Simple Design Alternatives to Improve Drainage and Reduce Erosion at Bridge Abutments

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ABSTRACT

Bridge approach settlement and the formation of the bump at the end of the bridge is a common problem that draws upon considerable resources for maintenance. Recently, a field and laboratory investigation was carried out to investigate bridge approach performance problems identified by Iowa DOT personnel. Field inspections of seventy-four existing and under construction bridges in Iowa revealed that inadequate drainage, wetting, induced soil collapse, and erosion are among the primary factors contributing to the approach slab performance problem. By characterizing backfill materials used behind bridge abutments, it was found that the specified granular backfill gradation is within the range of most erodible soils and is susceptible to increased compaction resistance due to the moisture bulking phenomenon. In addition, it was determined that a large portion of granular backfill particles are smaller than the perforation size in commonly used subdrain tile. To eliminate these problems, alternative backfill materials and drainage systems were evaluated in the laboratory using the newly developed scaled Bridge Approach Drainage Model (BADM). Using the BADM, measurements of void size, approach slab settlement, and drainage capacity were determined for thirteen different drainage/backfill designs. The results indicate that drainage performance can be greatly improved with the use of porous backfill, granulated tire chips, or geocomposite drainage systems. This paper presents a summary of the field investigation and simple design recommendations that can be implemented immediately to minimize problems associated with poor drainage, erosion, and void development at bridge approaches.

Key words: backfill—bridge abutments—bridge approach—drainage—erosion

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INTRODUCTION

Bridge approach settlement is a major problem that has gained national attention in recent years. In 1997, an NCHRP Synthesis Report *Settlement of Bridge Approaches (the bump at the end of the bridge)* (Briaud et al. 1997) showed that 25% of bridges nationwide suffered from bridge approach settlement problems with an annual maintenance cost of $100 million. According to a survey conducted by Laguros et al. (1990) of 61 different transportation agencies, bridge approach settlement is considered a “significant” problem in 70% of the agencies. Hoppe (1999) also reported that 44% of the state DOTs classify bridge approach settlement as a “major” problem. Seasonal temperature change, loss of fill material by erosion, poor construction practices, settlement of foundation soil, and high traffic levels are some of the reported major contributors to bridge approach settlement (Briaud et al. 1997).

In 2002, Iowa DOT personnel developed a research plan to investigate causes of bridge approach settlement specific to Iowa bridge designs and soil conditions. Results of this research study are reported in White et al. (2005). The research report includes (1) a detailed literature review with documentation of design, construction, and maintenance practices used by several state DOTs; (2) field inspection observations and documentation of existing bridge approach problems and construction problems; (3) characterization of the bridge approach pavement problems using elevation profiles and International Roughness Index (IRI) measurements; (4) characterization of backfill materials used behind bridge abutments with emphasis on compaction and erosion properties; and (5) analytical structural investigations on potential failure of the paving notch region and approach slab.

During field inspections, it was determined that two major causes of bridge approach settlement in Iowa are (1) poor surface and subsurface drainage and (2) erosion of the embankment and backfill materials, which form the focus of this paper. In addition to approach slab pavement problems, poor drainage and erosion lead to exposure of steel H-piles and void formation under concrete slope protection below the bridge. Poor drainage and severe soil erosion were observed at about 40% of the bridges inspected (White et al. 2005). At almost all bridges, however, some evidence of erosion was observed. These findings led to development of the Bridge Approach Drainage Model (BADM) system, which is a one-fourth scaled model of a bridge approach section that allows for the laboratory evaluation of various drainage tile, geosythetics, and backfill materials subject to controlled water infiltration conditions. Using the BADM system, measurements of void size, approach slab settlement, and drainage capacity of various design details were made and compared for optimization. The results of the BADM testing are described herein with newly proposed design details that can be implemented immediately to minimize problems associated with poor drainage, erosion, and void development at bridge approaches. Before presenting the results of the BADM tests, a brief review of backfill material specifications, compaction requirements, and drainage details documented in literature is provided. Complete details of this study can also be found at http://www.ctre.iastate.edu/research/detail.cfm?projectID=545.

