An Investigation of Sources of Asymmetric Thermal Expansion Behavior in Semi-Integral Bridges

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ABSTRACT

The typically poor long-term performance of deck expansion joints and the high cost of maintenance of these bridge components have led to an increased utilization of jointless bridge systems such as integral and semi-integral bridges. However, the elimination of expansion joints leads to some adverse secondary effects due to the cyclic interaction of the bridge with the abutments. This soil-structure interaction can cause gradual settlement of the backfill, backfill earth pressure increase, and lateral loading of the foundations. In addition to these issues, it has been observed that integral and semi-integral bridges do not necessarily experience the symmetrical thermal expansion and contraction that is typically assumed in design, even if the structure appears symmetrical in design. As a result, jointless bridges may expand more toward one abutment than the other in response to daily and seasonal changes in temperature. In this paper, some of the potential causes of the asymmetrical expansion of integral and semi-integral bridges are identified and discussed through analysis of some of the past field monitoring data as well as the available data published in literature. The identified causes include minor differences in foundation soil stiffness, depth of the foundation, environmental forces, and more.

INTRODUCTION

Semi-integral and integral bridge construction are becoming increasingly common in the USA as well as the rest of the world. The main characteristic of these bridges is the elimination of expansion joints at the ends of the deck and in between spans. Integral bridges are continuous single or multi-span bridges where the superstructure is constructed integrally with the sub-structure. In contrast, abutment wall and abutment caps are not integrally connected in semi-integral bridges, allowing the superstructure to move independently from the substructure.

The increasing popularity of these structures is due to the number of issues associated with deck expansion joints. Deck expansion joints are typically used to alleviate some of the stresses in the structure due to issues such as shrinkage, creep, thermal expansion/contraction and differential settlement of piers and abutments (Burke, 2009). As noted in Purvis and Burger (1983), there are several problems associated with deck expansion joints. These problems include the high rate of wear and tear, exposing the structure to harmful chemicals, and the relatively high cost of initial construction and maintenance. Therefore, many transportation agencies across the world have opted for other alternatives such as semi-integral and integral bridges. This has been justified by the fact that the cost of deck expansion joints significantly outweighs the benefits provided from the alleviation of secondary stresses for single and multi-span bridges of moderate length (Burke, 2009).

Expectedly, elimination of expansion joints leads to the displacement of abutment walls into and away from backfill. This cyclic loading which occurs daily with changes in temperature, can lead to ratcheting, settlement and earth pressure increase within the backfill (Mofarraj and Zornberg, 2022; Huntly and Valsangkar, 2013). This complex soil-structure interaction has been studied by many researchers using numerical, experimental, and field investigation methods. While a trove of valuable information has been learned through these efforts, the behavior of semi-integral and integral bridges is still not fully understood.

With the increased availability and affordability of instrumentation equipment, many transportation agencies have begun utilizing long-term monitoring programs to better understand the performance and behavior of sensitive infrastructure such as roadways and bridges. As a result, we are witnessing an increasing number of publications detailing the information found through various studies about the performance of semi-integral and integral bridge structures. A summary of the relevant publications which include long term field instrumentation data from semi-integral and integral bridges is presented in Table 1.

As summarized in Table 1, the field-based studies performed on integral and semi-integral bridges are quite variable in terms of instrumentation and monitoring efforts as well as the notable findings. In terms of notable conclusions, one can find documented cases of earth pressure increasing and reaching passive earth pressures and cases where the earth pressure has dropped to levels below the estimated active earth pressure. Similarly, conflicting observations are made regarding the displacement and rotation of the bridge abutments in response to daily and seasonal changes in temperature. One relatively common observation in these studies is the asymmetrical longitudinal thermal expansion of the monitored bridges which has been documented even for bridges that appear symmetrical in design. However, the sources of this seemingly unexpected behavior often have not been investigated or described in the published literature.

