Differential Movement at Embankment–Bridge Structure Interface in Illinois

James H. Long, Scott M. Olson, Timothy D. Stark, and Emile A. Samara

Settlement of roadway pavement surfaces near highway bridge abutments often leads to abrupt grade differences at the abutments. These grade differences subject vehicles to a bump, which may lead to driver discomfort and potentially unsafe driving conditions. Furthermore, differential movement requires costly and repeated maintenance work that usually impedes the flow of traffic. The sources of differential movement in Illinois can be divided into six major categories: (*a*) compression or erosion of materials at the approach embankment-abutment interface, (*b*) a broken approach slab, (*c*) compression of foundation soils, (*d*) compression or internal erosion of embankment soils, (*e*) poor construction grade control, and (*f*) areal distortion of foundation soils. An approach gradient equal to or greater than $1/100$ to $1/125$ appears to cause rider discomfort and therefore is proposed as a criterion for initiating remedial measures.

Even the casual observer is aware of the differential vertical movement that frequently occurs between roadway approach embankments and bridge structures. One of the first published studies on this problem was conducted for the Illinois Department of Transportation (IDOT) by Peck and Ireland (*1*). They illustrated the importance of backfill material and backfilling procedures on the differential movement at the embankment-bridge interface. Although this study was insightful, the problem of differential movement persists. Allen (*2*) concluded that bridge approach settlement is a widespread problem in the United States. Among other detrimental effects, differential movement results in excessive impact forces being applied to the structure and pavement, and discomfort and possible danger for the motorist. Repair of differential movement is expensive and time consuming. Stark et al. (*3*) presented results of a study with the main objectives of identifying the causes for differential settlement and developing design methods and effective maintenance and rehabilitation procedures to mitigate differential movement. This report summarizes some aspects of that study.

LITERATURE REVIEW

A comprehensive literature review (*1,2,4,5,6–25*) was conducted to determine the extent of differential movement problems in other states, the current knowledge of the causes of the differential settlement, and the current mitigation and rehabilitation techniques. Hopkins (*10*) surveyed 782 bridge approaches in Kentucky and found the following factors are possible causes of approach settlement: (*a*) settlement of the embankment or foundation soils due to shear distortion, (*b*) bearing capacity failure, (*c*) compression or consolidation (initial, primary, and secondary) of the embankment or foundation soils, (*d*) vibration and shock, (*e*) heave or swell, and (*f*) shrinkage caused by desiccation. Wahls (*22*) also discussed foundation conditions, approach embankment and abutment design and construction, approach slabs, special construction considerations, maintenance, and rehabilitation, as well as a few case histories highlighting innovative developments in the design and construction of bridge approaches. Wahls (*22*) attributed approach settlement to the following factors:

- Foundation compression (primary, secondary, and settlement caused by lateral creep);
- Embankment compression (primary, secondary, and lateral creep);
- Poor compaction near the abutment because of restricted access;
- Erosion of embankment soils at the abutment face;
- Improper drainage of the embankment and abutment backfill;
- Approach slab design; and
- Abutment and foundation type.

Wahls (*22*) suggested a tolerable relative rotation (differential movement divided by the length over which the settlement occurs) of $1/250$ for continuous-span bridges and $1/200$ for simply supported spans. Duncan and Tan (*7*) concluded that the recommendation for simply supported spans is too conservative and recommended a tolerable relative rotation of $1/250$. This criterion for simply supported spans was used to evaluate approach-slab performance during this study. Regarding differential settlement at the embankment-structure interface, Wahls (*22*) suggested that a differential settlement of 13 mm is likely to require maintenance.

Previous studies indicate that approach distress continues to be a pervasive and troublesome problem in most states. The primary causes of differential movement include foundation compression, embankment compression, erosion, and compression at or near the abutment. These settlements can result in structural movement and approach distress. Methods for mitigation include foundation improvement, increasing embankment stiffness, and proper drainage. Few options, such as pavement overlay and slab jacking, appear available for rehabilitation.