Backfill Materials

Ideal properties of backfill material include high compactability, no time dependent properties (e.g., consolidation), resistance to erosion, and elastic behavior. Backfill materials typically used behind bridge abutments are selected granular materials with some fines. FHWA (2000) recommends the use of backfill materials with less than 15% passing the No. 200 sieve. Wahls (1990) recommended the use of materials with a plasticity index (PI) less than 15%, percent of fines less than 5%, and compaction ranging from 95% of ASSHTO T-99 to 100% of ASSHTO T-180. Furthermore, Wahls (1990) reported that well-graded materials with less than 5% passing the No. 200 sieve provide for compaction with small vibratory compactors. CalTrans specifies a PI less than or equal to 15% and a relative compaction of 95% or more. Hoppe (1999) reported that 59% of the DOTs that responded to a survey limit the percent of soil passing the No. 200 sieve between 4% and 20%, with the fill placed and compacted in 150 to 200 mm lifts. However, about 50% of DOTs reportedly had difficulty obtaining the specified degree of compaction in the proximity of the bridge abutment because of compaction equipment space limitations. Iowa DOT currently specifies 20% to 100% passing the No. 8 sieve and 0% to 10% passing the No. 200 sieve for granular backfill. For compaction control, the majority of state DOTs require AASHTO T-99 as the reference laboratory compaction method (similar to Iowa DOT Laboratory Test Method 103). No moisture limits are specified for granular backfill according to Iowa DOT specifications.

Drainage Systems

Water that infiltrates down between the abutment and the bridge approach pavement or flows around the bridge can erode the backfill if not drained properly. According to Briaud et al. (1997), both surface and subsurface drainage need to be considered. An important design element is that surface runoff should be directed away from the bridge joints, slope protection, and abutment area.

A review of several drainage designs implemented by other state DOTs was carried out for comparison to practices in Iowa. The review shows that there are three main variations of subsurface drainage systems: (1) granular backfill with some porous backfill around a perforated drainage pipe, which is the current Iowa DOT design detail (see Figure 1); (2) adding a geotextile fabric around the porous fill and drain tile; and (3) using various vertical geocomposite drainage systems along the abutment face. Wrapping the porous fill with geotextiles helps reduce erosion and fines infiltration, while vertical geocomposite drains provide a pathway for water to reach the drain tile. Some states combine two or more of these details to increase the drainage efficiency.

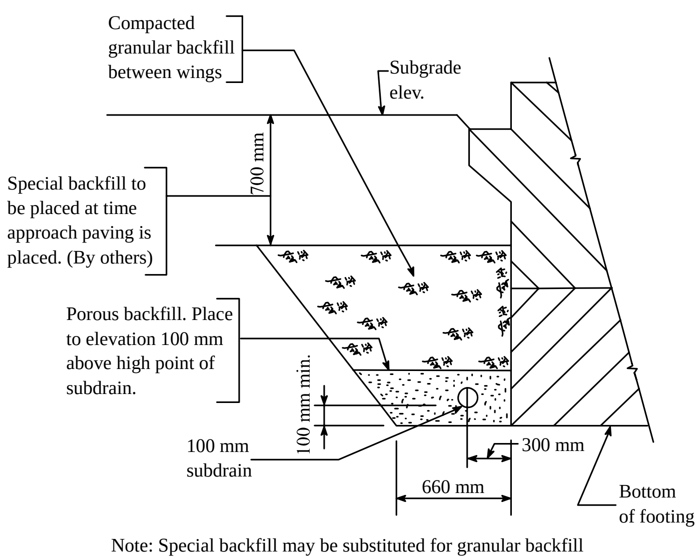

Figure 1. Typical Iowa DOT subdrain design (Iowa DOT Bridge Standards 2005)

FIELD RECONNAISSANCE

Bridge investigations were carried out in all six Iowa districts to document various problems reported by Iowa DOT personnel at bridge approaches. In total, sixty-six existing and eight under construction bridges were investigated. Evidence of inadequate drainage and soil erosion were observed more frequently than any other bridge approach problem. Therefore, it is believed that improving drainage and reducing erosion will greatly improve bridge approach performance. Additional problems observed included poor paving notch construction, poor backfill compaction and moisture control, and differential settlement between the bridge and embankment (fill and foundation) (White et al. 2005).

Drainage System

Inadequate drainage and severe erosion problems were observed at approximately 40% of the inspected bridges. Through visual assessment, it was determined that drainage and water infiltration problems occur due to ineffective subdrains and end drains, poor granular backfill characteristics (i.e., low permeability and poor compaction), and unsealed expansion joints.

