Field Monitoring of Soil-Structure Interaction in Semi-Integral Bridges

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ABSTRACT

Despite the rise in popularity of jointless bridges, their behavior is still not well understood. By eliminating expansion joints at the ends of the deck, the abutment backfill is affected by daily loading cycles due to thermally induced strains, leading to earth pressure ratcheting and backfill settlement. This study presents three years of monitoring data of a semi-integral bridge in Texas. This bridge was instrumented using a combination of earth pressure cells, laser distance meters, and temperature sensors. In this study, the effect of temperature variations on the evolution of earth pressures acting on abutment walls is evaluated. Results indicate that it is generally during the cold months that comparatively high increases in earth pressures develop, which do not necessarily lead to a symmetric response between the two abutments. Additionally, stress ratcheting was found to lead to excessive deformations in the wingwalls and loss of aggregates for the conditions that corresponded to the abutments under investigation.

INTRODUCTION

Conventionally, many highway bridges include expansion joints at the ends of the deck and/or in between adjacent spans to accommodate longitudinal deformations of the bridge due to changes in temperature, shrinkage and creep. While deck expansion joints in conventional bridges provide some advantages, such as minimizing the interaction between the deck and abutment, they have also been reported to result in important disadvantages (Arsoy et al. 1999). Specifically, and in addition to the upfront material and construction costs associated with adopting expansion joints in the design, they are also highly susceptible to deterioration and damage from factors, such as traffic loads, deicing chemicals and clogging by debris. As a result, several transportation agencies have attempted to eliminate the use of expansion joints, leading to the adoption of semi-integral and integral bridges as alternatives. In semi-integral bridges, the deck, girders, and abutment walls are integrated during construction. In these bridges, the superstructure is typically supported on elastomeric bearings and a deep foundation system. On the other hand, in integral bridges, the deck bearings are also eliminated as the abutment cap is integrally connected to the deck, girders and abutment walls.

An important issue arising from eliminating expansion joints at the ends of semi-integral bridge decks is the occurrence of cyclical lateral loading of the bridge abutments due to daily and seasonal changes in temperature. The magnitude of the displacements is understandably a function of bridge length as well as the weather conditions at the bridge location, being more severe for comparatively long bridges located in areas with a comparatively wide range of daily and seasonal temperatures. As this type of loading can lead to stress ratcheting (Gradual accumulation of plastic strains due to cyclic loading) and settlement of backfill soil (England et al. 2000), researchers have attempted to study this problem using in-situ, numerical and laboratory investigation methods.

For example, Clayton et al. (2006) conducted a series of cyclic triaxial tests and found that stress ratcheting is affected by the number of cycles, cycle strain, soil relative density, and shape of the particles. They reported that even in densely packed sand particles, cyclic strains lead to fabric changes (e.g. rotation and interlocking of particles) and dilative behavior, leading to stress ratcheting. Moreover, they observed changes in the internal friction angle of the material due to changes in density and fabric, leading to increasing passive earth pressures.

Interestingly, field data recorded from jointless bridges has not always indicated the occurrence of stress ratcheting in jointless bridges. For example, Civjan et al. (2013) noted a slight decline in earth pressures over 30 months of monitoring an integral bridge, with pressures reaching only 20% to 40% of the predicted passive pressure. In contrast, Huntly and Valsangkar (2013) recorded clear signs of stress ratcheting in an integral bridge. It should be noted that wingwalls have also been reported to show earth pressure increases. For example, Steinberg et al. (2004) monitored forces in the wingwalls of two semi-integral bridges in which they identified a non-linear relationship between bridge movements and forces induced in the wingwalls.

Several researchers (Xu et al. 2007; Jia and Kong 2015; Liu et al. 2021) have developed and/or used numerical models to model stress ratcheting due to cyclic loading of granular materials and studied the effect of different factors, such as cycle magnitudes, frequency, and relative density on the development of earth pressures.