VISUAL SURVEY

The initial objective of the study was to assess the magnitude of the differential movement problem in Illinois. To accomplish this objective, a visual (drive-by) survey was conducted during the summer of 1994 on 1,181 bridge approaches throughout Illinois to evaluate the frequency of differential approach settlement. The route driven by the visual survey covered approximately 2,200 km. The following data usually were collected for each approach: location, type and condition of pavement, height and length of the approach embankment, type of crossing, and bridge length and condition. A subjective rating system was developed to assess the magnitude of

J. H. Long, S. M. Olson, and T. D. Stark, Department of Civil Engineering, University of Illinois, MC-250, Urbana, IL 61801. E. A. Samara, Bridge Planning Section, Illinois Department of Transportation, 2300 S. Dirkson Parkway, Springfield, IL 62764.

differential settlement at the embankment-structure interface for each approach. The magnitude of differential settlement assigned to each of the ratings was based on correlations with bridge approaches where settlement magnitudes were measured before and during the survey. The rating system is shown in Table 1.

Bridges rated 3 or 4 were more thoroughly inspected (when possible) with a walk-around survey, which included comments, illustrations, and photographs of the condition of the embankment, bridge, and approach pavements. The results of the visual survey were grouped and analyzed into four categories: all approaches, grade separation versus water crossing, approach entrance versus exit, and height of approach embankment.

Figure 1 displays the results of all of the approaches surveyed in the visual survey. Approximately 15 percent of the approaches surveyed exhibited no noticeable bump at either the embankment/structure interface or the pavement/approach slab interface. Approximately 58 percent of the approaches exhibited a slight differential movement, usually less than 25 mm. Therefore, approximately 73 percent exhibited satisfactory performance for differential movement at the approach-structure interface. The remaining 27 percent exhibited poorer performance, with approximately 4 percent exhibiting differential movements greater than or equal to approximately 75 mm (ratings 3 and 4). Thus, approximately 46 of the 1,181 approaches surveyed exhibited a differential movement greater than or equal to about 75 mm and thus required repair. Overall, approximately 85 percent of the bridges surveyed exhibited some differential movement (ratings 1, 2, 3, and 4).

The statistics from this visual survey provided a snapshot of current conditions in Illinois and, accordingly, the percentage of bridge approaches exhibiting movement was greater than indicated by the survey. For example, bridge approaches that experience significant settlement require frequent maintenance. If maintenance for a bridge approach were performed before the drive-by survey, the rating would be lower than if no maintenance had been performed. Therefore, greater than 85 percent of the bridges surveyed exhibited noticeable differential movements. The persistent problem of differential settlement indicates that the current combination of design, construction, and mitigation are inadequate to prevent differential settlement at the approach embankment-bridge structure interface.

Grade Separation Versus Water Crossing

A comparison between bridges that are grade separations (e.g., highway or railroad crossings) and those that are water crossings (e.g., creeks, rivers, or lakes) is shown in Figure 2. During the survey, 578 approaches were identified as grade separations and 494 approaches were identified as water crossings. The sum of these two totals does not equal 1,181 because the initial portion of the visual survey was conducted in the evening, when it was difficult to discern the type of crossing. Therefore, these bridges were excluded from the comparison.

TABLE 1 Subjective Ratings System for Differential Settlement

Qualitative Visual Rating	Approach/Bridge Interface Description	Approximate Differential Movement
0	No bump	~ 0 mm
1	Slight bump	~ 25 mm
2	Moderate bump — readily recognizable	~ 50 mm
3	Significant bump — requires repair	~ 75 mm
4	Large bump — safety hazard	> 75 mm

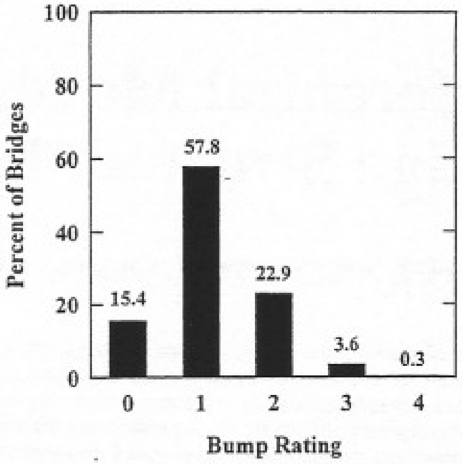

FIGURE 1 Ratings for all visual survey data, 1,181 approaches.

Previous investigations (*2,11,19*) suggested that water crossings usually are associated with larger differential settlements because of the compressible, saturated soils usually located near water crossings. Figure 2 fails to support this observation. The survey results indicated similar behavior for grade separations and water crossings, with a smaller percentage of water crossings showing readily recognizable differential movements. This probably was a result of the water crossings often being small creeks with minor embankments, but a large portion of the grade separations have approach embankments greater than 8 m in height.

