Engineering Structures 56 (2013) 1177–1191

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Observed integral abutment bridge substructure response

Scott A. Civjan [a,*], Emre Kalayci [b,1], Brooke H. Quinn [b,2], Sergio F. Breña [c,3], Chad A. Allen [d,4]

[a] University of Massachusetts – Amherst, Marston Hall 232, Amherst, MA 01003, United States
[b] University of Massachusetts – Amherst, Marston Hall 224, Amherst, MA 01003, United States
[c] University of Massachusetts – Amherst, Marston Hall 232A, Amherst, MA 01003, United States
[d] Vermont Agency of Transportation, Materials & Research Section, 1 National Life Drive, Montpelier, VT 05633, United States

ARTICLE INFO

Article history:
Received 29 August 2012
Revised 10 June 2013
Accepted 20 June 2013
Available online 27 July 2013

Keywords:
Bridge
Integral abutment
Instrumentation
Substructure
Soil
Pile

ABSTRACT

Two integral abutment bridges in Vermont, USA were instrumented and monitored to report behavior under seasonal thermal load. This paper describes substructure response from 30 months of field data. The bridges are single span steel girder bridges of approximately 40 m on pile foundations. One bridge is straight while the other has a 15° skew. Variations in substructure displacements, backfill pressures and pile moments are reported under hot, cold and moderate ambient temperatures. Abutment and pile deformation plots highlight maximum displacements at the top of piles that are often only 1/3 to 1/2 of the values at the top of the abutment. Maximum pile moments correspond to concentrated curvature at the pile–abutment interface which did not correspond to peak temperatures. Substructure deformation response was predominantly elastic under bridge contraction, but highly non-linear under bridge expansion and varied from year to year. No indication of soil ratcheting was observed in the backfill materials and design for full passive pressure appears to be overly conservative for these single span structures. No indications of pile yielding were observed in the Grade 345 steel piles. Backfill pressures were consistent across the abutment in the straight bridge, but highly variable in the 15° skew bridge.

1. Introduction

Integral abutment bridge (IAB) designs are often the choice for short to moderate span structures in both the US and Europe. However, design provisions vary widely and few design codes specifically address IAB requirements [1–5]. For instance, foundations of IABs in the UK often consist of spread footings or deep abutments embedded in soil, in the rest of Europe a range of pile types are used, and in the US a single line of H-piles are typically used to support abutments [3,5,6]. Different transportation agencies in the US have distinct criteria related to foundation restraint and therefore have contrasting recommendations of pile axis orientation and construction details near the pile top, such as recommendations to auger the top soil layers prior to pile driving and provision of steel tubing and loose infill surrounding the top of piles.

In light of the wide variation in design concepts and assumptions, it is not surprising that there are many recommended methods to account for the resulting soil–structure interaction in an IAB. Unfortunately, design concepts do not always correspond to realized bridge movements and deformations and often lead to conservatism in design. In the US the traditional separation of superstructure and substructure design groups often exacerbates discontinuity of design concepts. An example would be a substructure where the abutment design is based on a maximum expected soil pressure and the piles are independently designed based on axial load and expected maximum displacements at the top of the abutment due to superstructure thermal expansion and contraction. Pile top boundary conditions are often assumed as pinned or fixed and calibrated to use an effective pile length which differs from the actual value in an attempt to correct for the actual restraint provided by the superstructure. Full finite element models that account for the entire structure and soil–structure interaction can overcome this issue, but are rarely used in US design unless the IAB has a large skew angle, curvature, or other unique features.

An accurate IAB design requires modeling the soil–structure interaction at piles and abutments correctly. However, the behavior is complicated by cyclic soil response and variable soil properties which are not well defined for IAB design. This paper provides substructure field data from two IAB's constructed in Vermont and monitored since late 2009. The data highlight time dependent

* Corresponding author. Tel.: +1 (413) 545 2521; fax: +1 (413) 545 2840.
E-mail addresses: civjan@ecs.umass.edu (S.A. Civjan), ekalayci@thorntontomasetti.com (E. Kalayci), bhquinn@student.umass.edu (B.H. Quinn), brena@ecs.umass.edu (S.F. Breña), chad.allen@state.vt.us (C.A. Allen).
1 Permanent address: Thornton Tomasetti, 51 Madison Ave, New York, NY 10010, United States. Tel.: +1 (917) 661 7800; fax: +1 (917) 661 7801.
2 Tel.: +1 (774) 454 6638; fax: +1 (413) 545 2840.
3 Tel.: +1 (413) 545 0349; fax: +1 (413) 545 2840.
4 Tel.: +1 (802) 828 6924; fax: +1 (802) 828 2792.

0141-0296/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2013.06.029

characteristics of soil–structure interaction in both seasonal and daily response which can influence design decisions.

2. Soil structure interaction background

The design of the substructure components of IABs is generally governed by long term (seasonal) thermal load fluctuations and the resulting frame action of the structure. Soil behavior under thermal load includes hysteretic response under cyclic load which is not clearly defined for mixed soil types typical of backfill materials. For example, differences in load and unload response and soil ratcheting (increasing soil pressure under cycling at a constant wall displacement) should be accounted for. The non-linear response of soils is further complicated by dependencies on load history and load rate.

