The backfill behind the abutment and in front of the pile cap toe is assumed to be a medium-dense sand. In this soil type, a driven, rectangular, reinforced concrete (RC) pile is commonly selected, as it is economical and simple to install. While the abutment components are designed to satisfy all AASHTO LRFD under various load combinations (AASHTO, 2004); details of that portion of the design procedure will not be presented herein.

PROPOSED APPROACH

For bridge abutments, integrated ground anchors mainly act as pre-loads in the opposite direction of the lateral soil pressure to minimize lateral loads on the abutment. As working mechanisms are similar to these in retaining structure types, the ground anchor should be designed to satisfy critical conditions for a permanent ground anchor (FHWA, 1999). In abutment design, lateral pile responses are crucial. Moment and lateral forces mainly dominate the pile's lateral response. Therefore, the main objective of this study is to integrate ground anchors into the abutment to minimize lateral forces acting on the abutment foundation. As such, the objective function of the proposed approach is given in Eqn. 1:

$$\mathrm{argmin}(f, \{H_{base}, M_{base}\}) \qquad \text{Eqn. 1}$$

where H_{base} and M_{base} are, respectively, the lateral force along the longitudinal direction and the moment rotating around the transverse direction of the bridge at the base of the pile cap, after considering the impact of the ground anchors. However, as an overturning moment impacts pile response more significantly than lateral force, the objective function must minimize the moment at the pile cap base. Thus, a number of the ground anchors integrated into the abutment and their position can be simply determined according to Eqn. 2

$$nZ_{anchor} = \frac{M}{T_h} \qquad \text{Eqn. 2}$$

where n is the number of the ground anchors selected, Z_{anchor} is the distance from a centre of gravity of all ground anchors to the pile cap base, M is the moment around the transverse direction of the bridge at the pile cape base due to all loadings (superstructure loads, surface surcharged load, and lateral earth pressure) in the abutment without ground anchors, and T_h is the horizontal load of a ground anchor, which is calculated from Eqn. 3 as follows:

$$T_h = T \sin \alpha \qquad \text{Eqn. 3}$$

where T is the working load of a ground anchor, and α is the anchor's angle of inclination below the horizontal. The working load is preliminarily specified based on the type of the ground anchor, but the final value must be obtained from on-site testing. Furthermore, the inclination angle is selected to satisfy constructability concerns and minimize vertical working loads. Based on the ground anchor's design procedure, the ground anchor type and working load are initially selected. Then, the number of the ground anchors and their elevations are determined according to Eqn. 3, where these parameters must satisfy minimal requirements for the distance between adjacent ground anchors and the distance from the ground anchor head to the ground surface (FHWA, 1999). For investigating the impact of using ground anchors on lateral responses of piles and reducing abutment volume, the design practice is illustrated below.

DESIGN PRACTICE

Abutment description

Bridge structures selected in this practice are popular overpass bridges in urban regions of Vietnam. Two typical cross-sections of 2 and 3 traffic lanes were used. Each was 3.5 m wide, with a parapet on each side and overall cross-widths of 8.0 m and 11.5 m, respectively (Figure 2a&b). The side span was 33.0 m long and supported by a pre-stressed, RC beam with an I-section. Additionally, a closed end, high-stem, seat abutment was adopted (Figure 2c&d). This abutment type is constructed separately from the bridge superstructure, in which loading from the superstructure is transferred to the abutment foundation through bearing pads. As mentioned earlier, the abutment configuration must be designed to minimize the overturning moment at the pile cap base. For that, the centreline of the abutment wall must coincide with that of the pile cap, and expansion bearings are used to avoid application of braking forces to the abutment. This minimizes eccentric forces in the abutment wall and foundations due to the transfer of vertical loads from the superstructure.

This study considered 2 abutment heights (H_0=6.0 m and 8.0 m) corresponding to stem wall heights of H_1=2.77 m and 4.77 m (Figure 2c&d). Additionally, a medium-dense sand, with an angle of internal friction of 35^0 was used as backfill material and in front of the abutment toe. The abutment foundation extends through various soil layers obtained from one a borehole in Ho Chi Minh City, Vietnam (see next section for details). Driven concrete piles 40 cm x 40 cm x 24 m long were proposed (Figure 3) – compressive strength of the concrete and tensile strength of the steel were 30 MPa and 420 MPa, respectively. Thus, the allowable design load was around 5,986 kN in compressive strength and 162.3 kN-m in flexural moment.

By using the conventional method, the abutment geometry had a stem wall thickness of 1.0-1.5m, and was supported by at least 2 rows of piles, in which the front row is often battered to increase lateral load resistance. In a design example of a high stem abutment for a simple steel bridge with 46.3 m in span length and 4 traffic lanes, the abutment was subjected to 7.9 m of backfill and had a 1.37 m thick stem wall with 3 rows of piles (0.3 m in diameter) with the first 2 rows battered (Mn/DOT, 2004). In the study herein, a 1 m thick abutment stem wall and two rows of the piles were preliminarily proposed (Figure 2c). For the abutment subjected to an 8m of backfill height, the front row piles were battered with a slope of 1:6 horizontal to vertical (Figure 2c). In addition, the abutment foundation had 7 and 10 piles in each row for the abutments subjected to 6 m and 8 m of backfill height, respectively. The distance between adjacent piles in the row was also 1.15 m, which corresponded to 2.875 pile widths (D) – a value is within the proposed optimal spacing of 2.5-6D (Bowles, 1988). Furthermore, a 2.4 m wide pile cap was adopted (Figure 2c).