As bridges are considered to be in a state of static equilibrium during periods of thermal expansion and thermal contraction, it is possible to apply the principles of force equilibrium to investigate the potential underlying causes of asymmetrical thermal expansion/contraction integral and semi-integral bridges. In this paper, a simple stiffness model for the soil-structure interaction in integral and semi-integral bridges is described to provide a framework for the discussion of the field observations. Next, some of the available literature is assessed under this framework to identify the potential causes of the seemingly unexpected asymmetrical thermal expansion of integral and semi-integral bridges. It is worth noting that the goal of this paper is to provide a generally qualitative discussion regarding the potential causes for the observed asymmetrical behavior and to provide general guidelines on how to account for such behavior at the design stage. The authors intentionally refrain from using numerical descriptors in the course of discussion to not draw focus from the big picture elements. However, the audience is encouraged to review any of the referenced materials to gain a better understanding of the magnitude of the forces and displacements involved as well as other issues affecting jointless bridge behavior.

ABUTMENT SOIL-STRUCTURE INTERACTION MODEL DESCRIPTION

As described previously, the thermal expansion and contraction of integral and semi-integral bridges imposes displacements on the abutment walls and foundation elements. As these elements are in contact with soil, their displacements also induce additional stresses and strains within the abutment backfill and foundation soils. This is a relatively complex soil-structure interaction problem due to the complexity of determining the cyclic strain-stress behavior of soils and is beyond the scope of this paper. Instead, a simplified and qualitative model of the soil-structure interaction (SSI) affecting the abutments will be used to discuss the factors affecting the behavior of semi-integral bridges. The conceptual SSI model (Figure 1) shows the typical elements affecting SSI in a semi-integral bridge. This model can also be used for evaluating the behavior of integral bridges, with the exception that bearing elements can be ignored.

Table 1. Summary of studies on long-term field performance of integral and semi-integral bridges

Reference	Location	Bridge type	Notable Conclusions
Jorgenson (1973)	N Dakota, US	137 m long, 6 spans, concrete box girders, integral	asymmetric abutment movements with larger movements observed in the south abutment
Hoppe et al. (1996)	Virginia, US	98 m long, semi-integral, two span, steel girder, 5 deg skew	passive pressures, large settlement of backfill, large daily variation in girder stresses
Lawver et al. (2000)	Minnesota, US	66 m long, integral, prestressed concrete girders, 3 spans, H piles	abutment motion was mainly translational abutment expansion was effectively unrestrained the effect of environmental loads found to be larger than live load in some cases
Steinberg et al. (2004)	Ohio, US	26 & 96 m long, semi-integral, steel girders, 65 & 25 deg skew	wing wall earth pressure change, asymmetric wing wall pressures and abutment disp.
Abendroth et al. (2007)	Iowa, US	34 m long, single span, precast girder, skew, precast piles, integral	asymmetric abutment disp., in-plane deck rotation
Abendroth et al. (2005)	Iowa, US	61 & 96 m long, integral, skewed (30 & 15 deg), 3 spans, precast girder, steel piles	Abutment motion was asymmetrical data indicates that the skewed abutment was subject to flexural bending in the horizontal plane
Hoppe (2005)	Virginia, US	100 m long, semi-integral, 3 spans, steel plate girders	abutment wall EPS reduced earth pressure, backfill settlement, asymmetrical abutment displacement
Ooi et al. (2010)	Hawaii, US	24 m long, single span, integral, drilled shaft, precast girders	shrinkage and creep dominated compared to thermal strains, asymmetric abutment disp., backfill pressures below active pressure,

			asymmetric bridge response to flooding
Huffaker (2013)	Utah, US	97 m long, 3 span, skewed, pre-stressed girders, driven steel piles, integral	Asymmetric displacement records for the skewed abutments
Huntly and Valsangkar (2013)	New Brunswick, Canada	76 m long, 2 span, piles, integral	asymmetric abutment wall pressure, asymmetric abutment disp., earth pressure increase in one abutment, translational abutment wall movement
Mofarraj (2022)	Texas, US	90 m long, single span, semi-integral, prestressed concrete girders, drilled shafts	Earth Pressure ratcheting, backfill settlement, asymmetric thermal expansion, cyclic lateral loading of the foundation