While the use of jointless bridge technology has been gaining popularity across the world, according to the data collected by Burke (2009), southern US states have been less inclined to adopt such technologies. Specifically, semi-integral bridges are not considered standard practice in Texas. Although several jointless highway bridges have been constructed successfully in the State of Texas, the behavior of these structures under local conditions (climate, standard construction practices, abutment earth pressures, etc.) were deemed to require further understanding. To this end, a relatively short semi-integral bridge was constructed on a rural road in Anderson County, TX in 2017. This structure was instrumented by sensors to measure abutment earth pressures, deformations, deck temperature, and climate parameters. The main purpose of this research is to assess the performance and behavior of the structure, and generate recommendations for the design and construction of such structures, especially in locations with conditions similar to the current bridge site.

In this paper, after describing the structure, data collected from the sensors as well as relevant in-situ observations are presented. The data collected thus far is used to assess the performance of the structure, identify strengths and weaknesses of this design and provide recommendations for future jointless bridge construction projects.

PROJECT DESCRIPTION

The semi-integral bridge evaluated in this paper was built on County Rd 2133, overpassing Mack Creek outside of Palestine, TX, to replace an old one-lane bridge. This bridge is 21 m long and has two traffic lanes. The thickness of the cast-in-place deck ranges from 0.13 m to 0.2 m, with a width of 8 m and is supported by six precast pre-stressed concrete box girders. The abutment wall in this bridge is 0.91 m deep and 0.3 m thick. Due to the topography of the area, the bridge has a grade ranging from +0.8% (in its northern half) to +1.6% (in its southern half), resulting in the north abutment being at an elevation 0.25 m below that of the south abutment. A schematic of this structure along with the installed sensors is shown in Figure 1.

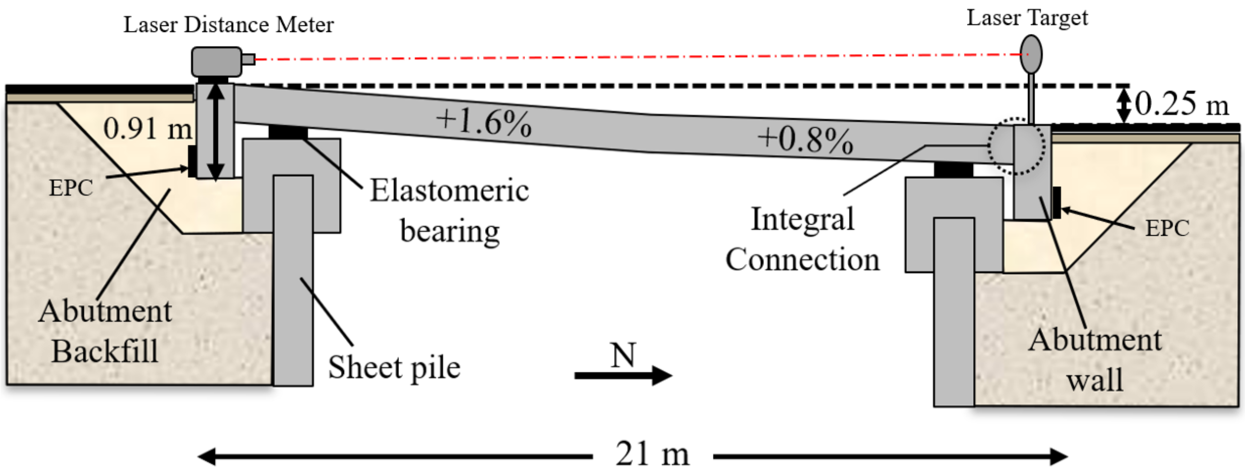

Figure 1. Schematic of Mack Creek semi-integral bridge and installed sensors. (EPC: Earth Pressure Cell)

The vertical loads from the bridge are transferred to the foundation soil using 6.7 m-long PZC-18 sheet piles. The bearing stratum at this site is composed of silty clay material that classifies as CL according to ASTM D2487 (2017), with a Texas Cone Penetrometer (TCP) count of 50 (TEX 132-E, 1999). The wingwalls were constructed using the same sheet pile profile. Consistent with the semi-integral nature of the bridge, its deck, girders and abutment backwalls were integrated. A 12 mm preformed bituminous fiber board attached to the back of the abutment cap prevents direct contact between the abutment wall and cap.

