Integral-Abutment Bridges: Geotechnical Problems and Solutions Using Geosynthetics and Ground Improvement

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ABSTRACT

The *integral-abutment bridge* (IAB) concept was developed at least as far back as the 1930s to solve long-term structural problems that can occur with conventional bridge designs. Unfortunately, the IAB concept as executed historically turns out to have its own inherent post-construction flaws. However they are fundamentally of a geotechnical, not structural, nature. As a result, bridge engineers, who are more familiar with dealing with structural issues, have been slow to recognize the true source of IAB problems and develop appropriate permanent solutions for them. Thus IABs represent an interesting case study in soil-structure interaction that requires the coordinated attention of both structural/bridge and geotechnical engineers working as a multidisciplinary team if the concept is to be improved for better long-term performance. This paper is intended to be an contribution toward that goal and illustrates the potential use of modern geotechnolgies for IAB problem solving.

THE EVOLUTION OF INTEGRAL-ABUTMENT BRIDGES

The conventional design concept used for most bridges with a short to medium span length consists of a superstructure resting on abutments as shown in Figure 1. There may be one or more intermediate piers but their absence or presence is not relevant to the present discussion and does not affect any of the conclusions and recommendations made in this paper.

Because of natural, seasonal variations in atmospheric air temperature, the bridge superstructure will change in temperature and concomitantly change dimensions, primarily in the longitudinal direction as also shown in Figure 1. Typical ranges of longitudinal displacement for relatively modest span lengths are of the order of several tens of millimetres (one inch). However, the abutments supporting the superstructure are for all practical purposes insensitive to air temperature so remain spatially fixed year 'round. The relative displacement between the moving superstructure and fixed abutments is accommodated by a synergistic combination of expansion joints and bearings as shown in Figure 1. Thus the key elements of conventional bridge design can be summarized as follows:

- Seasonal thermal displacements of the superstructure are natural and unavoidable. The magnitude of these displacements turns out to be relatively insensitive to the specific materials (steel versus portland-cement concrete (PCC)) used for the bridge components.

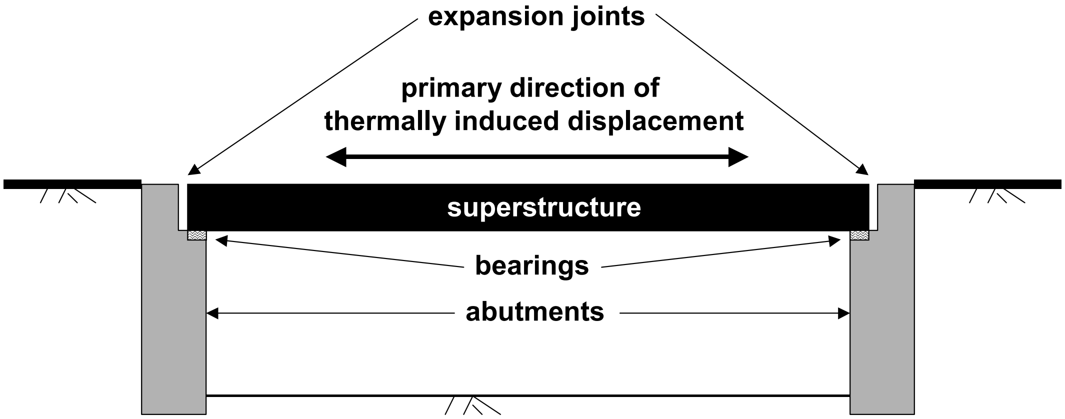

Figure 1. Basic Elements of a Conventional Bridge

- The abutments are for all intents and purposes rigid structural elements that are fixed in space and time (foundation settlements are not considered here as they do not materially enter into the present discussion). This makes the ground retained by the abutments also fixed in space and time.

- There are explicit measures taken to isolate the moving superstructure from the fixed abutments + soil and vice versa, at least in terms of longitudinal displacements.

Although the design concept shown in Figure 1 has been used for a long time and works well enough in practice, the expansion joint/bearing detail is often a source of significant post-construction structural maintenance and expense during the life of a bridge. Therefore, the IAB concept was developed to eliminate the troublesome and costly expansion joint/bearing detail. This is accomplished by physically and structurally connecting the superstructure and abutments as shown conceptually in Figure 2.