Approach Entrance Versus Exit

Bridge approach entrances and exits are compared in Figure 3. IDOT districts report that differential movements are equally likely

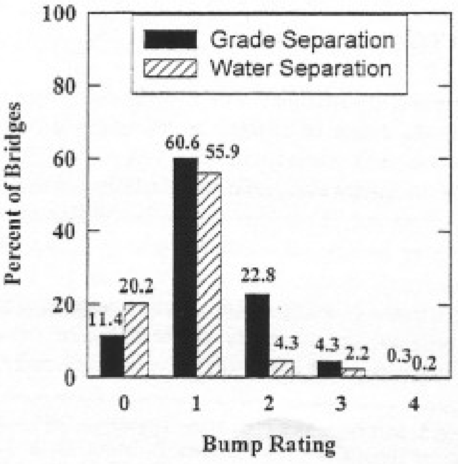

FIGURE 2 Effect of type of crossing on bump rating.

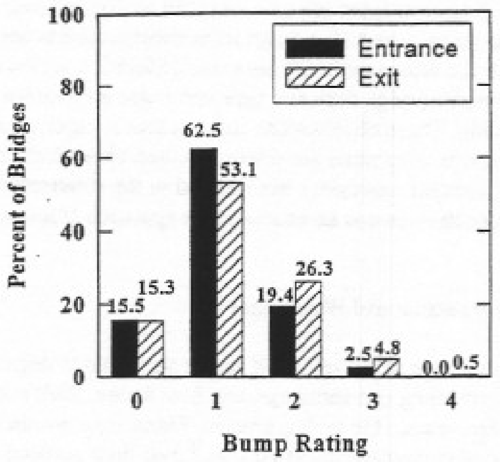

FIGURE 3 Entrance and exit approach comparison.

for entrances and exits; however, Figure 3 indicates that approach exits exhibit somewhat poorer behavior than entrances (ratings 2, 3, and 4). The difference may be caused by vehicles riding off the bridge structure, landing on the subsided exit slab, and generating an impact loading, or the differences simply may be a result of the limited number of observations.

Height of Embankment

Generally, more settlement is expected for higher embankments as a result of more compression within the embankment and the higher loads applied to the foundation materials. To investigate this hypothesis, embankments in the survey were separated into three categories: low embankments (generally ≤ 3 m high), medium embankments (between 3 and 8 m high), and high embankments (generally ≥8 m high). Of the 945 approaches categorized, 373 were categorized as low, 55 as medium, and 517 as high.

Figure 4 illustrates the effect of embankment height on approach differential settlement. Medium and high embankments display nearly identical behavior, which is only slightly worse than the approach embankment-structure interface behavior exhibited by low embankments. The only significant differences are for ratings of 0 and 3. Low embankments were given a rating of 0 more often than medium and high embankments. Low embankments also received a rating of 3 less often than medium and high embankments. In summary, these data suggest that higher embankments (greater than 8 m high) are more susceptible to differential movement at the approach-bridge interface than low embankments (less than 3 m high).

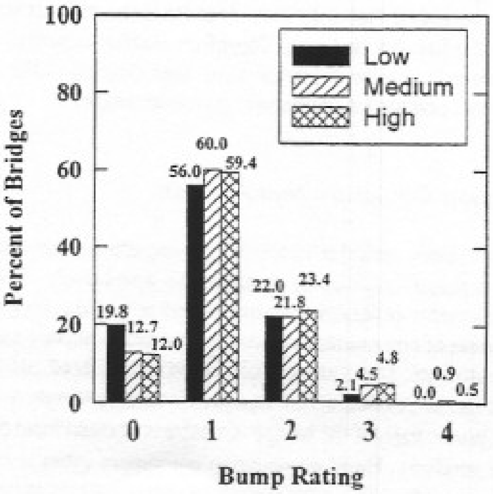

FIGURE 4 Effect of height of approach embankment on bump rating.

CAUSES OF DIFFERENTIAL MOVEMENT AT EMBANKMENT-STRUCTURE INTERFACE

Previous research and the investigations conducted during this study indicated that causes of differential movement are site-specific and there usually are several additive causes of differential movement at any one approach embankment–bridge structure interface. The additive or progressive nature of the causes leads to noticeable differential movement at the approach embankment–bridge interface. Likely causes of approach distress may be divided into three major categories: (*a*) differential settlement between the approach embankment and the bridge structure, (*b*) structural (bridge abutment, approach slab, approach pavement, or expansion joint) movement, and (*c*) design- and construction-related problems.