In the proposed approach of integrating ground anchors, initial abutment dimensions are depicted in Figure 2d. The stem thickness was selected to be slightly greater than that recommended for an integrated abutment wall thickness (NDDOT, 2008). Additionally, since lateral loads were reduced significantly, only one straight row of piles was needed for the abutment foundation., A total of 7 and 10 piles in the row were required, respectively, for bridge abutments with 6 m and 8 m of backfill height. Pile spacing was 1.15 m, and the pile cap width of 1.2 m was selected to satisfy clearance requirements between the side and the nearest edge of the pile cap (AASHTO, 2004). Ground anchor elevations were designed with respect to the objective function and minimum requirements for proper ground anchors (as will be discussed later).

Determine loads and load combinations

In abutment design, lateral response of the piles must be examined under various extreme load combinations, but for a simple case, a Service Limit I (SER I) according to AASHTO (AASHTO, 2004) was herein considered. Three loading combinations produced the severest conditions (Table 1 and Figure 4a-c). These involved vertical and lateral soil pressures, abutment gravity loads, live load surcharge on the abutment backfill material, and vertical loads from the bridge superstructure (Chen and Duan, 2000).

Table 1. Load combinations for Service Limit I at the bottom of abutment pile caps(*)

Design approach	Bridges	SER I: Case 1			SER I: Case 2			SER I: Case 3		
		V (kN)	H (kN)	M (kN-m)	V (kN)	H (kN)	M (kN-m)	V (kN)	H (kN)	M (kN-m)
Proposed approach	B1R: W8H6	3892.53	734.25	1442.58	2795.66	734.25	1442.58	981.03	734.25	1442.58
	B2R: W8H8	4162.23	1250.94	3352.43	3065.35	1250.94	3352.43	1250.73	1250.94	3352.43
	B3R:W11.5H6	4952.60	1055.48	2073.13	3554.08	1055.48	2073.13	1413.98	1055.48	2073.13
	B4R:W11.5H8	5340.29	1798.23	4818.53	3941.77	1798.23	4818.53	1801.67	1798.23	4818.53
Traditional approach	B1T: W8H6	4675.87	734.25	1801.75	3578.99	734.25	1417.84	1945.67	734.25	846.18
	B2T: W8H8	5303.07	1250.94	3483.29	4206.19	1250.94	3099.38	2572.87	1250.94	2527.72
	B3T:W11.5H6	6520.67	1055.48	2517.36	5122.15	1055.48	2027.87	2800.75	1055.48	1215.38
	B4T:W11.5H8	7422.27	1798.23	4934.58	6023.75	1798.23	4445.09	3702.35	1798.23	3632.60

Note: (*) Positive values of (V, H and M) refer to Fig. 4d.

Determine ground anchor characteristics

Ground anchor design should consider potential failure conditions for both itself and the abutment (FHWA, 1999). The ground anchors integrated into the abutment must be designed as permanent ones, as they will work throughout the abutment's life span. General parameters of ground anchors including type, quantity, working load, and unbonded and bonded length are presented herein, instead of a detailed procedure for their design, as this is already well-established (e.g. FHWA, 1999, Xanthakos, 1991).

A 15 mm diameter, pre-stressing steel strand satisfying ASTM A416, Grade 1860 (ASTM A416/A416M, 2010) was selected. Working load should not exceed 50% of the strand's ultimate tensile strength, which is 127.5 kN (Xanthakos, 1991). The ground anchor was to be installed at an angle of 10˚ below the horizontal. According to FHWA (1999) the unbonded lengths must be greater than 4.5 m to prevent significant seating losses, while a distance from the middle bond length to the ground surface needs to be at least 4.5 m to prevent grout leakage during installation (Figure 5). Thus, a minimum distance from the ground anchor to the ground surface (Z'_{anchor} in Figure 5) had to be no less than 3.55 m. In this case, the unbonded length was around 4 m. The minimum unbonded length was selected to satisfy the minimum distance requirement above, while the minimum bond length was determined from Eqn. 4 (Xanthakos, 1991), in which a safety factor of 2.0 was applied.

$$T_u = K_1 \pi D_b L_b \sigma'_v \tan\phi \qquad \text{Eqn. 4}$$

where K_1 is an earth pressure coefficient, D_b the effective fixed anchor diameter, L_b the bond length of the strand, and σ'_v the average effective overburden pressure adjacent to the fixed length (taken at midpoint). In this study, K_1 equals 1.0, and D_b is 300 mm. Thus, the recommended bond length is 5.4 m; obviously final parameters must always be determined from field testing.

Design and final loads are shown in Table 2. An elevation of ground anchors integrated into the abutments is illustrated in Figure 6, where one layer of ground anchors is used for Bridges 1R and 3R (Figure 6a) and two layers for Bridges 2R and 4R (Figure 6b). As such, the distance from the ground surface to the first layer was 3.7 m for the abutment of Bridge 2R and 3.55 m for Bridge 4R (Figure 6b).