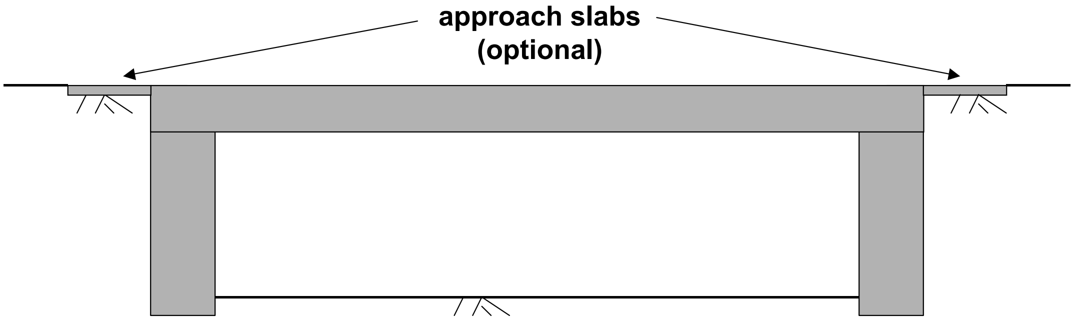

Figure 2. Basic Elements of an Integral-Abutment Bridge

IABs have been used for road bridges since at least the early 1930s in the U.S.A. [1]. Over the years and in different countries they have variously and synonymously been called *frame bridges*, *integral bridges*, *integral bridge abutments*, *jointless* *bridges*, *rigid-frame bridges* and *U-frame bridges*. There is also a design variant called the *semi-integral-abutment bridge*. Relevant to this paper is the fact that collectively such bridges have seen extensive and growing use worldwide in recent years because of their economy of construction in a wide range of conditions and using a variety of structural materials. Thus they comprise an important aspect of modern transportation-engineering practice as evidenced by the specialty conference for which this paper was prepared.

PROBLEMS WITH THE IAB CONCEPT

Overview

Although the IAB concept has proven to be conceptually successful in eliminating expansion joint/bearing problems as well as economical in initial construction for a wide range of span lengths, it has not turned out to be problem- and maintenance-free in actual service. This is because the IAB concept suffers from an inherent, fundamental flaw. Specifically, the IAB concept fails to explicitly and proactively address how the relative displacement between the moving superstructure and fixed ground is to be accommodated. This derives from the fact that the IAB concept fails to recognize that it does not, and cannot, fundamentally alter nature and the laws of physics and the resulting tendency of a bridge superstructure to undergo seasonal temperature and length changes in its longitudinal direction. All that has changed between conventional versus IAB bridge designs (i.e. Figure 1 versus Figure 2) are the details of how this thermally induced displacement occurs, and the nature of the resulting problems and maintenance issues it generates. Thus IABs as currently designed still have maintenance costs as did their jointed predecessors which inflates the true life-cycle cost of an IAB.

Causes

The fundamental cause of in-service problems for IABs as they are currently designed is illustrated in Figure 3. As the bridge superstructure goes through its seasonal length changes, it causes the structurally connected abutments to move inward and away from the soil they retain in the winter, and outward and into the retained soil during the summer. The specific mode of abutment movement is primarily rigid-body rotation about the bottoms of the abutments although there is a component of rigid-body translation (pure horizontal displacement) of the abutments as well. Because rotation is dominant, the magnitude of the range of horizontal displacements is thus greatest at the top of each abutment.

At the end of each annual thermal cycle, there is often a net displacement of each abutment inward toward each other and thus away from the retained soil as shown in Figure 3. The primary reason for this is that the inward winter displacement is typically of sufficient magnitude to cause an active earth pressure 'soil wedge' to develop adjacent to each abutment and follow the abutment inward, with the soil slumping downward somewhat in the process. Because of the fundamentally inelastic