Differential Settlement

Differential settlement between the approach embankment and the bridge structure may be attributed to local or areal distortion of the foundation soils, compression of the approach embankment, or local compression and erosion near the approach pavement–bridge structure interface. Differential settlement generally is considered to be the most predominant cause of approach distress because of difficulties in compacting embankment fill near the abutment. All of the bridges extensively investigated as a part of this study showed signs of differential settlement at the approach embankment-bridge structure interface.

Local Compression of Foundation Soils

During and after the application of an embankment load, compression of foundation soils includes initial compression, primary consolidation, secondary compression, and lateral distortion and creep. The amount and time rate of foundation settlement can be estimated when sufficient soil characterization has been conducted (*26,27*).

An example of compression of foundation soils on an approach-bridge interface is the US Route 34 bridge over US Route 67 approximately 25 km east of Galesburg, Illinois. This bridge approach was identified as unacceptable according to the drive-by survey. This bridge was completed in 1992 and is a steel-span bridge structure that carries east-west traffic over US Route 67. The structure is 34 m long and has two spans. The abutments are supported by piles. Approximately 150 to 230 mm of settlement had occurred within 1.5 years after construction was completed. The eastern and western approaches required fills of approximately 7.5 m, which were constructed on a subsurface layer of peat. The problematic peat layer is located at a depth of approximately 12 m from the top of the embankment and thus could not be removed economically before construction.

To reduce differential settlements caused by primary consolidation of the peat layer, a surcharge was applied to the approach embankments. Unfortunately, the surcharge was removed prematurely. The embankment had settled 160 mm in 2.4 months when the surcharge was removed. At the time of surcharge removal, settlement measurements showed no sign of arresting.

The results of elevation surveys showed that the westbound entrance had experienced approximately 84 mm of differential movement at a distance of 9 m from the abutment (before a pavement overlay in 1994). This movement corresponds to an approach relative gradient of 0.009, or 1/110. The westbound exit experienced approximately 78 mm of differential movement at a distance of 9 m from the abutment (before the 1994 overlay). This corresponds to an approach relative gradient of 0.0086, or 1/116. Movements at entrance and exit formed a cradle of settlement that extended over 15 m from the bridge structure.

In summary, differential movement at this site was caused primarily by consolidation of a foundation peat layer. The large foundation settlement resulted in failure of the approach slabs. The 9 m approach slabs were inadequate because they did not span the observed cradle of approach settlement of approximately 15 m.

Lateral Distortion and Creep

Lateral distortion develops when the shear stress sustained by a foundation soil for long-term equilibrium is above the threshold shear stress of the soil. Lateral distortion of an embankment is more prevalent if high-plasticity soils, such as plastic clay shales, are used as borrow materials. No bridge surveyed during this study clearly indicated lateral distortion as a major factor leading to approach distress.

Areal Distortion of Foundation Soils

Areal distortion of foundation soil caused by mine subsidence, subsurface fluid removal, or other mechanisms can adversely influence the performance of the approach-bridge interface. An example of the effect of areal distortion of foundation soils on the approach-bridge interface is the Interstate 72 bridge located 6 km east of Springfield, Illinois. This bridge was completed in 1977 and is a dual steel box girder-span bridge structure that carries east-west traffic over the Sangamon River. The structures are 250 m in length and each has six spans. The eastern approaches required 7 m of fill and the western approaches required fills of 6 m. The bridge is supported by two seat abutments with wingwalls founded on deep foundations.

Maintenance work performed in 1992 included replacement of the expansion joints and removal and repaving the upper 40 mm of approach pavement for a length of 30 m from the abutments. Elevation surveys were conducted in 1993 and 1994. The 1993 survey measured 105 mm of differential settlement between the entrance abutment and approach slab over the first 9.1 m. This corresponds to a relative gradient of 1/86. Differential movement of 160 mm was measured along a 24-m survey line, resulting in a relative gradient of 1/150. By 1994, the eastbound entrance approach settled an additional 28 mm. Over the first 9.1 m of the approach slab, a differential settlement of 140 mm was measured that corresponds to a relative gradient of 1/65. Over 24.4 m, 190 mm of differential movement was measured, resulting in a relative gradient of 1/128. All these approaches were designated unacceptable in the drive-by survey.