Table 2. Summary of design ground anchors and final loads at the bottom of a pile cap

Combination Loads	Design ground anchors				Final loads		
	T (kN)	Z_{anchor} (m)	n_{cal}	n_{select}	V (kN)	H (kN)	M (kNm)
The proposed approach-Bridge 1R: Bridge width = 8.0 m; Abutment height (H_0) = 6.0 m							
SER I: Case 1	127.50	2.45	4.70	4.00	3981.10	232.00	212.07
SER I: Case 2	127.50	2.45	4.70	4.00	2884.22	232.00	212.07
SER I: Case 3	127.50	2.45	4.70	4.00	1069.59	232.00	212.07
The proposed approach-Bridge 2R: Bridge width = 8.0 m; Abutment height (H_0) = 8.0 m							
SER I: Case 1	127.50	3.30	8.10	8.00	4339.35	246.44	37.57
SER I: Case 2	127.50	3.30	8.10	8.00	3242.47	246.44	37.57
SER I: Case 3	127.50	3.30	8.10	8.00	1427.85	246.44	37.57
The proposed approach-Bridge 3R: Bridge width = 11.5 m; Abutment height (H_0) = 6.0 m							
SER I: Case 1	127.50	2.45	4.50	5.00	5063.30	427.67	534.99
SER I: Case 2	127.50	2.45	4.50	5.00	3664.78	427.67	534.99
SER I: Case 3	127.50	2.45	4.50	5.00	1524.68	427.67	534.99
The proposed approach-Bridge 4R: Bridge width = 11.5 m; Abutment height (H_0) = 8.0 m							
SER I: Case 1	127.50	3.45	11.10	10.00	5561.69	542.60	486.61
SER I: Case 2	127.50	3.45	11.10	10.00	4163.17	542.60	486.61
SER I: Case 3	127.50	3.45	11.10	10.00	2023.07	542.60	486.61

Pile foundation

While ground anchors reduced lateral loads (horizontal load and transverse moment) on the abutment, they slightly increased the vertical load at the pile cap base. To provide pile capacity for heavy bridge loads, the pile length was preliminarily selected as 24 m to be driven through 3 soil layers (Table 3), with the pile tip embedded 3.3m into the dense sand. Allowable, axial capacity of a single pile was 1119 kN based on an empirical formulation proposed by AASHTO (2004), where the α-method was used to estimate skin resistance in cohesive soil and the Standard Penetration Test (SPT) method was applied to obtain skin and tip resistance in sand.

Table 3. Soil properties(*)

Soil layer	Thickness (m)	Density (kg/m^3)	Undrained shear strength (s_u -kN/m^2)	Friction angle (ϕ-degree)
Medium stiff clay	11.1	1810	37.7	
Stiff Clay	9.6	1967	55.38	
Dense sand	8.2	1990		35

** Note: Ground water level table is 1.5 m below the top of the medium stiff clay*

For investigating lateral response of piles, pile-soil interaction was analyzed by the FB MultiPier analysis program, which is a non-linear finite element analysis program capable of analyzing multiple bridge pier structures and interactions between pile cap/piles and soil (Hoit et al., 2005). The program allows use of multiple element types (e.g. membrane, plate and beam elements) to model foundation components and to implement several soil models (Hoit et al., 2005). To simplify the analysis, only the pile cap and piles were modelled, rather than the whole abutment and its foundation (Figure 7a). A membrane element was selected for the pile cap and a beam element for the pile. In this case, the connection between the pile cap and piles was fixed. Additionally, a p-y curve for each soil layer was determined based on input parameters (Table 4) and the built-in soil model in the FB MultiPier program. The loading at the stem wall base was assigned to nodes belonging to the pile cap, along the length of the stem at the pile group's centreline. The defined loads were assumed to have a uniform distribution along the stem (Figure 7b), and three load cases were applied for each abutment foundation (Table 2).

Table 4. Input value parameters for FB-MultiPier Analysis(*)

Depth of soil layer		Soil type	Lateral model (p-y curve)	Unit weight (kN/m^3)	Undrained shear strength (kPa)	Friction angle (degree)	Subgrade modulus (kN/m^3)	Strain ε_{50}
from	to							
0.0	-1.5	Cohesive	Clay (O'Neill 1984)	18.10	37.7			0.02
-1.5	-11.1	Cohesive	Stiff clay	19.10	37.7		19,850	0.02
-11.1	-20.7	Cohesive	Stiff clay	19.67	55.38		31,850	0.02
-20.7	-24.0	Cohesionless	Sand (O'Neill 1984)	19.90		35	62,280	

(*)Note: ε_{50} and ε_{100} are respectively values of strains at one-half and a full maximum principal stress. ε_{100} for the first soil layer modeled by O'Neill clay model is 0.06 and the medium stiff clay from the borehole modeled as clay (O'Neill 1984) and stiff clay.