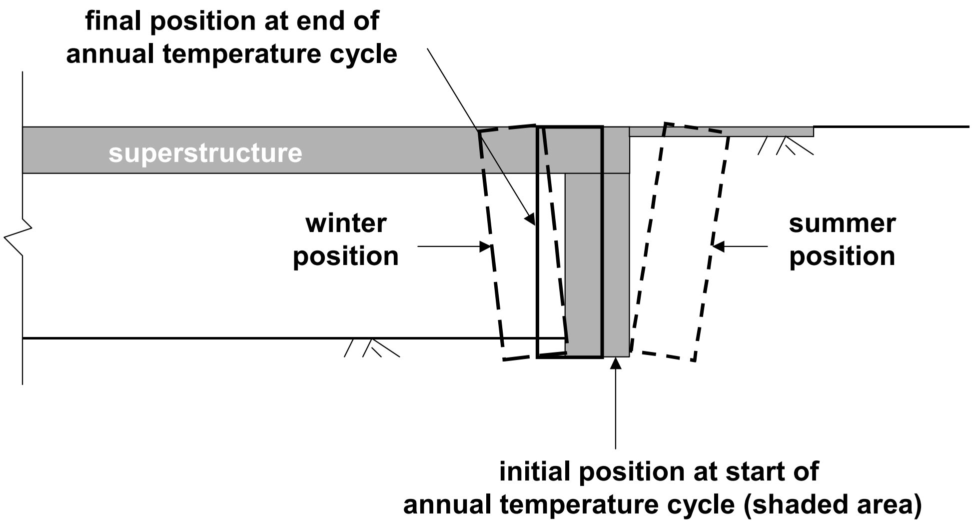

Figure 3. Thermally Induced IAB Abutment Displacement

nature of soil behavior, this inward/downward soil displacement is not fully recovered during the outward summer cycle. It is relevant to note that this net inward/downward soil displacement will occur no matter what type of soil is used and how well it was compacted during original construction. It is also of interest to note that this tendency to develop a net inward displacement of the abutments is exacerbated when the bridge superstructure is composed primarily of PCC due to the inherent post-construction shrinkage of PCC.

Consequences

There are two significant consequences of the annual thermal cycle of IABs. The first was recognized at least as far back as the 1960s [2,3,4] and is the relatively large lateral earth pressures that develop on the abutments during the annual summer expansion of the superstructure. These pressures can approach the theoretical passive state, especially along the upper portion of the abutments where horizontal displacements are largest. Passive earth pressures are typically an order of magnitude greater than the at-rest pressures for which a bridge abutment should typically be designed. This tenfold increase in lateral earth pressures far exceeds any normal margin of structural safety built into the design and thus can result in structural distress and even failure of an abutment.

Recent research indicates that this long recognized seasonal increase in lateral earth pressures may be a more significant and potentially problematic issue than initially thought. This is because the summer-seasonal increase in pressures is not necessarily constant over time but can increase over time. The reason is that not only is one seasonal cycle of inward-outward-inward displacement nonlinear, but each succeeding season is nonlinear with respect to the preceding one. This means each winter the abutment moves inward slightly more than it did the preceding winter and each summer it moves outward slightly less than it did the preceding summer. As a result of this net soil displacement inward toward the abutments and the fact that the bridge superstructure still expands each summer the same amount as the preceding year, the summer lateral earth pressures increase over time as the soil immediately adjacent to each abutment becomes increasingly wedged in. This overall behavior is a geo-phenomenon called *ratcheting*. The soil mechanics behavior causing ratcheting is quite complex but is well- and thoroughly described in the literature [5].

Because ratcheting causes each summer's lateral earth pressures to be somewhat greater in magnitude than those from the preceding year, it means structural failure of the abutments may take years, even decades, to develop, a happenstance observed in practice for other types of earth-retaining structures where thermally induced ratcheting occurs [5,6,7]. Given the relatively long design life of most IABs (typically 100 years or more), ratcheting represents a potentially serious long-term source of problems, primarily structural distress and failure of the abutments.

The second significant consequence of the annual thermal cycle of IABs is also related to the net inward displacement of the abutments and has become fully appreciated only in recent years. This is the subsidence pattern that develops adjacent to each abutment as shown in Figure 4. This is the result of the above-described phenomenon of accumulated, irreversible soil-wedge slumping behind each abutment. The consequences of this subsidence depend on whether or not an approach slab was constructed as part of the bridge. If there is no slab, there will be a difference in road-surface elevation occurring over a short distance creating the classical 'bump-at-the-end-of-the-bridge' condition. If there is a slab, initially it will span over the void created underneath it by the subsided soil. However, with time and traffic the slab can fail structurally in flexure.