The bridge and approach embankments are located over an abandoned deep mine and significant mine subsidence has been identified near the bridge by IDOT personnel. Elevation surveys showed that the entire bridge deck and approach slabs, all founded on piles, are settling. These observations indicate that a major cause of this movement is deep mine subsidence located beneath the structure. The differential movement has resulted in the structural failure of the approach slabs and an unacceptable approach gradient.

Soil Degradation and Weathering

Volume change of the soil itself can be attributed to degradation of the soil, swelling and shrinkage, and frost action. Soils such as clay shales are susceptible to degradation. These soils weather or slake because of environmental effects, and their finer portions are more susceptible to erosion and compression.

Some soils, such as expansive clays, may experience volume change during cycles of swelling and shrinking. Inclusion of such soils in an embankment can have a detrimental effect on the approach pavement.

Volumetric changes caused by frost action also can adversely affect approach pavements. The freezing of water that is not properly drained can produce large and nonuniform heave. The occurrence of frost action is more likely near bridge ends where a difference in thermal conditions exists. This cause could not be clearly linked to distress observed in the bridges investigated.

Hydrocompression Caused by Long-Term Inundation

Wetting-induced compression, or hydrocompression, is defined as the densification of a soil caused by the addition of water at constant total vertical stress (*28–31*, ASTM STP892). Wetting also can cause swell or settlement depending on the compaction conditions, soil type, and magnitude of total vertical stress. Oedometer tests on compacted soil specimens can be used to develop a relationship between axial strain and total vertical stress for various embankment heights. This relationship can be used to estimate the magnitude of hydrocompression and hydroexpansion of the embankment material caused by water infiltration. On the basis of observations of water ponding on embankments after rainfall, it is anticipated that the water content of embankments does increase, at least temporarily, during the life of a structure. Therefore, mechanisms that contribute to hydrocompression are present (to some degree) in Illinois, but no study was conducted to quantify its contribution.

Inadequate Compaction Near Abutment

Several states consider inadequate compaction near the abutment to be a major contributor to approach distress (*2*). The approach embankments generally are constructed before the bridge structure. A volume of embankment then is excavated to allow construction of the abutments. The abutment cone then is backfilled and compacted. However, large compaction equipment cannot operate near the abutment, particularly if the bridge structure is skewed from the mainline of the roadway. Hand-compaction equipment often is employed to compact the backfill in the restricted area, resulting in inadequate or nonuniform compaction. Illinois employs an uncompacted granular backfill in the abutment cone to reduce these problems.

Drainage and Erosion Problems

Drainage is a major concern for maintaining satisfactory performance of approach pavements. Water from the bridge deck, surface drainage, or from subsurface flow should be prevented from entering the approach embankment. Poor drainage in basecourses and upper embankment layers can lead to erosion and piping of fines, which can undermine support for approach slabs and abutments. Poor drainage can also lead to freeze-thaw volume changes, swelling or collapse volume changes in certain soils, and can apply excessive pressures to abutment backwalls.

The US 20 bridge near Rockford, Illinois, illustrates the effect of drainage and erosion problems on a bridge approach. This bridge is a dual-span steel bridge structure over Stone Quarry Road and a railroad crossing. The westbound and eastbound structures are 85 m and 88 m long, respectively, and each have six spans. During the visual survey, the westbound lane of the bridge was rated as 3 (significant bump—requires repair) at both the entrance and exit approaches.

The eastern approaches required fills approximately 7 m high, and the western approaches required approximately 9 m of fill. A visual inspection of the bridge structures revealed that extensive erosion was occurring at the slope faces of all of the approaches. As shown in Figure 5, the runoff drains directly onto the concrete slope facing. The practice of draining the bridge deck onto the concrete slope facing is common; however, it can been seen that in this case the runoff falls directly onto a construction joint in the slope facing. The runoff probably infiltrated below the slope facing and eroded the embankment material as it flowed downslope. This erosion led to a loss of support under the slope facing and additional damage to the facing.

Erosion also was occurring because of water infiltrating the embankment from joints in the overlying pavement. This is referred to as a roof leakage. Water infiltrates through pavement joints, joints between the shoulder and pavement, and bridge-pavement joints. Infiltrated water can flow around the abutment and underneath the slope facing (Figure 6). The soil is eroded through joints in the concrete slope facing, at the toe of the slope facing, and the remedial riprap. Interviews with IDOT field crews revealed that at this site it was necessary to remove eroded material at the foot of the slopes several times a year, and several repairs have been made to the slope facing.