Subsurface Drainage Tiles

At all bridge sites investigated, visual observations were made as to the conditions of the subdrain tile. The inspections showed that many subdrains were completely dry, partially collapsed, or plugged with soil and debris (see Figure 2). In addition to visual observations, the subdrains of six bridge sites were inspected using a special Iowa DOT forensic camera ("snake" camera) that is inserted through the subdrain outlet using a special cable and camera head. The inspections using this procedure confirmed earlier visual inspections of collapsed and plugged subdrains.

Monitoring new bridges under construction also revealed that out of eight bridges, only two bridges had the proper porous backfill material around the perforated subdrain (see Figure 1). Other bridges used granular backfill directly around the subdrain, which is believed to contribute to plugging of the drain tile. Determining the grain-size distribution for six granular samples collected at six bridge sites and comparing them to the average opening sizes of the perforated subdrains revealed that, on average, about 70% of the granular backfill gradation is finer than the average openings of the perforated subdrain (about 2 mm). On the other hand, porous backfill with no particles smaller than the No. 8 sieve has virtually no material finer than the openings of the perforated subdrain.

Figure 2. Example of a blocked subdrain outlet (Bridge No. 9266.2R218, District 5)

Expansion Joints and Surface Water

Unsealed expansion joints inhibit proper surface drainage by allowing water infiltration through the joint and down into the bridge approach backfill (see Figure 3). The majority of expansion joints observed were not sealed sufficiently to prevent water infiltration. Iowa DOT uses flexible foam filler, which is a common joint filler type, but recently, recycled tire chips are increasingly being used over flexible foam. Both types of joint filler however do not completely seal the expansion joint. Currently, Iowa DOT practices do not intend for the expansion joints to be sealed. This is primarily due to a lack of identifying a suitable joint sealing system capable of withstanding the harsh environmental conditions in Iowa.

In addition to unsealed expansion joints, ineffectiveness of redirecting surface runoff and infiltrated water away from the bridge can also contribute to erosion and ponding water in the pavement shoulders and erosion of the slope protection from the embankment under the bridge.

(a) Deteriorated joint filler (Bridge No. 2034.20035, District 5)

(b) Missing joint filler (Bridge No. 9265.7L218, District 5)

Figure 3. Typical unsealed expansion joints

Soil Erosion

Erosion of soil under the approach slab, at the shoulders, at the embankment under the bridge, and along the abutment sides are all forms of erosion observed during field inspections (see Figure 4). If not mitigated, soil erosion can lead to other problems, such as exposure of steel H-piles, undermining of abutment, faulting of pavement, or failure of the slope protection cover under the bridge.

Besides the inability to redirect surface runoff, soil erosion under approach slabs is also attributed to the use of erodible backfill materials. Briaud et al. (1997) provided a range of most erodible soils and reported that soils with silt and fine sand are more erodible than other types. The erodible range of soils was compared to the Iowa DOT gradation requirement for granular backfill and the grain-size distribution obtained for four different granular backfill samples collected at new bridge sites. It was found that the Iowa DOT gradation requirement and the gradations from the field samples have a common region with the range of most erodible soils. This is primarily attributed to the wide range allowed to pass the No. 8

sieve. Currently, Iowa DOT specifies 20% to 100% passing the No. 8 sieve. Limiting the percentage passing the No. 8 sieve to 60% would shift the grain-size distribution away from the range of most erodible soils.

(a) Bridge No. 9703.40020, District 3 **(b) Bridge No. 7871.5L/R029, District 4**

Figure 4. Erosion (a) at an embankment under the bridge and (b) under a slope protection

Wetting-induced soil collapse is another important factor that increases the likelihood of soil erosion. Upon saturation, granular soil can collapse creating a void and, thus, a water path, which facilitates additional soil erosion and progressive approach slab settlement (see Figure 5). Laboratory testing was conducted to measure the Collapse Index (CI), which is the change in the sample height upon saturation relative to its original height, for the granular and porous backfill materials used behind bridge abutments in Iowa. The highest CI measured for granular material was 6% when placed at the bulking moisture content range (3% to 7%), while porous material did not collapse at any moisture content (0% to 12%). Most of the field moisture contents measured at new bridge sites were within the bulking moisture content range making the backfill susceptible to collapse upon saturation. For a fill height of 3.0 m, a typical granular material would be expected to settle about 18 cm.