Experimental testing has been used to quantify expected IAB abutment backfill pressures. In general, lateral backfill pressure is calculated as the product of effective stress and earth pressure coefficient K [7], which for lateral translation of an abutment (Fig. 1a) would result in linearly varying backfill pressure with depth, but is also applicable to abutment rotation (Fig. 1b). However, Arsoy [8] derived analytical results for backfill pressures behind IAB abutments and points out the importance of deformations due to wall translation versus wall rotation on abutment pressures. In typical US designs the abutment is supported by piles so the substructure response differs from experimental studies as shown in Fig. 1c, where the amount of translational/rotational interaction depends on the relative rotational stiffness of the superstructure and substructure components. Dicleli [9] analyzed backfill pressures on a multiple span IAB and noted triangular backfill pressure distribution for abutments shorter than 3 m (10 ft) and parabolic distribution when abutment depth exceeded 5 m (16 ft), likely indicating that the shallow abutments exhibited less rotational deformation, but recommended that a triangular stress distribution was appropriate for design. In laboratory scale tests Fang et al. [10] showed a linear pressure distribution with depth for translational abutment movements and non-linear for rotational. Fang et al. [11] showed a similar linear distribution for translational movements, but less than expected K_p values for dense sands. Full scale abutment sections of 2.44 m (8 ft) depth with a variety of configurations and backfill materials have been tested [12,13]. In these tests abutments supported by footings resulted in abutment rotation with peak pressure at 0.6–0.9 m (2–3 ft) from the top of the abutment, linearly decreasing to zero at base. Abutments supported by piles (HP8X36 Gr. 250 MPa (36 ksi) in weak axis bending) resulted in approximately constant pressure in the top half of the abutment and higher pressure near the bottom of the abutment than obtained in shallow foundation tests. The authors noted that "designing for full passive pressure leads to an over-conservative abutment design." These full scale tests showed no significant differences upon re-load cycles (three total cycles for footings, two for pile supported foundations), though backfill pressures decreased slightly. Specimen re-load stiffness was similar, though hysteresis was often noted in unloading steps. Pile yielding occurred in all deep foundation tests at abutment deflections of approximately 25 mm (1 in.).

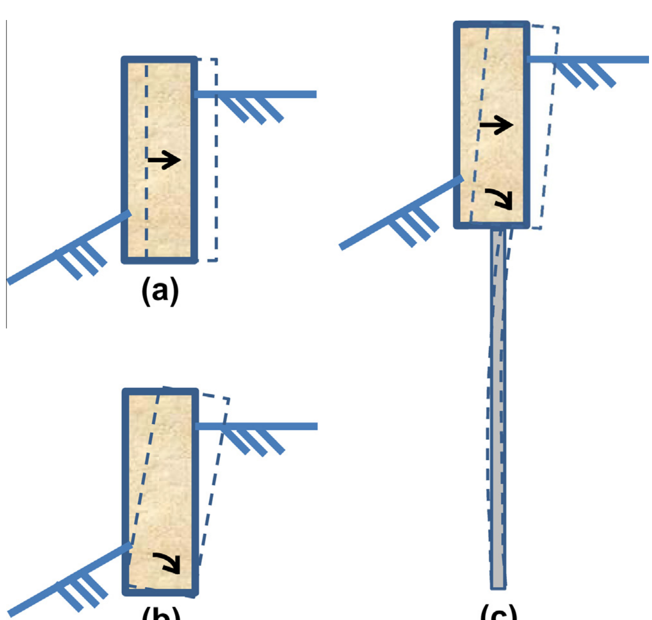

Fig. 1. Abutment displacement modes: (a) translational, (b) rotational and (c) combined mode.

Cyclic response of backfill has been addressed through laboratory research in the UK [6,14–16] and Australia [17]. These studies evaluated stiff overconsolidated clay and fine quartz sand and reported soil ratcheting of backfill pressures under load cycling in sands that were not observed in the clay specimens. These studies modeled abutments in which the entire abutment deformation was rotational. These studies expanded on the soil behavior reported by England et al. [18,19] who specifically noted the potentially serious concern of soil ratcheting for IAB's. These concerns have led some DOT's to design for full passive pressure (i.e. VTrans [20]), while others do not (i.e. MassDOT [21]). In the UK an empirical equation is used to quantify backfill pressures, which are lower than the full passive pressure (BA 42 [22]), though Bloodworth et al. [6] point out the conservatism in both of these approaches when one considers the finite number of extreme seasonal cycles based on a 120 year design life. While Lutenegger et al. [12] did not observe increases in soil pressure upon re-loading, field test data results are mixed. Increases in backfill pressures during first-year data were reported by Breña et al. [23] and Hasiotis and Xiong [24], while Franco [25] did not report any pressure increase. Kim and Laman [26] reported data on 4 bridges; some indicated increases in backfill pressures while others did not. Review of the existing field data in these studies shows a tendency for soil ratcheting primarily in multiple span structures while no increase in backfill pressures have been reported for the shorter single span IABs.

P–y curves implemented in springs distributed along the pile length based on API [27] are often used to simulate soil–structure interaction in IAB pile design. *P–y* curves are a form of non-linear Winkler springs assumed to be adequate to capture complicated soil–structure interaction. Because these springs were developed for monotonic loading they are typically assumed to load and unload along the same path, which neglects the hysteretic response of soil. Cyclically loaded piles with IAB abutment constraints that excluded soil–structure interaction were tested by Arsoy et al. [28,29], and indicated that flexible piles were advantageous in preventing abutment damage under cyclic load. Burdette et al. [30,31] constructed a full scale test which accounted for relative superstructure rotational restraint on the abutment, with piles oriented about their strong axis and driven into stiff clay or compacted fill materials. The study concluded that while moments at the top of piles may lead to abutment cracking at the connection, this did not compromise the function even at extremely large displacements and pile moments. Further testing by Burdette et al. [30] noted that "Generally, but not necessarily, the load–deflection relationship 'softened' with increasing tests", which was "more pronounced if tests were performed on consecutive days rather than having a waiting period for the soil to 'reconstitute'." (p. 27) Pile lateral strength in clay soil did not degrade with cycled load after