FIGURE 5 Damage to slope facing causing significant erosion of embankment soil.

Volume and Weight of Traffic

Excessive traffic loads (overloads) can result in pavement distress. It is not uncommon for overloads to occur, which can lead to structural distress, such as cracked approach slabs. Problems caused by traffic can occur when traffic volume or weight exceed original design service loading.

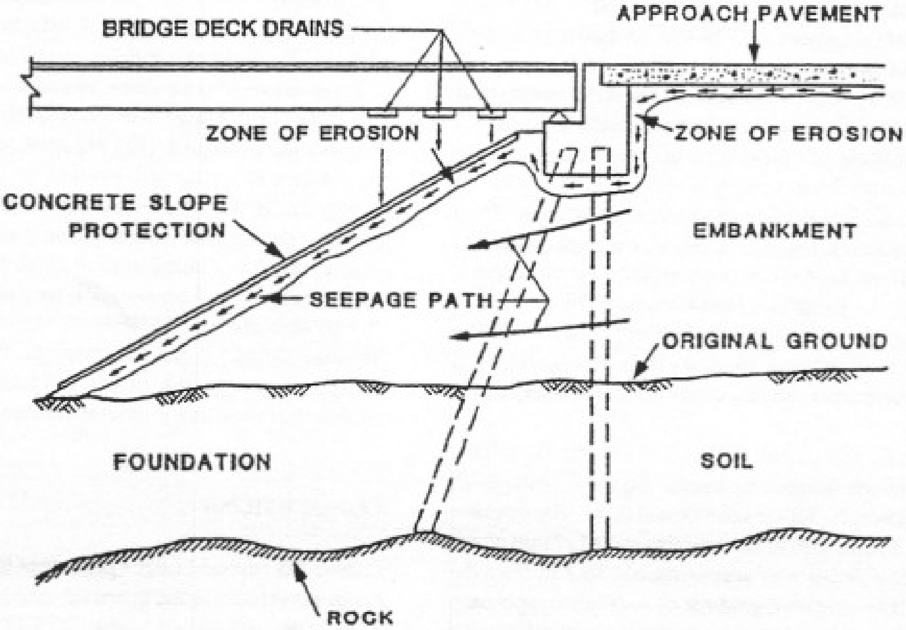

FIGURE 6 Schematic of embankment erosion and seepage leading to loss of support beneath abutment and slope facing [modified from (*24*)].

Structural Movement

The movement of abutments, approach slabs, approach and bridge deck pavements, and expansion joints can lead to differential movement at the approach embankment-bridge structure interface.

Movement of Abutment

Vertical movement, horizontal movement, and tilting of abutments can cause significant approach distress. Vertical movement of abutments can be caused by settlement of soils that support the abutment, downdrag on deep foundation elements, loss of abutment support caused by embankment erosion beneath and around the abutment, or areal distortion. Horizontal movement of abutments can be caused by excessive lateral pressure due to water pressure or compaction, thrust forces from the bridge deck or approach pavement induced by thermal forces, swelling pressure of embankment soil, or lateral distortion of embankment or foundation soils. Furthermore, abutment movement can lead to other approach problems, such as closing or opening of expansion joints. Many bridges thoroughly investigated during this study exhibited abutment tilting and cracking.

Movement of Approach Slabs

The movement or breakage of approach slabs is a significant cause of differential movement between the approach and the bridge structure in Illinois. The most prevalent type of slab movement is the cracking and breakage of the approach slab at the juncture between heavy and lightly reinforced concrete. A crack in an approach slab usually leads to a gradient-type bump at the approach. Other types of possible slab movement (although less common in Illinois) include movement at the abutment paving notch or excessive movement at the approach sleeper slab.

An example of the effect of approach slab cracking and breakage on the approach-bridge interface is the Interstate 39 bridge over the Soo Line railroad, located approximately 12 km south of Rockford, Illinois. The bridge was completed in 1979 and is a dual precast, prestressed concrete I-beam-span structure that carries two-way traffic over the Soo Line railroad. Both structures are about 50 m long and have two piers. Both the northern and southern embankments required fill heights of approximately 11 m above the original ground surface.