Results from three possible load cases under Service Limit I are shown in Table 5 and Fig. 8. All pile displacements in this case study were below the allowable limits used in pile design, where were 82.5 mm for vertical displacement (Hambly, 1979), 25.4 mm for the horizontal displacement, and 0.008 for angular distortion (AASHTO, 2004). In general, lateral responses of piles in the proposed abutments were larger than those in the traditional abutment. For example, the lateral displacements and rotations of piles in Bridge 4T were respectively approximate 1.8 and 1.9 times of those in Bridge 4T. The largest lateral displacement was 3.43 mm in Bridge 4R and 1.90 mm in Bridge 4T, while the maximum settlements were 1.34mm in Bridge 2R and 1.35 mm in Bridge 2T. Also, the maximum rotation around the transverse direction of the piles did not exceed $1.84x10^{-3}$ radians in Bridge 4R (Figure 8b). From these observations, although lateral loads at the pile cap base decreased significantly [e.g. for Case 1 of SER I, in Bridge 4R, the overturning moment was around 10% of the one in Bridge 4T (486.61 kN-m vs. 4934.58 kN-m) (Table 1&2)], the lateral displacement in Bridge 4R was 1.9 times greater than in Bridge 4T (3.43 mm for Bridge 4R vs. 1.80 mm for Bridge 4T), because the two rows of piles in the abutment foundation of Bridge 4T made the foundation significantly stiffer compared to that of one row of piles in Bridge 4R.

Additionally, the maximum internal forces (axial, shear, and moment) of all piles in both abutments were smaller than the allowable capacity of the single pile. The internal forces in the piles in the proposed abutments are slightly larger than ones in the traditional abutments. The maximum axial force in the piles in the proposed abutment was 590.8 kN (Bridge 2R-Table 5) corresponding to 53% of the allowable axial capacity of the pile by 1119 kN. Additionally, for the traditional abutment, the maximum axial force was 726.4 kN (Bridge 2T-Table 5) that was approximate 65% of the allowable axial capacity of the pile. Similarly, in the proposed abutments, the largest bending moments in the piles were approximately 55% of allowable bending moments of the pile (89.4 kN-m vs. 162.3 kN-m) as found in Bridge 4R, while in the traditional abutments, the pile's bending moments were less than 35% of the allowable ones (57.1 kN-m vs. 162.3 kN-m in Bridge 2T) (Table 5).

Table 5. Summary of maximum displacements and forces in pile[(*)]

Bridges	Load case	Pile responses			Forces in pile		
		Δy (mm)	Δz (mm)	θ_{xx} ($x10^{-3}$ radians)	V (kN)	H (kN)	M (kNm)
Proposed approach: Bridge 1R: Bridge width = 8.0m; Abutment height (H_0) = 6.0m	SER I: Case 1	1.56	1.21	0.93	537.34	26.11	49.14
	SER I: Case 2	1.56	0.85	0.93	383.83	26.10	49.14
	SER I: Case 3	1.55	0.33	0.93	155.30	26.11	48.93
Proposed approach: Bridge 2R: Bridge width = 8.0m; Abutment height (H_0) = 8.0m	SER I: Case 1	1.14	1.34	0.60	590.82	29.06	32.03
	SER I: Case 2	1.13	0.97	0.60	437.32	29.06	31.94
	SER I: Case 3	1.14	0.45	0.60	208.75	29.09	31.89
Proposed approach: Bridge 3R: Bridge width = 11.5m; Abutment height (H_0) = 6.0m	SER I: Case 1	2.75	1.09	1.58	486.80	34.01	78.93
	SER I: Case 2	2.73	0.77	1.57	349.28	34.02	78.56
	SER I: Case 3	2.73	0.33	1.57	155.61	34.03	78.53
Proposed approach: Bridge 4R: Bridge width = 11.5m; Abutment height (H_0) = 8.0m	SER I: Case 1	3.43	1.30	1.84	574.45	44.40	89.35
	SER I: Case 2	3.37	0.97	1.81	437.04	44.55	87.76
	SER I: Case 3	3.37	0.45	1.81	207.53	44.56	87.67
Traditional approach: Bridge 1T: Bridge width = 8.0m; Abutment height (H_0) = 6.0m	SER I: Case 1	1.86	0.24	0.85	543.94	45.21	44.00
	SER I: Case 2	1.65	0.97	0.71	435.22	45.48	38.24
	SER I: Case 3	1.37	0.59	0.52	272.81	45.91	30.05
Traditional approach: Bridge 2T: Bridge width = 8.0m; Abutment height (H_0) = 8.0m	SER I: Case 1	1.80	1.35	1.09	726.41	27.43	57.06
	SER I: Case 2	1.82	1.11	0.99	631.64	34.70	51.10
	SER I: Case 3	1.89	0.76	0.87	490.14	45.43	44.87
Traditional approach: Bridge 3T: Bridge width = 11.5m;	SER I: Case 1	1.85	1.21	0.82	535.63	45.55	43.52
	SER I: Case 2	1.67	0.97	0.70	438.13	45.80	38.39

Abutment height (H_0) = 6.0m	SER I: Case 3	1.39	0.60	0.51	275.69	46.22	30.24
Traditional approach:	SER I: Case 1	1.80	1.32	1.06	715.81	28.34	56.21
Bridge 4T: Bridge width = 11.5m;	SER I: Case 2	1.83	1.11	0.98	631.72	34.88	51.08
Abutment height (H_0) = 8.0m	SER I: Case 3	1.90	0.76	0.86	491.33	45.52	44.92

[(*)]*Note: Δy and Δz are respectively pile's lateral and vertical displacements while θ_{xx} is a pile rotation around a transverse direction of the bridge.*

Observing lateral displacements and internal forces along the pile length in the proposed abutment were graphically similar to those in a traditional abutment (Figure 8). Large lateral displacements and rotations occurred at the pile head. Similarly, the maximum shear occurred at the pile head, while the maximum bending moments occurred at approximately 2 m below the pile head. So, the ground anchors reduced the extent of lateral displacements and forces in the piles but did not change their general behaviour.