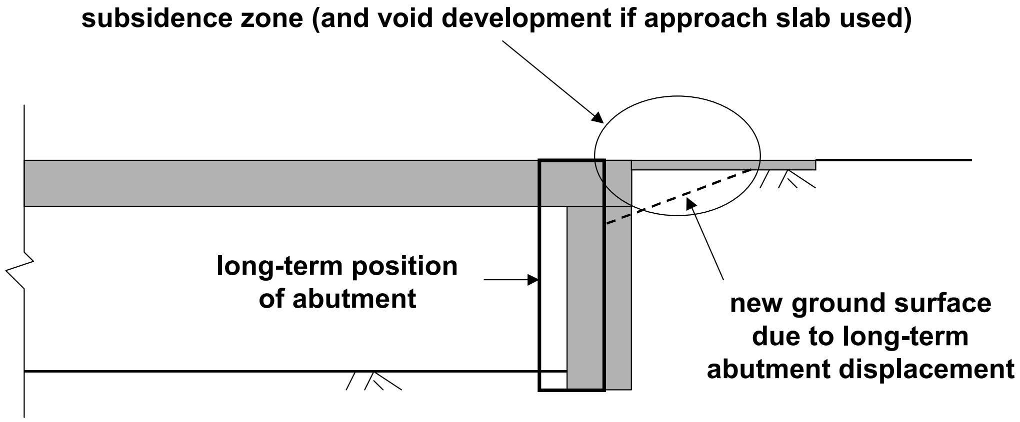

Figure. 4. Ground-Surface Subsidence behind IAB Abutments

Subsidence behind IAB abutments has received much more interest in recent years compared to the traditional concern over increased lateral earth pressures. This is because experience indicates subsidence develops and becomes problematic relatively soon (a few years at most) after an IAB is placed in service [8,9,10,11,12] whereas the ratcheting buildup of lateral earth pressures might not create problems for decades as noted above. For example, [11] noted that a survey of 140 IABs with approach slabs in the State of South Dakota, U.S.A. found a void under virtually every slab. The void depths ranged from 13 to 360 mm (0.5 to 14 in), and the voids extended as much as 3 m (10 ft) behind the abutment.

PROBLEM SOLUTIONS

Overview of Past Efforts

Although most recent research into defining IAB problems has focused on the newly identified issue of subsidence behind abutments, some recent work related to developing actual solutions for IAB problems has focused on the traditional issue of lateral earth pressures alone [1,11,13]. Specifically, various types of relatively compressible materials (generically referred to herein as *compressible inclusions*) such as either resilient or normal expanded polystyrene (EPS) geofoam and tire shreds have been placed behind IAB abutments. Conceptually, a compressible inclusion is intended to serve as a sacrificial cushion between a relatively rigid earth retaining structure and the adjacent ground with the overall goal of reducing lateral earth pressures. A recent overview of the compressible-inclusion concept with an emphasis on earth retaining structures used for transportation facilities can be found in [14].

While these research efforts are a step in the right direction, available information suggests they are significantly incomplete. Research to date indicates that although the use of a compressible inclusion can be highly effective in reducing the summer increase in lateral earth pressures it is totally ineffective for controlling subsidence behind the abutments. In fact, experience indicates the presence of a compressible inclusion may even exacerbate the subsidence problem even as it addresses the summer lateral earth pressure problem. This is because the highly compressible nature of a compressible inclusion that is so desirable under summer expansion of an IAB becomes a detriment when winter contraction occurs. As the superstructure contracts and pulls each abutment away from the retained soil, the relatively weak compressible inclusion between abutment and soil is unable to restrain the soil from slumping and displacing inward toward the abutment. This actually results in subsidence behind the abutment that is larger in magnitude than if no compressible inclusion were present. This has been observed for at least one IAB that was studied thoroughly where a compressible inclusion consisting of recycled tire fragments was used with an approach slab [11]. It has also been observed in large-scale, 1-g physical-model testing where a compressible inclusion composed of resilient-EPS geofoam was used with a coarse-grain-soil backfill [12].

Proposed Improved Solutions: Basic Concepts

Because of the current extensive use of IABs, there is a critical need to develop solutions to correct the behavioral deficiencies inherent in all IABs as they are typically designed and constructed at the present time. As noted previously, past efforts to develop improved designs based on the use of a compressible inclusion alone have not been a total success because they did not address both problems, i.e. the seasonal buildup of lateral earth pressures on the abutments and ground-surface subsidence adjacent to the abutments.