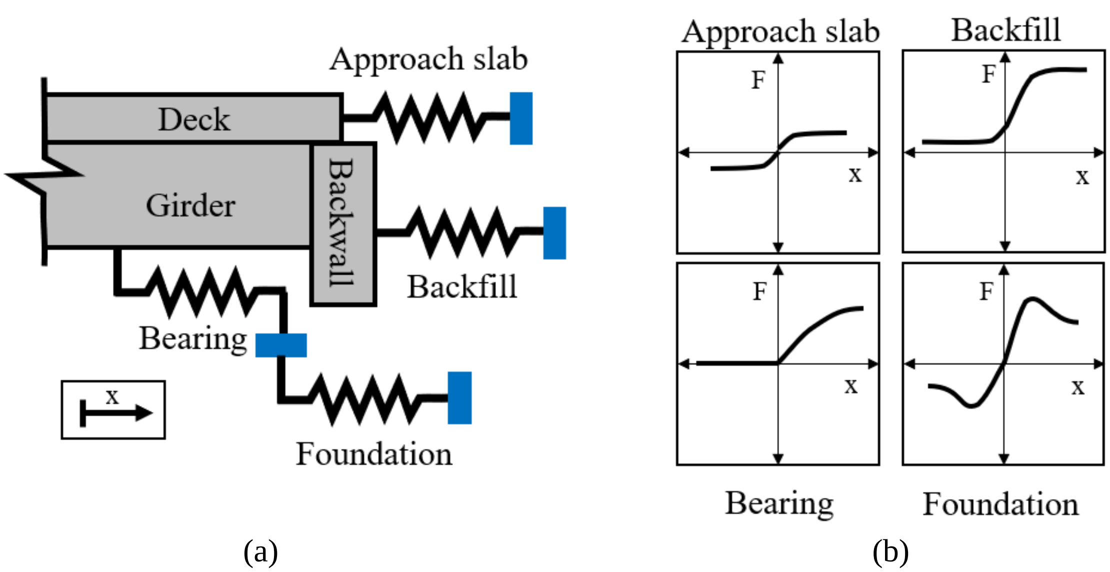

Figure 1. Semi-integral bridge abutment resistance model: (a) Soil-structure interaction model diagram showing elements that resist thermal expansion/contraction of a semi-integral bridge; and (b) hypothetical force-displacement diagram of resisting elements (positive 'x' signifies abutment wall displacement toward backfill).

The conceptual SSI model in Figure 1 shows that with the thermal expansion of the bridge, horizontal reaction forces in the approach slabs, backfill, foundation, and bearings would develop to resist the superstructure expansion. On the other hand, during thermal contraction of the bridge, some of these forces are expected to change direction (e.g., lateral foundation resistance) while some others are only expected to reduce in magnitude but not change direction (e.g., backfill reactions). Figure 1 (b) shows the approximate shape of the force-displacement relationship for each of these elements. As can be seen, the relative contribution of each element to SSI changes based on the magnitude of displacement and the direction of displacement in a single cycle and therefore can be quite non-linear as sketched in Figure 1 (b). Moreover, the stiffness of some components can increase with cycling (e.g. backfill ratcheting), while the stiffness of some components can decrease with cycling (e.g. cyclic degradation of foundation stiffness in clay deposits).

The model described above provides a visual and qualitative framework for understanding the forces that are exerted on each end of the bridge in response to the thermal expansion/contraction of integral and semi-integral bridges. Considering the static equilibrium during thermal expansion and contraction of bridges, there must be a balance between the total horizontal forces applied to each side of the bridge at any point in time. For example, it is expected that the sum of backfill and foundation resistances be nearly equal between the two abutments in a single-span integral bridge without approach slabs. Therefore, if such bridge experiences asymmetric thermal expansion, it would indicate that one abutment is stiffer and that is why smaller displacements have occurred to mobilize the same magnitude of resisting forces as the other abutment.

In the next section, the information reported in some of the case studies summarized in Table 1 are analyzed to indicate some of the common causes of asymmetric thermal expansion and provide design considerations for future projects.

DISCUSSION

In this section, the descriptions and analysis of the semi-integral and integral bridges used for SSI discussion based on the qualitative model explained in the previous section are presented.