The approach slabs are 30 m in length, with only the first 9 m being heavily reinforced. Beyond 9 m, the approach slabs taper from 370 to 230 mm in thickness. Inspection of the approach pavement revealed cracks at about 7.5 to 9 m from each of the abutments, which corresponds to the location of the transition from heavy to light steel reinforcement. Two large cracks were observed in the pavement at distances of 30 and 36 m north of the southbound bridge entrance. These cracks roughly correspond to the end of the 30 m approach slabs.

Elevation surveys for the southbound and the northbound lanes extended 150 m from the bridge abutments. Figure 7 presents an expanded scale elevation plot for the southbound lanes. The entrance approach (left side of Figure 7) exhibits a maximum of 117 mm of differential settlement at a distance of approximately 10.7 m from the abutment. This results in a relative gradient of $^{1}/_{91}$. The exit approach (right side of Figure 7) exhibits a maximum of 94 mm of differential settlement at a distance of 9.5 m from the abutment. This corresponds to a relative gradient of $^{1}/_{100}$. A relative gradient criterion may be applicable for assessing ride quality and therefore useful for determining repair and overlay needs.

Problems in Design and Construction

Approach distress can result from problems or errors in the design and construction of bridge approach embankments and structures. The problems or errors can be the result of the engineer's specifications or design. Distress also can be caused by the contractor exercising poor construction control, or overexcavating for the abutment. Finally, it is the role of the inspector to ensure proper construction procedures are being followed and proper materials are being used. Ensuring inspectors are properly trained and staffed can have significant impact on minimizing differential settlement caused by construction.

Engineer-Related Problems

The engineer is responsible for modifying standard design procedures and specifications to suit site-specific situations. The engineer must specify structural components, materials, and compaction properties that produce long-term satisfactory performance of both the approach embankment and the bridge structure. For example, the location of bridge deck and embankment drainage systems may have to be modified to minimize damage to concrete slope facings. At the approach embankment-bridge structure interface, the engineer must specify a foundation system that is adequate to support the applied loads and an approach slab that will be structurally sound for the life of the bridge.

Poor Construction Grade Control

Proper construction grade control is essential to avoid a bump at the embankment-structure interface before traffic is allowed access to the roadway. The approach pavements, when constructed, must coincide with profile elevations specified in construction plans. In addition, the vertical curve design should be satisfied.

An example of poor grade control on the approach-bridge interface is the US 20 bridge over Stone Quarry Road. Although approach overlays were completed in 1992, distinct changes in elevation along the westbound profile still resulted in a bump for the motorist. A comparison of the existing profiles and the original profiles indicated that the repaving effort reestablished the vertical curve along the eastbound profile but failed to reestablish the vertical curve along the westbound profile. Therefore, it is recommended that pavement overlays for remediation of differential movement be designed to reestablish the original vertical curve design. This can be accomplished by performing an elevation survey and determining the location and the thickness of the overlay required before repair.

CONCLUSIONS

Illinois has several bridge approaches that exhibit distress or differential movement at the approach embankment-bridge interface. In 1994, a visual (drive-by) survey of 1,181 approaches in Illinois indicated more than 27 percent of these approaches exhibit a significant bump (differential movement) at the approach embankment–bridge