The backfill material used in this abutment is a crushed rock aggregate with a maximum particle size of 16 mm. A geotextile was used to cover the bottom and sides of the backfill area. The internal friction angle of the backfill material, obtained by a series of consolidated drained triaxial tests, is 37 degrees. The top of the backfill was paved with a 0.2 m-thick subgrade material and a 0.15 m-thick asphalt concrete layer to create a flexible approach roadway. A layer of riprap was also placed around the sheet piling to protect the foundation from erosion and scour from potential flooding of the creek. As mentioned, the bridge does not have any expansion joints and therefore all thermal deformations are transferred to the abutment backfill and flexible approach roadways. The construction of this bridge was concluded in July 2017.

INSTRUMENTATION OVERVIEW

The instrumentation of this bridge was completed in two separate phases, with the initial instrumentation phase carried out during the construction of the bridge and the secondary instrumentation phase carried out 2.5 years later, in 2020.

The initial instrumentation phase included installation of Geokon model 4810 vibrating wire Earth Pressure Cells (EPC) on the abutment walls. Two EPCs were installed on each abutment wall (1.35 m from the center line of the bridge on either side) and measured earth pressures at the lowest point on each wall. The EPCs were connected to two Geokon model 8002-4 LC2X4 data loggers set to take readings once an hour, and mounted on the underside of the bridge to protect from potential flooding and direct sunlight. In addition to earth pressure readings, data logger panel temperature, representing ambient air temperature in the shade, was collected hourly as well. More details about this phase of instrumentation can be found in Walter (2018).

Following the data collected from the earth pressure cells over the first two years of the project, it was also decided to install additional sensors at the site to gather information on the effect of climate variables and thermal deformations of the bridge as well. The sensors used in this phase include:

1. ClimaVue50 – A compact weather station that includes a pyranometer, anemometer, temperature sensor, drip counter gauge and relative humidity sensor.
2. SI-111SS Infrared Radiometer – A sensor to measure the surface temperature of an object using a thermopile for measuring bridge deck surface temperature.
3. OptoNCDT ILR 1181-30 – An industrial grade time-of-flight laser distance meter capable of measuring distances up to 150 m with a resolution of 0.1 mm to measure the length of the bridge at regular intervals.

The weather station and infrared radiometer were mounted on top of a pole to record appropriate measurements. The laser distance meter was installed on one side of the deck and aimed at a target plate mounted on the opposite side of the deck, allowing it to continuously measure the total length of the deck. Data from these sensors is collected by a Campbell Scientific CR6 logger, transmitted daily via a cellular modem and automatically processed by a cloud-based python program developed by the researchers. Although the research team intended to collect data from both sets of sensors for the lifetime of the project, the EPCs began experiencing technical difficulties two years after installation and stopped providing data. Therefore, no direct overlap between the two sets of data exists. This was determined to be due to damage to the buried portion of the sensor cables as indicated by the post failure sensor lead resistance measurements and it led to loss of all sensors in a span of one month. However, as both data sets are complemented by ambient air temperature measurements, it is possible to speculate a link between cyclic deformation and earth pressure changes between the two data sets.

Regarding the EPC data, it is worth noting that these sensors were tested in a controlled laboratory environment at different pressures and with less than 0.1% fluctuations, there is high confidence in the field recorded values and the daily fluctuations recorded. The seemingly large fluctuations seen in Figure 2 are considered to be the result of daily temperature variations.

INSTRUMENTATION RESULTS AND DISCUSSION

The data collected from the EPCs mounted on the abutment walls is presented in Figure 2. As shown in the figure, the pressure readings collected from both abutments started at somewhat similar levels, with the south abutment earth pressure fluctuating between 7 kPa and 25 kPa over the first two months after construction, while the north abutment experienced an average drop in pressure during these two months, from a range of 10 to 25 kPa (July 2017) to the range of 3 to 15 kPa (September and October 2017). Therefore, not only do the earth pressures on the north side drop on average over the first 3 months, they also appear to have fluctuations of smaller magnitude. Moreover, throughout the monitoring period, the south abutment shows an increasing trend in earth pressures with comparatively larger daily and seasonal fluctuations in relation to those experienced in the north abutment.

