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**INTEGRAL-ABUTMENT BRIDGES:
A COMPLEX SOIL-STRUCTURE INTERACTION CHALLENGE**

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ABSTRACT: *Integral-abutment bridges* (IABs) are a unique and interesting case study in soil-structure interaction. They were developed to solve long-term structural problems that occur with traditional bridge designs but, as an unanticipated result, created new problems of a geotechnical nature that manifest themselves only after an IAB is placed in service.

One problem associated with IABs that tends to develop relatively rapidly is ground subsidence adjacent to abutments. This results in the classical 'bump at the end of the bridge' or potential failure of the approach slab if one is used. The other IAB problem develops in the longer term and involves the irreversible buildup of lateral earth pressures on the abutments due to a soil-mechanics phenomenon called *ratcheting*. These pressures can lead to structural failure of the abutments.

With the increased worldwide use of IABs in recent years, there is widespread interest in developing design solutions to the in-service deficiencies exhibited by IABs as they are designed currently. Fundamental to achieving this goal is developing a clear understanding of how and why the geotechnical problems develop. Research indicates that the primary cause of all problems is irreversible displacement of the soil retained by the abutments of IABs.

Research also indicates that design solutions can be achieved using a variety of geosynthetics in an innovative, synergistic fashion. First and foremost, a self-stable zone of material must be established behind each abutment. This can be achieved using either a reinforced soil mass or some type of geofabric (EPS blocks or foamed concrete). Secondly, an EPS-geofabric geocomposite must be placed between this stabilized zone and the back of the abutment to act as a *compressible inclusion*. This inclusion serves both as an expansion joint to accommodate seasonal displacement of the abutment as well as to provide insulated drainage. An important benefit is that these solutions can be implemented as part of either new construction or the rehabilitation of existing IABs.

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THE EVOLUTION OF INTEGRAL-ABUTMENT BRIDGES

Traditionally, the design concept for most bridges 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 important to the present discussion. Because of natural, seasonal variations in air temperature, the bridge superstructure will change in temperature and concomitantly change dimension in its longitudinal direction, also as shown in Figure 1. However, the supporting abutments are for all practical purposes insensitive to air temperature so remain spatially fixed year 'round. To accommodate the relative displacement between the moving superstructure and fixed abutments and prevent temperature-induced stresses from developing within the superstructure, expansion joints and bearings are used as shown in Figure 1.

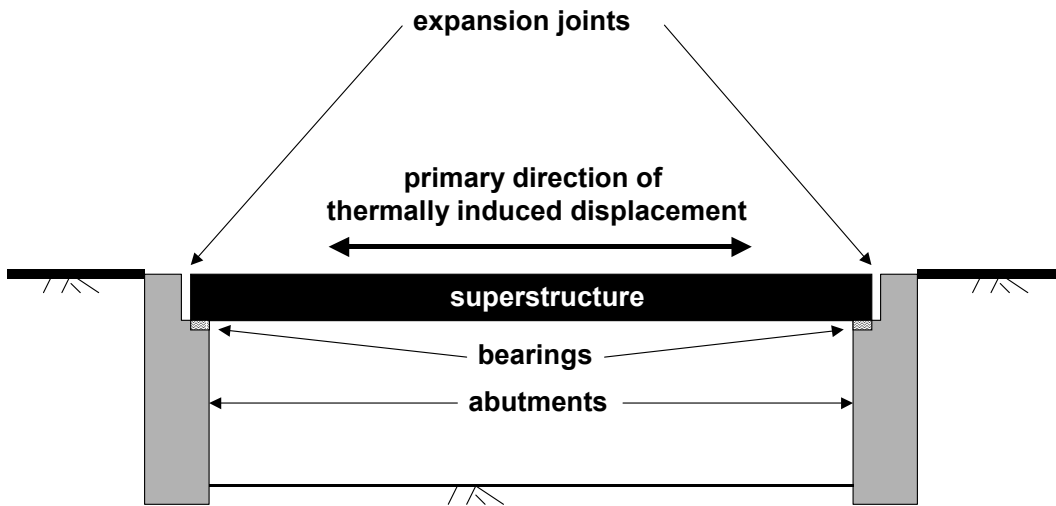


FIG 1. Basic Elements of a Conventional Bridge

Although this design works well in concept, 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 concept was developed to physically and structurally connect the superstructure and abutments as shown in Figure 2 to create what is called an *integral-abutment bridge* (IAB). This structural solution effectively eliminates the troublesome and costly expansion joint/bearing detail. IABs have been used for roads since at least the early 1930s in the U.S.A. (Card and Carder 1993). Over the years and in different countries they have variously and synonymously been called *frame bridges*, *integral bridges*, *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 such bridges have seen extensive 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.