(a) Bridge No. 7779.0065, District 1 **(b) Bridge No. 9703.40020, District 3**

Figure 5. Void formation under the approach slab

BRIDGE APPROACH DRAINAGE MODEL (BADM)

Due to the high frequency of drainage problems observed in the field, a one-fourth scaled bridge approach model was constructed in the laboratory to evaluate the following:

- The current Iowa DOT drainage and backfill specifications
- The current drainage and backfill field practice
- Various backfill and drainage alternatives based on previous related research and practices of other states

The BADM system consists of an approach slab, abutment, backfill, and a drainage pipe. The model is scaled to about one-fourth of the original dimensions, except for the drainage pipe and soil which are full-scale. The model is 74 cm high, 58 cm wide and 81 cm long. Plexiglas is used to retain the backfill material inside. A perforated HDPE pipe with a 10 cm diameter similar to the subdrain used in the field is installed behind the abutment.

Water is forced to flow through a 2.5 cm expansion joint at the approach slab/abutment interface, through the drainage system, and out of the subdrain. The water is then collected in a collector and pumped back into the model via a submerged water pump (see Figure 6). To disperse the water before flowing into the expansion joint, a perforated Plexiglas tank is placed on top of the expansion joint. The inlet flow is altered until a maximum steady state flow condition is achieved. Once steady state flow is reached, the flow rate is fixed until the end of the test.

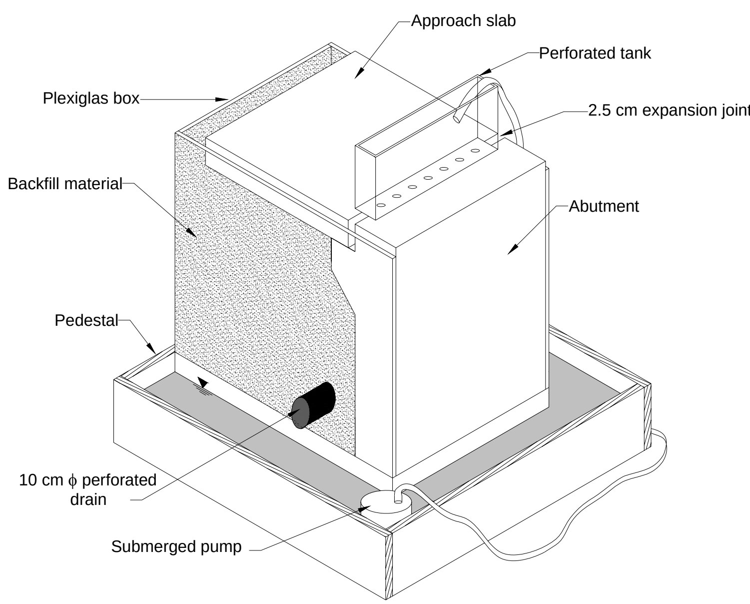

Figure 6. Schematic of Bridge Approach Drainage Model (BADM) system

To compare different drainage details, each test was allowed to run for four hours in a steady state condition. Settlement at the end of the approach slab, void development, and maximum steady state flow rate were recorded for each experiment. Settlement was calculated by measuring the difference between the approach slab elevation before and after the test. In addition, the time needed for water to flow out of the drain was noted.

Thirteen different models using granular and porous backfill materials with geocomposite drains, tire chips, and geotextile reinforcement were tested. A summary of the results is presented in Table 1. The most poorly performing model (producing minimum flow, maximum void, and maximum differential settlement) was the model simulating current practices observed in the field (No. 3 in Table 1), whereby granular backfill materials were poorly compacted at the bulking moisture content with no porous backfill around the drainage pipe.

The current Iowa DOT design also performed poorly when the granular backfill material was placed within the bulking moisture content range. A settlement of 5.1 cm, a void of 11.4 cm, and a maximum steady state flow of 32 cm^3/sec were measured (No. 1 in Table 1). The maximum steady state flow measured was considered low compared to values measured from other tests. By placing the granular backfill material at higher moisture contents (w = 12.6%) (No. 2 in Table 1), settlement and void formation were eliminated, but the maximum steady state flow remained low.