DISCUSSION

The introduction of ground anchors in abutment design can reduce significantly lateral loads involving lateral forces and moments about the bridge transverse axis. Through the design procedure proposed in this paper, at the bottom of the pile caps lateral forces can be reduced an average of 70% (from 59% for Bridge 3R to 80% for Bridge 2R) and moments reduced an average of 87% (from 74% in Bridge 3R and 99% in Bridge 2R). However, vertical forces are slightly increased by an average of 6% due to projection of the allowable load of the ground anchors in the vertical direction. This implementation ensured that the abutment structures satisfy all critical quantities of the design specification. For example, displacements and internal forces in piles are below recommended limits. As such, a horizontal displacement of the pile is only 13.5% of the acceptable horizontal displacement (3.43 mm vs. 25.4 mm), while the maximum angular distortion is 0.5% of the acceptable ones (0.00004 vs. 0.008), in which the maximum vertical displacements is 1.34 mm (Bridge 2R) against 33 m of a span length. Also, the maximum bending moment was no more than 55% of the allowable. Additionally, by comparing the bridge abutment designed by the traditional approach, there is only one row of piles instead of two. For the traditional abutments subjected to 8 m of backfill height, the front row of those piles must be battered against large lateral loads. Integrated ground anchors into the abutment can reduce a number of piles, which also leads to a decrease in the pile cap dimensions and stem wall thickness. As such, the ground anchor abutments reduced the number of piles by 50% and the necessary abutment geometry (involving the pile cap and the stem wall) by approximate 37%. Consequently, this saved 40% and 50% of the material in the stem wall and pile cap volume, respectively (Figure 9).

CONCLUSION

Traditionally, large lateral earth pressures in bridge foundations due to high abutment backfills are accommodated by increasing the number of piles or the pile size. There are two alternatives to reduce this effect: (1) decrease the lateral earth pressure or (2) insert structural components to resist this load. Using this second approach, ground anchors were incorporated into the bridge abutment design. The design minimized the moment rotating around the transverse direction of the bridge, because this usually causes pile lateral response to exceed critical limits. Four examples of the high stem abutments with backfill heights of 6-8 m were investigated for lateral pile response, where a pair of typical bridge cross-sections (8.0m and 11.5 m with a side span length of 33.0 m) were checked. Service Limit I according to the AASHTO specification was used in this investigation. Results from the ground anchor abutments were compared to ones from the traditional approach. The integrated ground anchors reduced lateral forces by an average of 70% and moments by 87% at the pile cap base. All displacements, lateral forces, and bending moments were less than the critical limit values. The maximum bending moment in the pile reached approximately 55% of the allowable bending moment, and axial forces in piles were less than 65% of estimated capacity. The proposed approach reduced the number of piles by 50% and the abutment volume by 37%. However, several assumption and simplifications were made in this case study, and the implementation of the work requires extending various load combinations and project characteristics. Now, extensive analysis is needed by the community to determine full applicability of the proposed approach.

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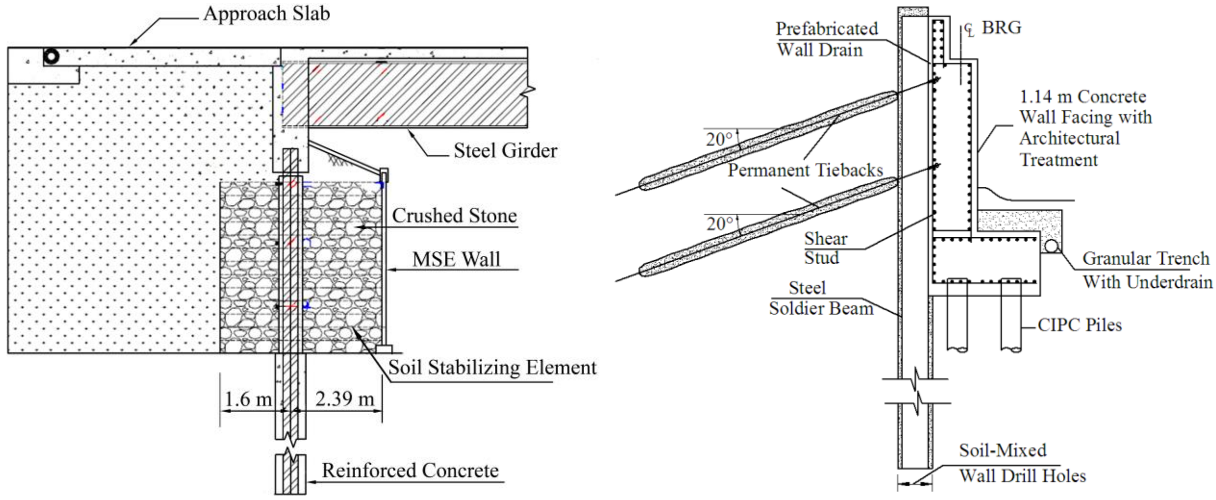
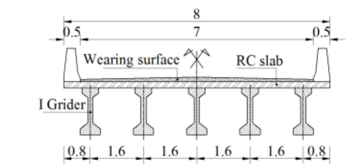