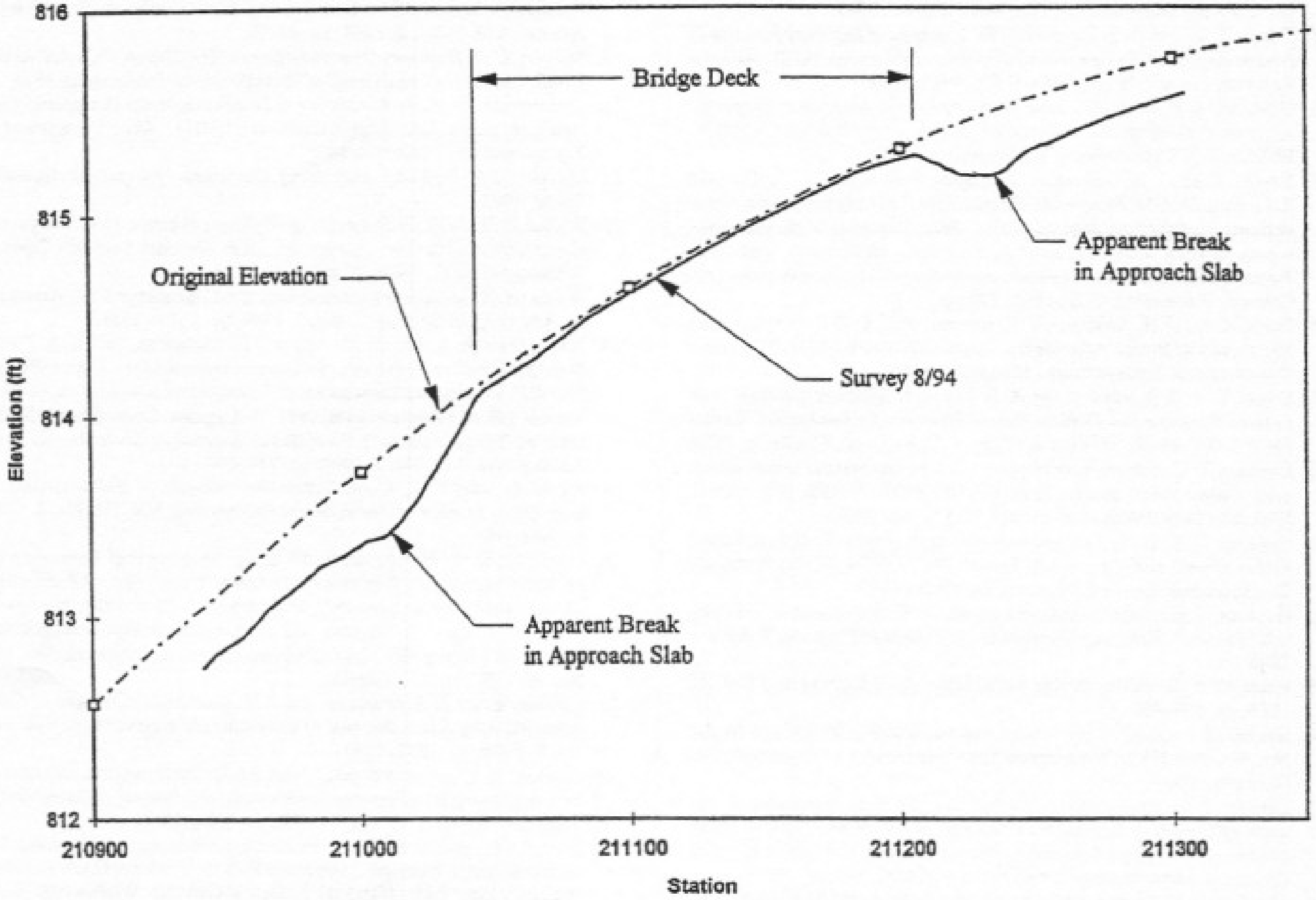

FIGURE 7 **Effect of broken approach slab on entrance and exit elevation survey.**

interface. This differential movement leads to various degrees of rider discomfort. Adjacent states (Iowa, Wisconsin, Michigan, Ohio, Indiana, Missouri, and Kentucky) exhibit a similar percentage of approach embankment–bridge distress. Differential movement in Illinois can be divided into six major causes: (*a*) local compression or erosion of materials at the approach embankment–abutment interface, (*b*) a broken approach slab, (*c*) compression of foundation soils, (*d*) compression or internal erosion of embankment soils, (*e*) poor construction grade control, and (*f*) areal distortion of foundation soils caused by mine subsidence or other areal mechanisms.

A visual survey revealed that differential movement or rider discomfort can occur at different locations depending on the approach-abutment geometry and the cause of the differential movement. In Illinois, the differential movement generally occurs at the approach embankment–abutment interface, the end of the approach slab, or at a break or crack in the approach slab, which usually occurs at the transition from heavy steel reinforcement to less reinforcement. Significant rider discomfort usually is felt with a settlement of greater than or equal to 50 to 75 mm. However, it was found that most approach distress and rider discomfort was manifested in an approach-relative gradient. The approach-relative gradient is defined as the differential settlement divided by the length over which the settlement occurs. This led to the development of the following criteria for the design and remediation of differential movement at the approach embankment–bridge interface. For new construction, an approach-relative gradient of less than $^1/_{200}$ (*23*) should be satisfied to ensure rider comfort. The criterion for initiating remedial measures—significant rider discomfort—is an approach gradient of greater than or equal to $^1/_{100}$ to $^1/_{125}$. The approach gradient can be estimated easily from an elevation survey of the approach that extends at least 60 m from the bridge.

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