The first structure considered is the China Creek Semi-Integral Bridge in North Texas. This is a 27 meters long single span bridge and is supported by four 11 meters deep drilled shafts at each abutment. China Creek Bridge is one of the first semi-integral bridges built in the state of Texas and has been instrumented with a large array of sensors, including displacement transducers, strain gauges, earth pressure cells and shape arrays. A detailed description of this bridge, including the collected instrumentation data is available in Mofarraj (2022) and Mofarraj and Zornberg (2023).

As described in Mofarraj (2022), this bridge exhibited highly asymmetrical response, with the point of fixity of the bridge (neutral thermal expansion point of the bridge deck) changing seasonally and going from a position closer to the east abutment during the winter months to a position closer to the west abutment in the summer months. As a result, larger movements were experienced on the west abutment during the winter months, whereas larger movements were experienced by the east abutment over the summer months. Considering the SSI model presented earlier, it can be seen that during the winter months (bridge contraction), the backfill pressures are at the minimum and do not change significantly with more thermal contraction once the active state is mobilized within the backfill soil mass. Subsequently, at this stage a majority of the abutment reactions are expected to come from the foundations. With the drilled shafts being structurally similar, it can be inferred that slightly softer foundation soils (i.e., soil deposits below the backfill) exist over the west side compared to the east side which has led to asymmetric thermal movements of the bridge abutments during the cold months. As a result, it was also observed that each year the center point of the bridge moved slightly eastward compared to the preceding year.

During the summer months, it was observed that the bridge primarily expands towards the east side. Considering the elements involved in the SSI model (Figure 1), we can infer that during bridge expansion, backfill earth pressures can increase significantly, ultimately reaching lateral earth pressures as high as the passive earth pressure. The asymmetric behavior observed during the summer months indicate that the west abutment backfill has been much stiffer than the east abutment backfill, causing the bridge to primarily expand eastwards. Therefore, in the case of this semi-integral bridge, the asymmetric thermal expansion behavior is attributed to the difference in foundation stiffness as well as the backfill stiffnesses, causing a seasonal shift in behavior.

The second structure of interest is an integral bridge in Iowa, USA which is described in Abendroth et al. (2007). This integral bridge also exhibited clear signs of asymmetrical thermal expansion behavior. While the authors did not go into the details of potential causes for this behavior in this research, it is likely that this behavior is caused by the difference in the stiffness of the foundation soils. As described by the authors, the west abutment soils had a slightly higher blow count which is likely to have contributed to the eastward thermal expansion of the monitored bridge.

Another structure of interest is the integral bridge studied by Ooi et al. (2010) in Hawaii, USA. This structure initially exhibited relatively symmetrical thermal expansion behavior with relatively small thermal expansions overall, due to the site’s small temperature variations. However, after one year of being in service, the authors started to observe asymmetrical behavior. According to the authors, a likely cause of this behavior is the change in hydrodynamic forces applied to the bridge from the meandering stream of water passing underneath the bridge. Therefore, in this case the asymmetrical behavior has likely been caused by a change in external conditions after being in service for some time, unlike the other bridges discussed before.

The last structure of interest is the integral bridge monitored by Huntly and Valsangkar (2013) in New Brunswick, Canada. In this study, the authors observed that the abutment wall movements and the abutment earth pressures were asymmetrical between the two sides. During the three-year monitoring period, the west abutment wall continued to displace further towards the abutment backfill during the periods of thermal expansion. In addition, the authors observed a continuous increase in the degree of rotation of the west abutment wall during the monitoring period. According to the authors, the west abutment wall is supported on piles that are 2 meters shorter than the piles on the east abutment. While the reasons behind this choice was not explained in this report, it can be speculated that the difference in the length of the piles and the difference between the foundation soils has likely resulted in a difference in the lateral stiffness of the foundation elements between the two sides, resulting in the asymmetric thermal expansion of the bridge. In addition, the accumulation of rotation in the west abutment wall indicates that there is an accumulation of plastic strains in the foundation soil, due to cyclic degradation of the foundation soils.