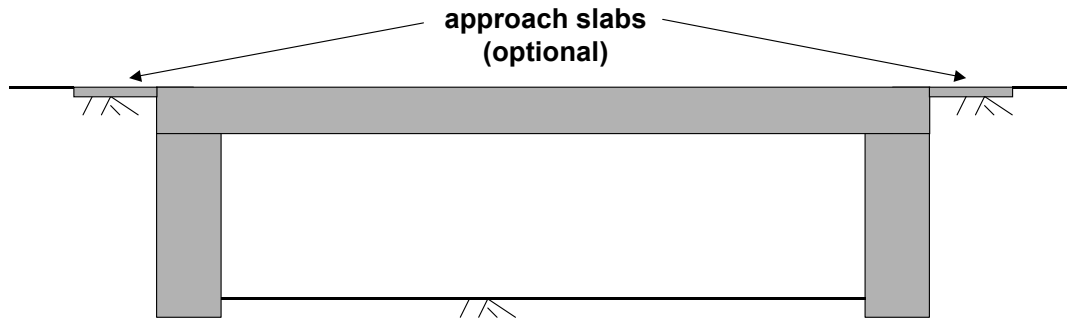


FIG 2. Basic Elements of an Integral-Abutment Bridge

PROBLEMS WITH THE IAB DESIGN CONCEPT

Overview

Although the IAB concept has proven to be 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- or maintenance-free in service. This is because the IAB concept 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. All that has changed are the details of how this thermally induced displacement occurs, and the nature of the resulting problems and maintenance issues they generate. Thus IABs 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 shown in Figure 3. As the bridge superstructure goes through its seasonal length changes, it causes the structurally connected abutments to move away from the soil they retain in the winter and into the soil during the summer. The mode of abutment movement is primarily rotation about the bottom although there is a component of translation as well. The magnitude of the seasonal range of horizontal displacements is thus greatest at the top of each abutment and is typically of the order of several tens of millimetres (one inch).

At the end of each annual thermal cycle, there is often a net displacement of each abutment 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 an abutment and follow the abutment inward, slumping downward somewhat in the process. Because of the inelastic nature of soil behavior in general, this inward soil displacement is not fully recovered during the outward 'summer' cycle. Note that this net inward displacement will occur no matter how 'properly' the soil was placed (i.e. compacted) during original construction. This tendency to develop a net inward displacement is

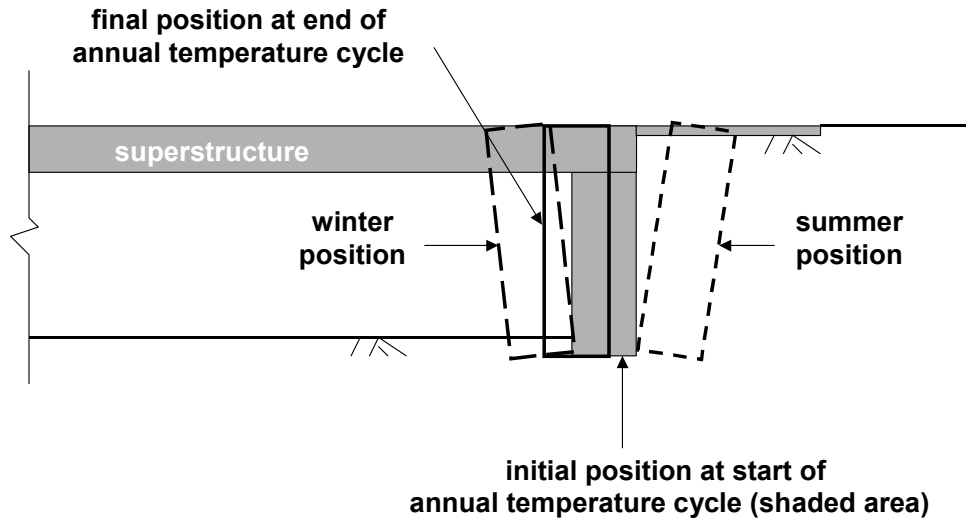


FIG 3. Thermally Induced IAB Abutment Displacement

exacerbated when the bridge superstructure is composed primarily of portland-cement concrete (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 (Broms and Ingleson 1971; Card and Carder 1993; Sandford and Elgaaly 1993) and is the relatively large lateral earth pressures that develop along the back of each abutment during the annual summer expansion of the superstructure. These pressures can approach the theoretical passive state, especially along the upper portion of the abutment where horizontal displacements are largest. Passive earth pressures are typically an order of magnitude greater than the at-rest pressures for which an abutment would typically be designed. This increase far exceeds any normal structural safety factors and thus can result in structural failure of an abutment.