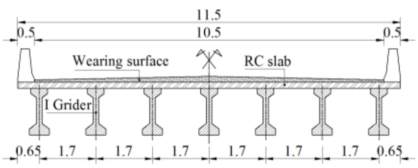
a) The MSE abutment of I-95 Bridge, New Jersey (after Khodair and Hassiotis 2005)

b) Revised abutment (after Anderson 1998)

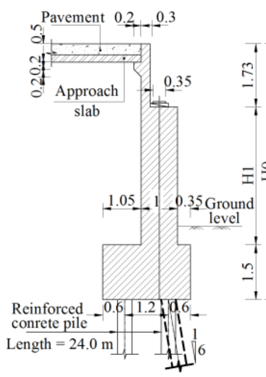
Figure 1. Current approaches to resist large lateral loads applied on bridge abutments



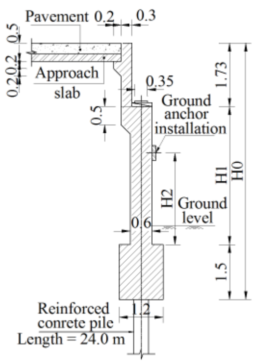
a. Cross section of the bridge with 2 traffic lane



b. Cross section of the bridge with 2 traffic lane



c. Cross section of traditional abutments (*)



d. Cross section of proposed abutments

(*) The front pile is battered in the abutments subjected to 8m in the backfill height

Figure 2. Configurations of bridge cross-sections and proposed abutment

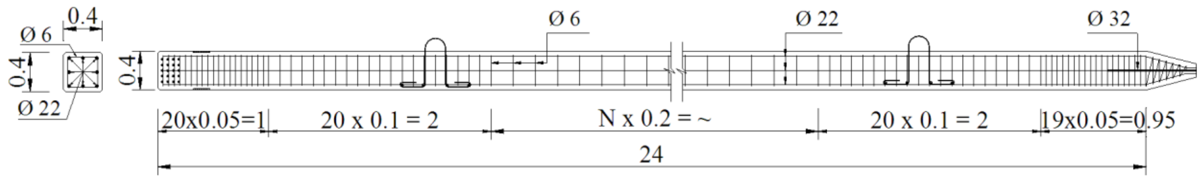
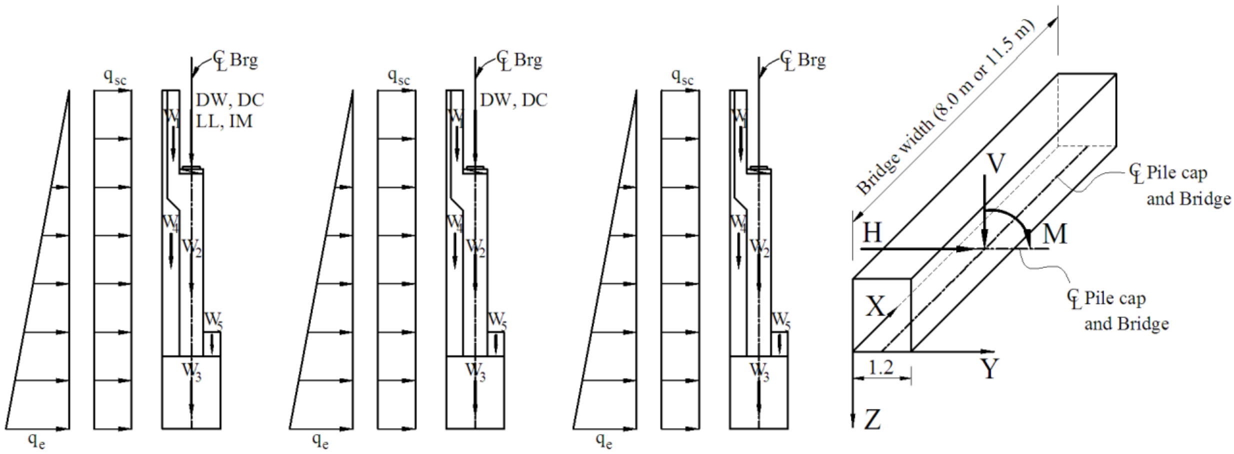


Figure 3. RC pile configuration



a. Case 1 b. Case 2 c. Case 3 d. Application of loads

* Note: DW: dead load of wearing surface; DC: dead load of superstructure; LL: Vehicular live load; IM: vehicular dynamic load allowance; q_{sc}: live load surcharge; q_e: lateral earth pressure; W_1-W_3: dead load of abutment components; W_4 and W_5: dead load of soil blocks.

Figure 4. Abutment designed load and load combinations (*)