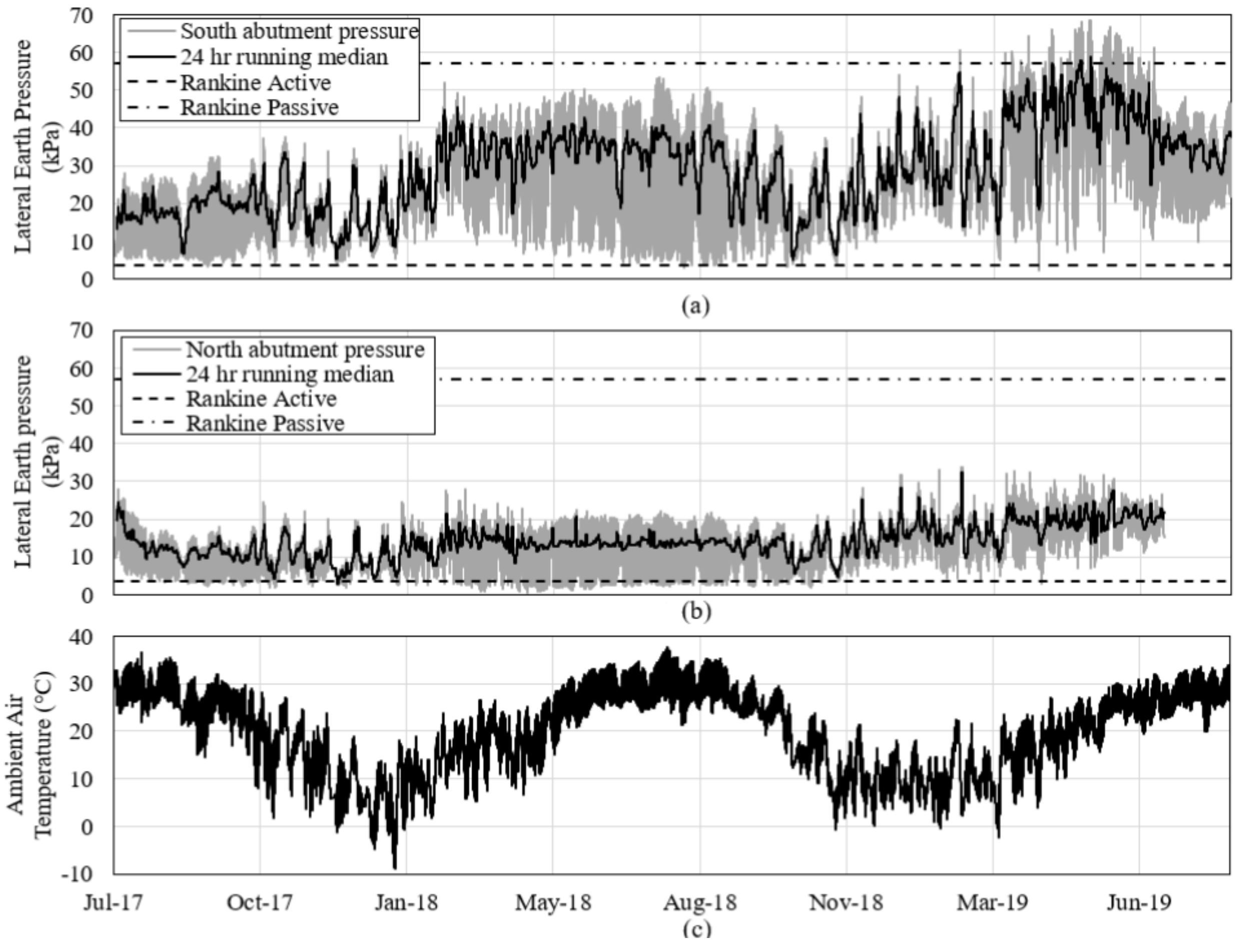

Figure 2. Data collected during the first phase of instrumentation: (a) south abutment EPC data; (b) north abutment EPC data; and (c) ambient air temperature.