Recent research indicates that this long-recognized seasonal increase in lateral earth pressures may be a more-significant issue than initially thought. This is because the summer-seasonal increase in pressures is not necessarily constant over time but can, in fact, actually increase over time. The reason is that not only is one seasonal cycle of inward-outward displacement non-linear but each succeeding season is non-linear with respect to the preceding one. This means that 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 toward the abutments, the summer lateral earth pressures increase over time as the soil immediately adjacent to each abutment becomes increasingly wedged in, a geophenomenon called *ratcheting*. The soil-mechanics behavior causing ratcheting is complex but well-described in the literature (e.g. England 1994).

Because ratcheting causes each summer's lateral earth pressures to be somewhat greater in magnitude than those from the preceding year, it means that structural

failure may take years, even decades, to develop, a happenstance observed in practice for other types of earth-retaining structures where thermally induced ratcheting occurs (England 1994; England and Dunstan 1994; England et al. 1995). 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 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

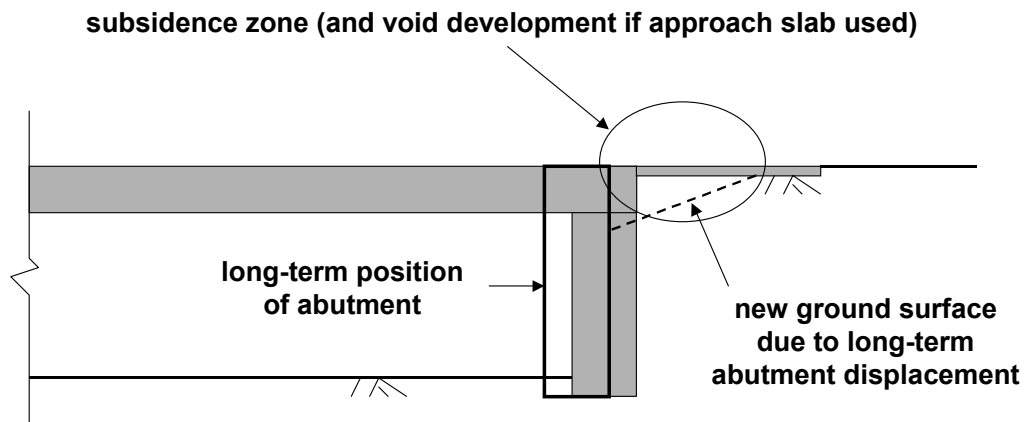


FIG. 4. Ground-Surface Subsidence behind IAB Abutments

traffic the slab can fail in flexure.

Subsidence behind IAB abutments has received much more research interest in recent years compared to the traditional concern over increased lateral earth pressures. This is because experience indicates that subsidence develops and become problematic relatively soon (a few years at most) after an IAB is placed in service whereas the ratcheting buildup of lateral earth pressures might not create problems for decades (Briaud et al. 1997; Ng et al. 1998; Reid et al. 1998a; Reid et al. 1998b; Reeves and Filz 2000). For example, Reid et al. (1998b) 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

Past Efforts

Although current research into defining IAB problems may be focusing on the recently identified issue of subsidence behind abutments, recent research into developing actual solutions for IAB problems is still focused on the traditional issue of lateral earth pressures alone (Carder and Card 1997; Humphrey et al. 1998; Reid et al. 1998b). Specifically, various types of relatively compressible materials (generically referred to herein as *compressible inclusions*) such as expanded polystyrene (EPS) geofoam and tire shreds have been placed behind IAB abutments.

While these research efforts are a step in the right direction, available information suggests that they are significantly incomplete. Research to date indicates that use of a compressible inclusion can be highly effective in reducing the summer increase in lateral earth pressures but is totally ineffective at controlling subsidence behind the abutment. In fact, experience indicates that the presence of a compressible inclusion may even exacerbate the subsidence problem even as it solves 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 the bridge 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 toward the abutment and downward. This 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 (Reid et al. 1998b). 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 (Reeves and Filz 2000).

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 designed currently (and were in the past). 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 aspects of the problem, 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 used to develop the improved solutions presented subsequently:

- Expansion and contraction of a bridge due to seasonal temperature changes is unavoidable. This means the tendency for differential horizontal displacement between an IAB and the ground surface adjacent to its abutments is unavoidable.
- The ground adjacent to IAB abutments must be made 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 bridges (Figure 1).
- There must be a design detail or element between the self-stable ground and IAB abutments to reliably and predictably accommodate the relative movement between them. This detail must conceptually replace the expansion joint/bearing detail of a conventional bridge (Figure 1). Simply leaving a void as has been suggested in the past by some is not considered an acceptable design detail. Experience indicates that a void is difficult to construct routinely and reliably (Edgar et al. 1989), and it cannot be depended on to remain for the long service life of the bridge.