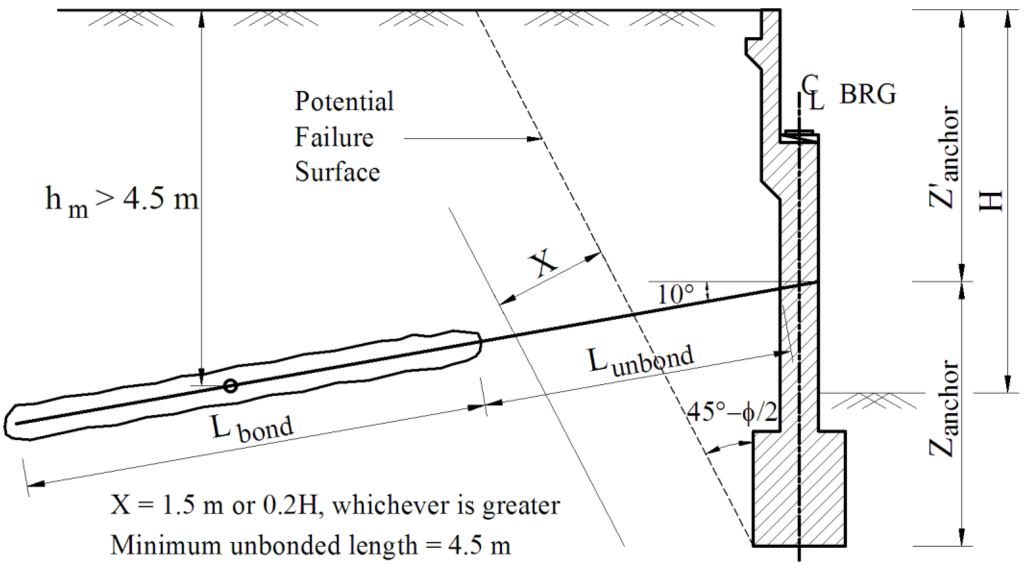
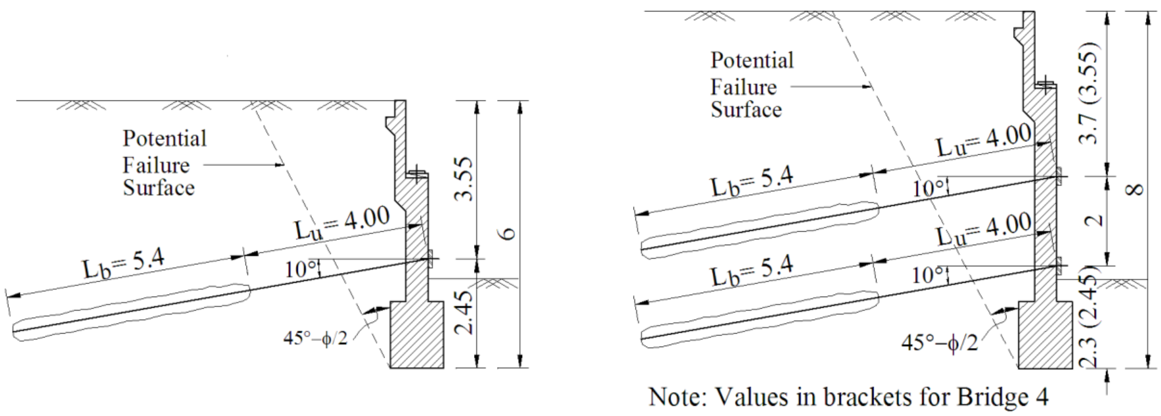