Table 1. Summary of BADM test results

Description	**Settlement (cm)**	**Void (cm)**	**Maximum flow rate (cm^3/sec)**	**Time for water to drain (min)**	**Erodible Backfill (yes/no)**	**Collapse Susceptible Backfill (yes/no)**
1. Iowa DOT design, granular backfill with average moisture content = 3.0% (bulking)	5.1	11.4	32	10	yes	yes
2. Iowa DOT design, granular backfill with average moisture content = 12.6% (non-bulking)	None	None	31	12	yes	no
3. Field practice-1, granular backfill with average moisture content = 3.0% (bulking) (without porous fill around subdrain)	5.7	10.2	33.5	10	yes	yes
4. Field practice-2, granular backfill with average moisture content = 5.5% (bulking) (with porous fill around subdrain)	5.7	5.1	67	11	yes	yes
5. Geotextile (CONTECH C-60NW non-woven fabric) around porous backfill, granular backfill with average moisture content = 4.8% (bulking)	5.1	6.4	82	10	yes	yes
6. Geotextile (CONTECH C-60NW non-woven fabric) around porous backfill and reinforcing geotextile (CONTECH C-80NW non-woven fabric) for granular backfill with average moisture content = 5.2% (bulking)	2.5	4.4	63	7	yes	yes

Table 1. (*continued*)

Description	Settlement (cm)	Void (cm)	Maximum flow rate (cm^3/sec)	Time for water to drain (min)	Erodible Backfill (yes/no)	Collapse Susceptible Backfill (yes/no)
7. Geocomposite vertical drain (Tenax Ultra-Vera™) and reinforcing geotextile (CONTECH C-80NW non-woven fabric) for granular backfill with average moisture content = 4.2% (bulking)	5.4	12.7	222	4	yes	yes
8. Geocomposite vertical drain (STRIPDRAIN 75) and reinforcing geotextile (CONTECH C-80NW non-woven fabric) for granular backfill with average moisture content = 3.7% (bulking)	6.4	3.8	383	1	yes	yes
9. Geocomposite vertical drain (STRIPDRAIN 75) and reinforcing geotextile (CONTECH C-80NW non-woven fabric) for granular backfill with average moisture content = 12.0% (non-bulking)	None	None	383	1	yes	no
10. Tire chips (18 cm thick) behind the abutment, geofoam vertical separator (2.5 cm thick) and granular backfill with average moisture content = 3.9% (bulking)	4.8	5.1	552	1	Tire chips – no Granular Backfill - yes	Tire chips – no Granular Backfill - yes
11. Tire chips (18 cm thick) behind the abutment, geofoam vertical separator (2.5 cm thick) and reinforcing geotextile (CONTECH C-80NW non-woven fabric) for granular backfill with average moisture content = 4.0% (bulking)	3.2	None	554	1	Tire chips – no Granular Backfill - yes	Tire chips – no Granular Backfill - yes
12. Tire chips (18 cm thick) behind the abutment, geofoam vertical separator (2.5 cm thick) and reinforcing geotextile (CONTECH C-80NW non-woven fabric) for granular backfill with average moisture content = 12.0% (non-bulking)	None	None	552	1	Tire chips – no Granular Backfill - yes	no
13. Porous backfill with average moisture content = 4.6% (non-bulking)	None	None	92	4	no	no

Three drainage details performed much better than the other tests. These details are (1) using a geocomposite drain with backfill reinforcement and moisture content above bulking (No. 9 in Table 1); (2) using tire chips behind the bridge abutment (No. 12 in Table 1); and (3) using porous backfill material (No. 13 in Table 1).

For the geocomposite drain with backfill reinforcement (No. 9 in Table 1), the drainage detail consisted of a vertical geocomposite drain which was 1.9 cm thick HDPE polymer (see Figure 7). The geocomposite drain was laminated with a non-woven, needle-punched geotextile. Granular backfill material was placed at a 12% moisture content and compacted every 5 cm lifts to an average relative density of about 65%. Geotextiles were used as backfill reinforcement. The first reinforcement layer was placed on top of 7.6 cm of granular backfill lift at the bottom of the model. Additional geotextile layers were placed every 13 cm. At the abutment face, the geotextiles were folded and embedded under the overlying reinforcement. The length of the embedded geotextile was approximately 13 cm. After four hours of running the test, no void or settlement developed, and the maximum steady state flow measured was 383 cm^3/sec, which is approximately 12 times higher than the value measured using the specified Iowa DOT drainage detail (Nos. 1-3 in Table 1).