This asymmetry is observed beyond the first few months of data as well. The data indicates that the two abutments experience very different levels of earth pressures due to thermal expansion/contraction of the bridge. Earth pressure levels ranging from 10 kPa to 50 kPa were recorded in the south abutment in summer 2018 (Double the levels measured in summer 2017), with levels ranging from 20 kPa to 65 kPa measured in summer 2019. Average earth pressures appear to have increased by 15 kPa to 20 kPa each summer before a sharp drop in mid-summer 2019. In contrast, the north abutment experienced much lower levels of stress ratcheting, with an average increase of about 5 kPa each year. Possible explanations for this asymmetric response include the sloping grade in the bridge, uneven compaction of the backfill observed during the bridge construction, and/or not placing backfill on both sides simultaneously. For example, a sloped bridge is expected to expand asymmetrically due to a portion of its weight being supported by the lower elevation abutment (North abutment in this case), leading to asymmetric loading of abutment backfills. Similarly, uneven backfill placement (e.g. placing backfills several days apart or uneven compaction of them) leads to different levels of resistance against thermal expansion of the deck, leading to each abutment backfill experiencing a different level of deformation. Similarly, Laaksonen and Kerokoski (2007) reported asymmetrical expansion/contraction of an integral bridge due to uneven compaction of the backfills.

Figure 3. Gap formed between the wingwall and side of the abutment wall.

Seasonally, the magnitude of daily earth pressure fluctuations is observed to be larger in warm seasons, while average daily earth pressures remain essentially constant. The magnitude of daily earth pressure changes in winter are relatively smaller most days, with sharp increases in earth pressure levels observed during periods in which average temperatures increase. Considering the trends in average daily temperatures, the highest earth pressures of the year are observed during the summer, and average earth pressures rise during the preceding spring and winter.

Another relevant observation from the data in Figure 2 is that the measured earth pressures on the south abutment wall clearly exceed Rankine's passive earth pressure (Rankine 1857) in summer 2019. The stress ratcheting phenomenon caused by daily cyclic thermal expansion/contraction of the deck observed in this bridge appears to have led to full mobilization of the passive pressure at the location of the EPCs. Moreover, it should be noted that even during warm seasons, the abutment earth pressure reached values as low as the Rankine active earth pressure on several occasions and therefore caused the abutment wall to experience the full range of earth pressures in a matter of only a few days.

In summer 2019, the earth pressure on the south abutment wall dropped in the month of May. This is a somewhat unexpected behavior considering the high temperatures and behavior observed previously, at least based on the responses previously reported in the literature (Civjan et al. 2013; Frosch and Lovell 2011). A visual inspection of the bridge was conducted to identify any likely causes. During this bridge inspection, a sizeable gap between the wingwall (sheet pile) and side of the abutment wall on the south wall was detected (Figure 3). Closer inspection of this gap revealed the development of a void in the area which was originally filled with granular fill during construction. Therefore, it is possible that the earth pressure increase led to deformations in the wingwall, allowing for the loss of backfill. While no EPC was installed on the wingwalls in this project, other researchers, such as Steinberg et al. (2004), have previously reported considerable increases in earth pressures acting on wingwalls of semi-integral bridges, and it is thus conceivable that stress increases led to excessive deformations in the wingwall. In addition to earth pressure increases, this issue may have been exacerbated by the drainage of surface runoff through this gap, causing additional erosion of the fill as evidenced by the accumulation of small brush and leaves in the gap. A lesson learned from this evaluation is the need to design wingwalls as members subject to stress ratcheting and also include surface runoff drainage systems in proximity to semi-integral bridges to minimize erosion, backfill loss and approach roadway settlement. Other researchers, including Burke (2009), have provided recommendations regarding the importance of providing a proper drainage system for jointless bridges as well.