Figure 5. Vertical spacing requirement for ground anchors

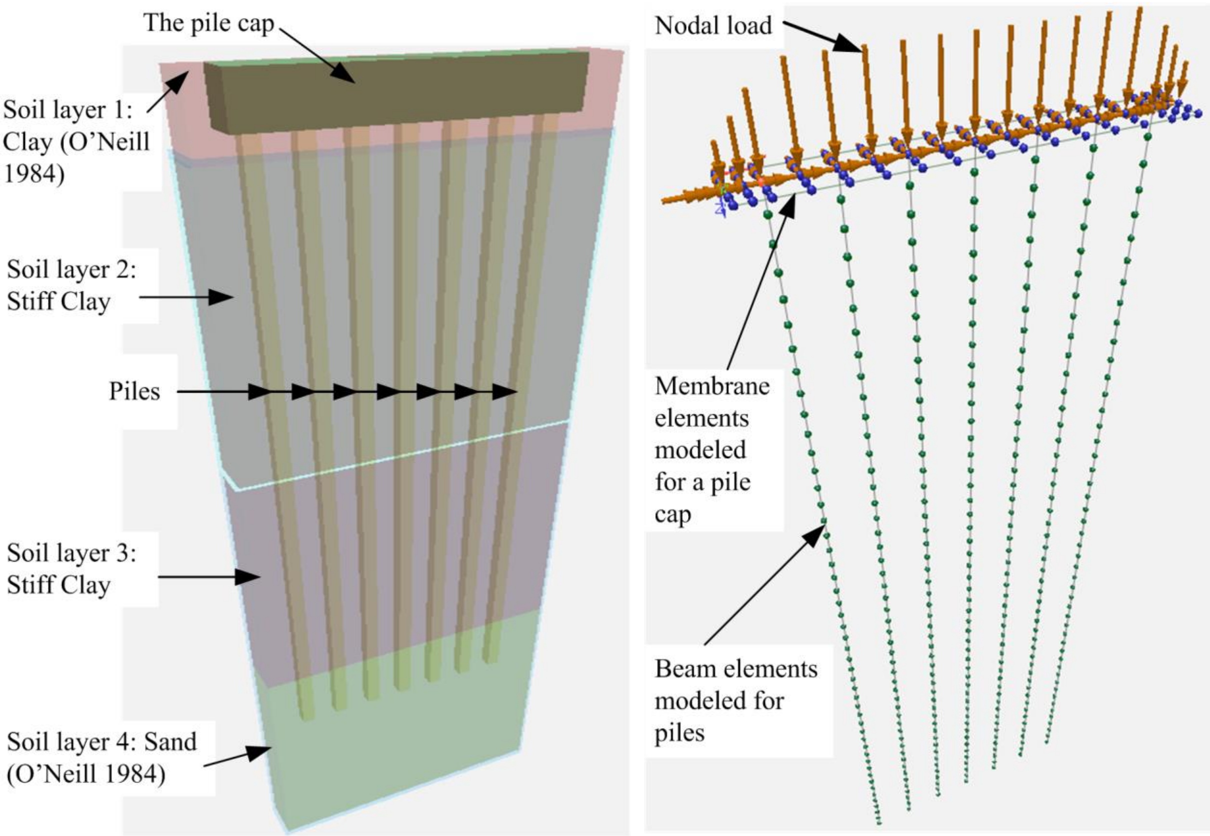


a. Abutments of Bridge 1 and 3 with 6 m of backfill height

b. Abutments of Bridge 2 and 4 with 8 m of backfill height (*)

Note: (*) Values in brackets for Bridge 4

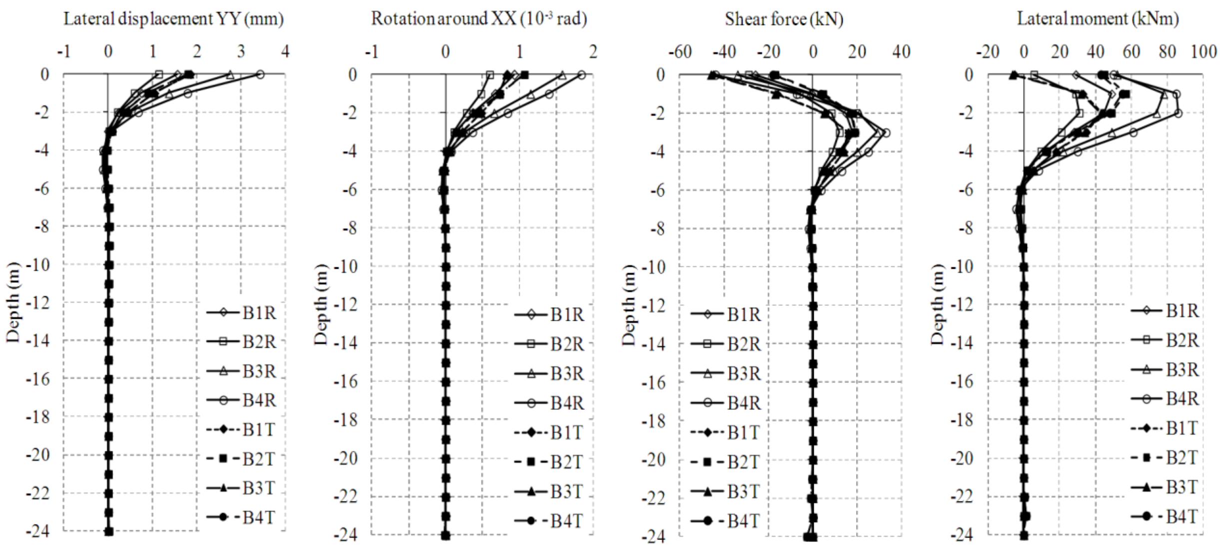
Figure 6. Location of ground anchors in the bridge abutments



a. 3D model of the abutment foundation

b. FEM model of the abutment foundation with applied loads on nodes along the stem wall

Figure 7. Model of the proposed abutment foundation by using pile and cap problem in FB-MultiPier program



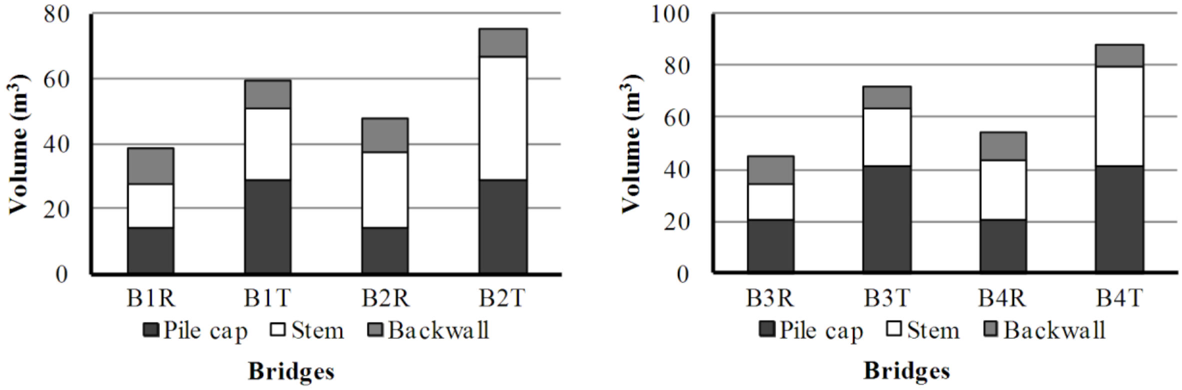
a. Lateral displacement

b. Rotation around XX-axis

c. Shear force

d. Bending moment

Figure 8. Lateral displacements and internal forces in a pile along a pile length



a. Abutments subjected to 6 m of backfill b. Abutments subjected to 8 m of backfill

Figure 9. Compared volume of the proposed and traditional abutments