The key to developing improved solutions that address both problems is a thorough understanding and appreciation of the fundamental physical processes that affect both conventional bridges as well as IABs. The following key concepts and considerations were identified by the author and used to develop the improved solutions presented subsequently:

- Expansion and contraction of a bridge superstructure due to seasonal temperature changes is inevitable and unavoidable as it is a natural phenomenon that simply cannot be changed in any significant way. This displacement will occur regardless of the specific structural concept used for the bridge design. This means the tendency for differential horizontal displacement between an IAB and the ground surface adjacent to its abutments is unavoidable and must be addressed explicitly.

- The ground adjacent to IAB abutments must be made inherently self-stable on a permanent, year-'round basis to prevent development of subsidence during the seasonal winter contraction of the IAB. In essence, the ground itself must provide the non-yielding, seasonally constant retention function formerly provided by the abutments of conventional bridge design (Figure 1).

- There must be a design detail involving a structural element or material between the self-stable ground and moving IAB abutments to reliably and predictably accommodate the relative movement between them. This detail conceptually replaces the expansion joint/bearing detail of conventional bridge design (Figure 1). Simply leaving a void between ground and abutment as has been done occasionally in the past is not considered an acceptable design detail. Experience indicates that a void is difficult to construct routinely and reliably in practice [15], and it cannot be depended on to remain for the long service life of a bridge.

Proposed Improved Solutions: Concept Details

A detailed numerical study was conducted by the author to both define the key behavioral aspects of IABs as well as investigate potential solutions using geosynthetics [16]. That study drew heavily on the knowledge gained during the 1990s about geofoams in general and EPS geofoam in particular [17]. Although the revised designs developed and presented in [16] will increase the construction cost of IABs, the anticipated superior post-construction, in-service performance of such IABs should more than make up for the increase by reducing future maintenance and repair costs. Similarly, implementing these revised designs retroactively on existing IABs should be cost effective by reducing their future maintenance and repair costs.

Two different design concepts were developed to accommodate different site conditions. Both are shown schematically in Figure 5. The one likely to be more cost effective in most applications is shown in Figure 5(a) and is appropriate for sites where compression and/or stability of the native soils underlying the approach embankment to the bridge is not an issue. The concept utilizes geosynthetic tensile reinforcement (likely geogrids or geotextiles) to create a *mechanically stabilized earth* (MSE) mass within the retained soil adjacent to each abutment. This reinforced soil mass would be inherently self-stable for the design life of the bridge. In addition, a relatively thin (typically of the order of 150 mm (6 in) thick) layer of resilient-EPS-