Proposed Improved Solutions: Concept Details

A detailed numerical study was conducted to both define the key behavioral aspects of IABs as well as investigate potential solutions using geosynthetics (Horvath 2000). That study drew significantly from the knowledge gained during the 1990s about geofoams (Horvath 1995). Although the revised designs developed in Horvath (2000) will increase the construction cost of an IAB, 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, improperly designed IABs should be cost effective by reducing future maintenance and repair costs as well.

Two different design concepts were developed to accommodate different site requirements. They 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 underlying soils is not an issue. It 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 resilient-EPS geofoam compressible inclusion is used between the abutment and MSE mass. This inclusion is designed to be 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 its reinforcement (from summer heat), and can be designed to serve as chimney drain which is necessary in any event. Functionally, this inclusion allows the reinforcement within the soil to strain in tension during the winter contraction of the IAB (which prevents the soil from slumping downward toward the abutment) as well as allows the abutments to move seasonally in either direction with minimal restraint. Summer increases in lateral earth pressures are reduced to relatively small magnitudes. Overall, lateral earth

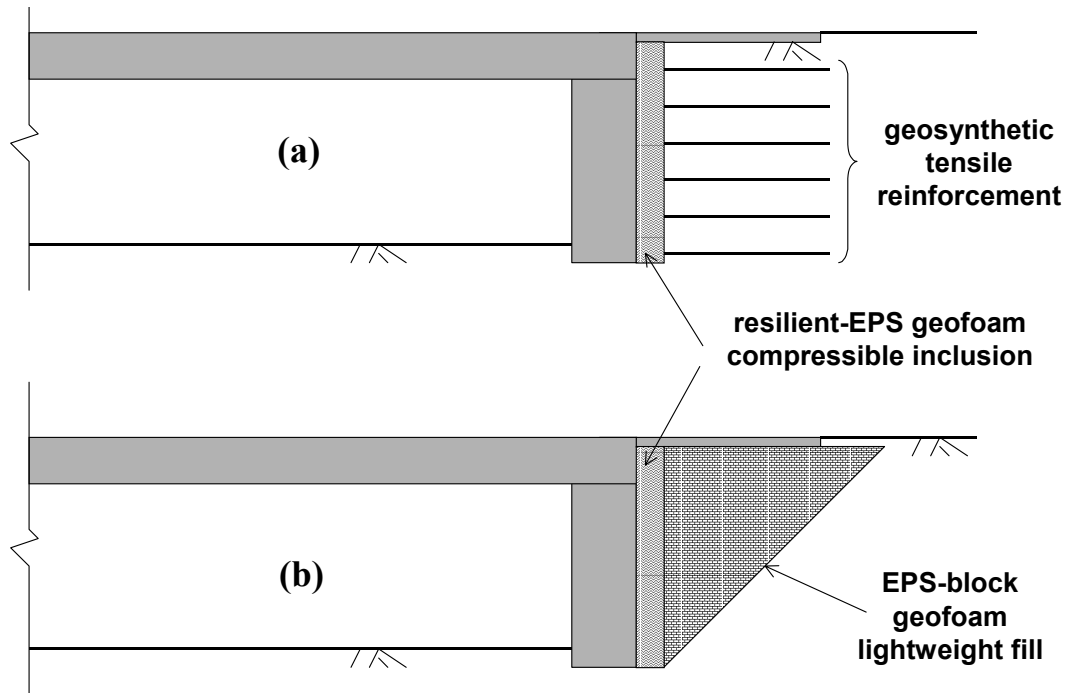


FIG. 5. Proposed New IAB Design Alternatives

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 geofoam (most likely EPS blocks but alternatively foamed PCC) is used in lieu of the MSE mass. A layer of highly compressible resilient-EPS geofoam is again used to function as an expansion joint/thermal insulation/chimney drain. This alternative is expected to be the one of choice for sites where the underlying soils are soft and compressible. The extraordinarily low density of EPS-block geofoam in particular (approximately 1% that of soil) would function as a lightweight fill to 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. The resulting savings would likely more than compensate for the use of a geofoam material in lieu of soil.

CONCLUSIONS

Integral-abutment bridges are an interesting example of how new problems of a geotechnical nature were inadvertently created in the process of solving chronic structural problems that are inherent in traditional bridge designs. These geotechnical problems consist of both seasonal and long-term buildup of lateral earth pressures on abutments and ground-surface settlement adjacent to the abutments. Either or both of these outcomes can result in serviceability or collapse failures of the bridge or its components and thus are serious.

The newly created geotechnical problems produced by IABs as currently designed turn out to be a complex problem in soil-structure interaction, and understanding all

aspects of the problem is crucial if a complete solution is to be developed. Research suggests that any successful solution to the problems surrounding IABs must address the need to both:

- more or less rigidly support the ground adjacent to the abutments on a permanent, year-'round basis and
- provide for a compressible inclusion between abutment and adjacent ground to serve as an engineered, in-ground replacement to the traditional expansion joint of traditional bridges.

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