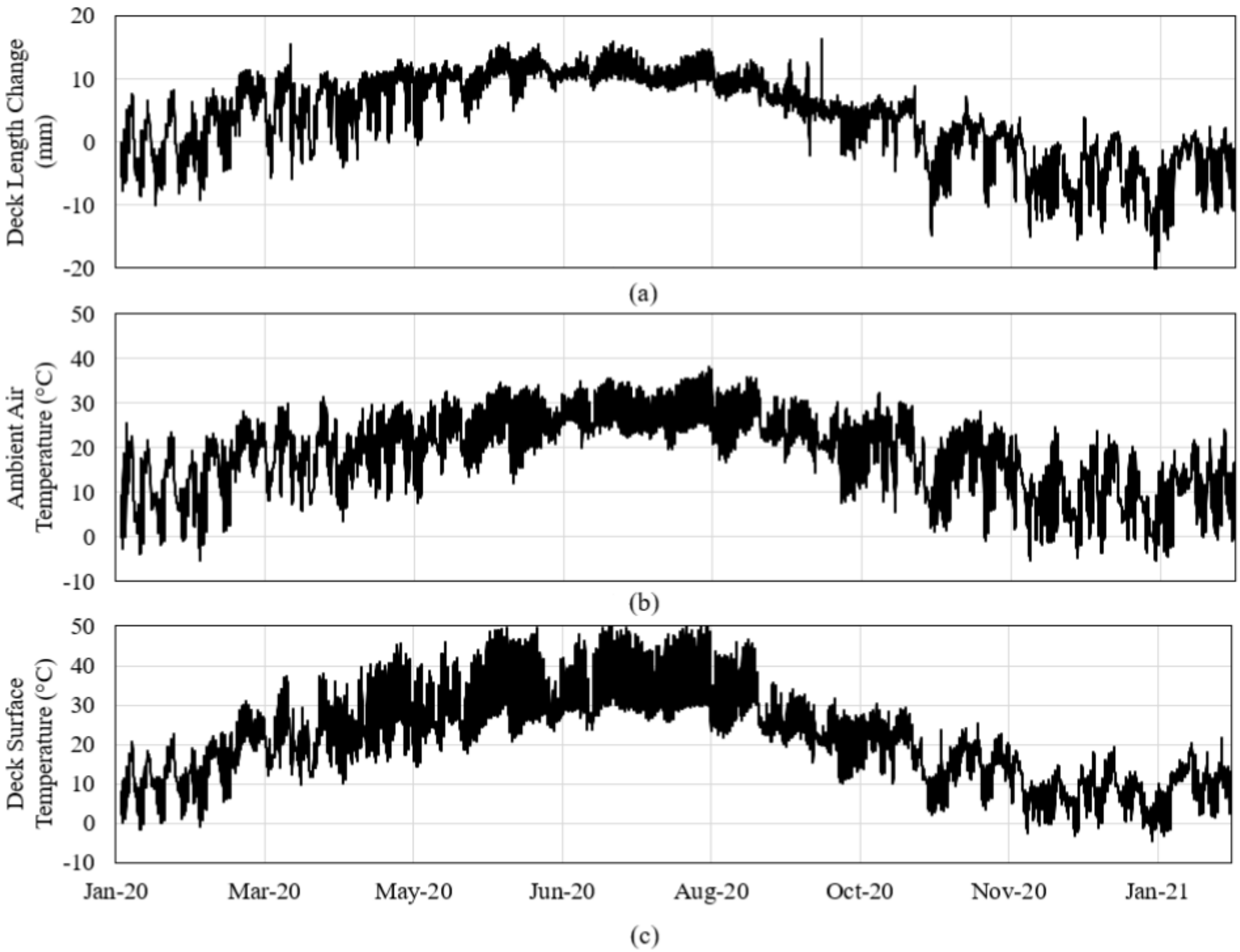

Figure 4. Data collected during the second phase of instrumentation: (a) laser distance meter; (b) ambient air temperature; and (c) deck surface temperature.