Overall, it can be seen that asymmetrical thermal expansion behavior can happen due to small and sometimes unnoticeable changes in the conditions of the structure which leads to a noticeable change in the short-term and long-term behavior and performance of jointless bridges. Moreover, some of the identified causes of this behavior such as the difference in foundation soil stiffnesses are unavoidable. Overall, it would be possible to recognize some of these conditions during the planning and design stage for integral and semi-integral bridges and potentially predict if asymmetrical behavior is likely to occur and design the structural components to withstand such behavior. However, considering the number of cases where such behavior has been observed and the complexity of this SSI analysis, it may be more feasible for the bridge design engineers to analyze the structure’s performance under various cases of asymmetrical thermal expansion/contraction and ensure the stresses in the foundation, abutment wall and other parts of the bridge are within the tolerable limits if the bridge expands asymmetrically.

A practical solution for a more resilient jointless bridge design would be to recognize that more than 50% of the total expected thermal movements can be experienced by each abutment. While currently sufficient data does not exist within the available literature to make a general rule, abutments have been observed to experience annual displacement cycles as large as 70% of the total estimated thermal expansion of the bridge (Mofarraj, 2022).

It is a possibility that overestimating the expected abutment displacements can potentially lead to expensive and unfeasible designs in some cases (especially with long multi-span bridges). In such cases, it may be justified to perform a more sophisticated analysis that considers the interaction between the components identified in the conceptual SSI model shown in Figure 1. This approach would require the engineers to estimate the force-displacement behavior for each of the identified components in Figure 1 through computer modeling and laboratory testing. These efforts may involve performing pushover analysis of the foundation elements and laboratory testing of the backfill and foundation soils (e.g., triaxial testing).

CONCLUSIONS

Integral and semi-integral bridges are great alternatives to conventional bridges because of the overall positive performance and the reduced maintenance needs compared to the conventional bridges. Over the past decades, several integral and semi-integral bridges have been instrumented and studied in detail by various researchers across the globe. A common but lesser discussed observation regarding the behavior of jointless bridges is the seemingly unexpected asymmetric thermal expansion behavior of these bridges, even in cases where the structure looks symmetrical in design. In this paper, some of the case histories on bridges that exhibited asymmetrical thermal expansion were evaluated to identify some of the potential causes for this type of behavior. Overall, it can be concluded that:

- Due to the elimination of deck expansion joints, integral and semi-integral bridges interact with the foundations, abutment backfills, approach slabs and bearings during thermal expansion and contraction. These elements exhibit very different behaviors compared to one another in terms of magnitude and direction and their response to the thermal expansion/contraction of the bridge can be highly non-linear.
- The forces acting on the abutments of the integral and semi-integral bridges can be significantly different depending on the season. For example, the majority of the SSI forces during bridge contraction (cold months) are from the soil-foundation interaction, whereas backfill lateral earth pressures can become dominant during thermal expansion (summer months), and change the governing behavior and the position of the point of fixity.
- Due to the non-linearity of the SSI with various elements in integral and semi-integral bridges, the point of fixity of jointless bridges can change seasonally, resulting in a change in the direction of the thermal movements depending on the seasons.
- The difference in the length of the foundation elements and/or the stiffness of the foundation soils is identified as one of the main contributors to the asymmetrical thermal expansion of integral and semi-integral bridges.
- Another identified reason for asymmetrical behavior of integral bridges is a change in loads, such as the change in hydrodynamic forces applied to the structure from the meandering stream underneath the bridge.

- Given the relatively high number of observed cases with asymmetrical thermal expansion/contraction, it is recommended to design jointless bridges considering the possible variability between the elements resisting the thermal expansion of jointless bridges. The variability can be due to many factors such as difference in backfill placement and compaction efforts, difference between the lateral stiffness of the foundation elements.
- A practical but simple approach to accounting for asymmetrical response of the jointless bridges is to overestimate the expected displacement of abutment walls. While enough data for making a general recommendation does not exist, in some cases, abutment wall displacement magnitudes as high as 70% of the total bridge thermal expansion have been observed. However, a more sophisticated approach would involve characterization of the behavior of the elements resisting the expansion and contraction of the bridge and may involve efforts such as pushover analysis of the foundation elements and laboratory testing of the foundation and backfill soils.

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