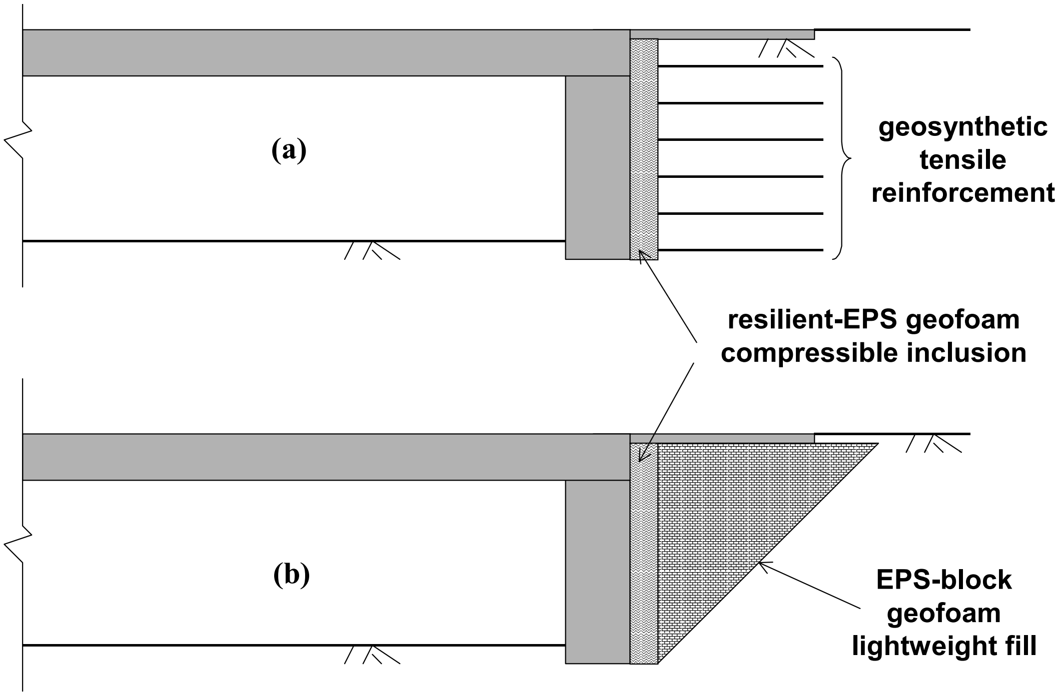

Figure 5. Proposed New IAB Design Alternatives

geofoam would be used as a compressible inclusion in a 'chimney' orientation between the abutment and MSE mass. This durable inclusion is highly compressible and thus functions as the desired expansion joint between the abutment and MSE mass. Note that the compressible inclusion also thermally insulates the retained soil (against winter freezing) and the geosynthetic tensile reinforcement (from summer heat which can increase geosynthetic creep), and can be designed to also serve as a drain for ground water. Functionally, this compressible inclusion allows the reinforcement within the soil to strain in tension (which prevents the soil from displacing inward and downward toward the abutment each winter) as well as allows the abutments to move seasonally in either direction with minimal restraint. Thus summer increases in lateral earth pressures are reduced to relatively small magnitudes. Overall, lateral earth pressures acting on the abutments are significantly reduced from current design levels which would achieve a cost savings in the structural design of the abutment.

The other design alternative is shown in Figure 5(b). A self-stable wedge of some kind of geofoam (most likely EPS blocks [18] but alternatively foamed PCC) or geocomb blocks would be used as a solid lightweight-fill material in lieu of the MSE mass. A relatively thin layer of highly compressible resilient-EPS geofoam is again used multifunctionally as a compressible inclusion/thermal insulation/chimney drain. This alternative is expected to be the one of choice for sites where the soils underlying the approach embankment are soft and compressible. Use of a lightweight fill material would minimize settlements and enhance stability of the ground adjacent to the bridge as well as greatly reduce the loads acting on the abutment and the deep foundations that would likely be supporting it in such soil conditions. Solid lightweight-fill materials such as various types of geofoam are particularly attractive here as they are inherently self stable even when constructed with vertical side slopes. Although geofoam materials are inherently more expensive than soil on a strictly volumetric comparison the resulting overall savings would likely more than compensate for the use of a geofoam material in lieu of soil. The benefits of accelerated construction by using geofoam materials should also be considered.

Proposed Improved Solutions: Additional Comments

For the sake of completeness, it should be noted that in cases where the ground underlying the approach embankment is weak and compressible there are other potential alternatives to using a solid lightweight-fill material as shown in Figure 5(b) that might be cost-effective on a project-specific basis [19]. This includes using a granular type of lightweight fill material (expanded-shale aggregate, tire shreds, etc.) in combination with geosynthetic tensile reinforcement to stiffen and retain the material as an equivalent MSE mass as shown in Figure 5(a). Alternatively, some type of ground improvement might be performed to strengthen and stiffen the native soils in situ prior to constructing the approach embankment. After performing the ground improvement, the approach embankment could be constructed using normal soil and an MSE mass adjacent to the abutments as shown in Figure 5(a).

SUMMARY AND CONCLUSIONS

IABs are an interesting example of how new problems were inadvertently created in the process of solving old problems. IAB problems are fundamentally geotechnical in nature and can manifest themselves both structurally and geotechnically any time in the life of an IAB. The primary cause of both short- and long-term IAB problems is the irreversible net inward and downward displacement of the soil retained by IAB abutments. This will occur regardless of the type of soil used and how well it was compacted during construction. The resulting problems consist of irreversible subsidence behind the abutments and the ratcheting buildup of 'summer' lateral earth pressures on abutments. Either or both of these outcomes can result in serviceability or collapse failures of the bridge components and thus are serious.

Research also indicates that relatively simple and cost-effective design solutions to eliminate these problems can be achieved using a variety of modern geosynthetics and/or ground-improvement technologies in an innovative, synergistic fashion. Because the problems encountered with IABs as currently designed turn out to be a complex problem in soil-structure interaction, any successful solution must address the need to both:

- support the ground adjacent to the abutments on a permanent, year-'round basis and

- provide for a compressible inclusion (essentially an expansion joint) between abutment and adjacent ground to serve as an engineered, in-ground replacement to the expansion joint/bearing detail of conventional bridges.

Several specific suggestions for improved IAB designs were presented in this paper. An important benefit is that these solutions can be implemented as part of the rehabilitation of existing IABs in addition to being applicable for new construction.

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