As discussed previously, additional sensors were mounted on the bridge in January 2020 to collect supplementary field performance data. The change in length of the deck measured by the laser distance meter is shown in Figure 4a. As shown in the figure, this sensor successfully captures hourly changes in the length of the deck due to changes in temperature. During the first year of monitoring, the bridge appears to have experienced 25 mm of deformation from winter to summer. Bridge deformations of about 5 mm a day during the summer and 10 mm a day during the winter are common, despite relatively similar daily ambient air temperature changes between the two seasons (Figure 4b). This behavior is likely caused by the increased duration of sun exposure during summer days in combination with the reduced thermal conductivity of concrete at higher temperatures (Kim et al. 2003), which slows its rate of cooldown. A comparison of ambient air temperature with deck surface temperature data (Figure 4b and Figure 4c) from winter and summer provides additional evidence that during the winter, deck surface temperature and ambient air temperature remained relatively close (±3.5 °C difference on average), while in the summer, the deck surface temperature remained considerably higher (6 - 8 °C hotter on average) compared to the ambient air temperature, even at night.

Consideration of the EPC data (Figure 2a & Figure 2b) in conjunction with the deformation data (Figure 4a) may explain why, despite mobilization of active conditions in both summer and winter, it was only during the winter when an increase in average earth pressure was observed. As indicated by the deformation data, while 5 mm of daily movement has been sufficient to mobilize an active state in the soil mass, it appears to be insufficient to allow stress ratcheting to occur. Therefore, it is the larger amplitude deformations experienced during the cold season that allowed for local failure, recompaction and fabric changes within the backfill soil, leading to stress ratcheting and increases in earth pressure. This is consistent with the experimental findings reported by Clayton et al. (2006) regarding the strain magnitude dependency of stress ratcheting in which they identify the rearrangement of particles (fabric changes) as well as densification of material in cyclic loading conditions as underlying mechanisms for stress ratcheting.

This evidence may have major implications regarding the behavior of semi-integral and other jointless bridges. Specifically, under similar conditions, a comparatively longer bridge may experience stress ratcheting during summer months as well, leading to faster development of the stress ratcheting phenomenon. The choice of construction material, such as steel versus concrete, can also significantly affect the heat flow rate and thermal expansion of the bridge. A second implication is that in locations with smaller daily or seasonal temperature fluctuations, improved performance of jointless bridges can be expected and thus a positive experience with these structures in one location may not be successfully repeated in another location with larger diurnal temperature variations.

CONCLUSION

Data obtained from an instrumented semi-integral bridge located in Anderson County, TX was evaluated to assess the field performance of semi-integral bridges in the state of Texas, where semi-integral bridge design has not yet been adopted as standard practice.

The instrumentation data collected from this semi-integral bridge reveals the following relevant trends:

- An asymmetric earth pressure response was observed between the two abutments. The south abutment has experienced larger magnitude earth pressures, reaching theoretical Rankine passive pressure, while the north abutment wall experienced much smaller stress levels overall. This asymmetry may have been caused by a number of issues, including slope of the bridge, uneven compaction of the abutment fill and/or not placing abutment backfills simultaneously. This implies that symmetrical behavior in such structures should not be necessarily assumed for the purposes of design or analysis of the structure.
- The highest earth pressure levels for both abutments were observed to develop during warm summer days. However, even the small amount of thermal contraction experienced

by the bridge at night during the summer months led to earth pressures corresponding to Rankine active earth pressure. This resulted in stress cycles of comparatively larger magnitude experienced over the summer months.

- The trends observed in the EPC data revealed that earth pressure ratcheting occurred during the colder months of the year (November to March), resulting in an approximately 50% to 100% increase in average daily earth pressures each year.
- A drop in the south abutment earth pressures was observed during summer 2019. While unusual, it was likely due to the loss of backfill in this abutment. Field inspection revealed the formation of a gap between one of the wingwalls and side of the abutment wall, which was likely caused by increasing earth pressures. Moreover, erosion due to drainage of surface runoff is thought to have exacerbated this problem. This could be avoided in future semi-integral bridges by designing wingwalls considering full mobilization of passive pressures in the backfill. Additionally, to minimize the risk of erosion, implementation of a proper surface runoff drainage system in proximity to semi-integral bridges is highly recommended.
- The daily variation of deck deformation magnitude appears to have been greater in colder months, despite similar ambient air temperature ranges in winter and summer. While both conditions can lead to the development of active conditions within the soil mass, stress ratcheting is only observed during the colder months when larger magnitude deformations occur frequently. This is likely because the larger magnitude deformations allow for the changes in fabric and densification levels necessary for stress ratcheting to occur.

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