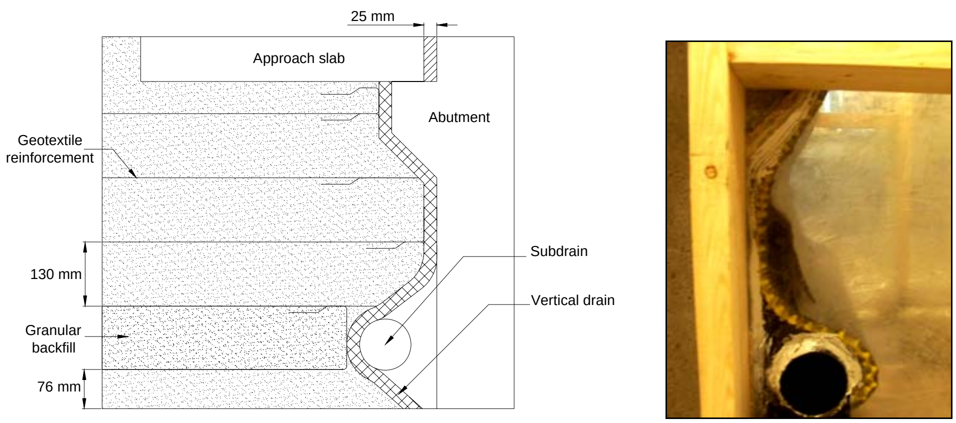

Figure 7. Using geosynthetic vertical drain at the face of the abutment with soil reinforcement

Similar to drainage detail No. 9, No. 12 (see Table 1), which uses tire chips behind the bridge abutment, showed good performance. The purpose of test No. 12 was to evaluate the use of tire chips as a drainage material, as well as its effectiveness in alleviating settlement and void development. Tire chips were placed behind the abutment without compaction over an 18 cm wide zone. For a separation barrier, a 2.5 cm thick foam board was placed between the tire chips and the granular backfill (see Figure 8). Granular backfill material was placed at a moisture content of 12%, and compacted in 5 cm lifts. An average relative density of about 70% was achieved. After four hours of running the test, the use of tire chips combined with saturated granular backfill eliminated settlement and void formation. The maximum steady state flow measured was 552 cm^3/sec, which is 43% higher than the drainage detail No. 9 and 17 times higher than drainage details Nos. 1 through 3. Although 30% of the tire chips were smaller than the drainage pipe openings, none of the tire chips were washed out. Even though this drainage detail No. 12 resulted in the highest flow capacity, this detail may require more complex construction.

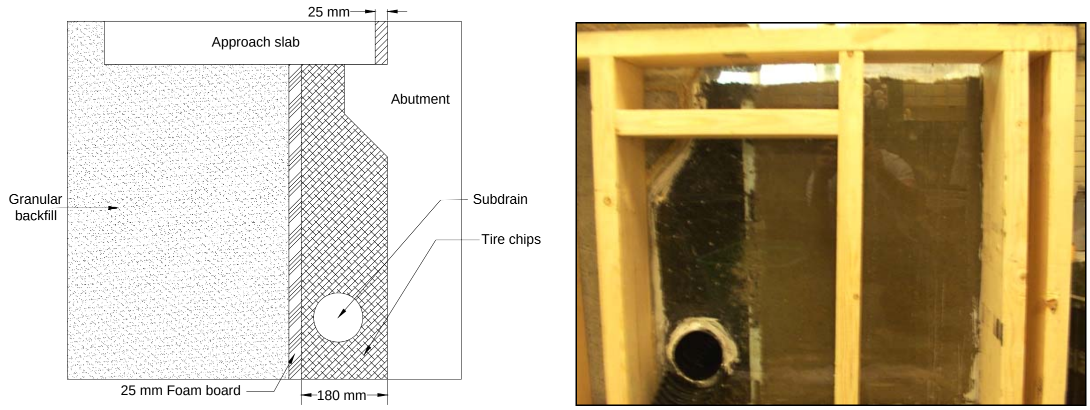

Figure 8. Using tire chips behind the bridge abutment

Another successful drainage detail was drainage model No. 13 (see Table 1), where porous backfill was used as a substitute for the granular material behind the abutment (see Figure 9). The drainage detail was evaluated based on the excellent performance of the porous material in the collapse test (no measurable collapse). The porous fill was placed at a moisture content of 4.6% and compacted every five cm to an average relative density of about 71%. The porous backfill prevented void formation and approach slab settlement. Furthermore, the maximum steady state flow measured was 92 cm^3/sec, which is approximately three times higher than the maximum steady state flow measured using the current Iowa DOT specification drainage detail (Nos. 1 through 3). However, the maximum steady state flow was lower than the measured using a geocomposite vertical drain and tire chips. Despite the relatively low flow, drainage detail No. 13 can be applied at bridge sites due to its good performance and simple construction sequence.

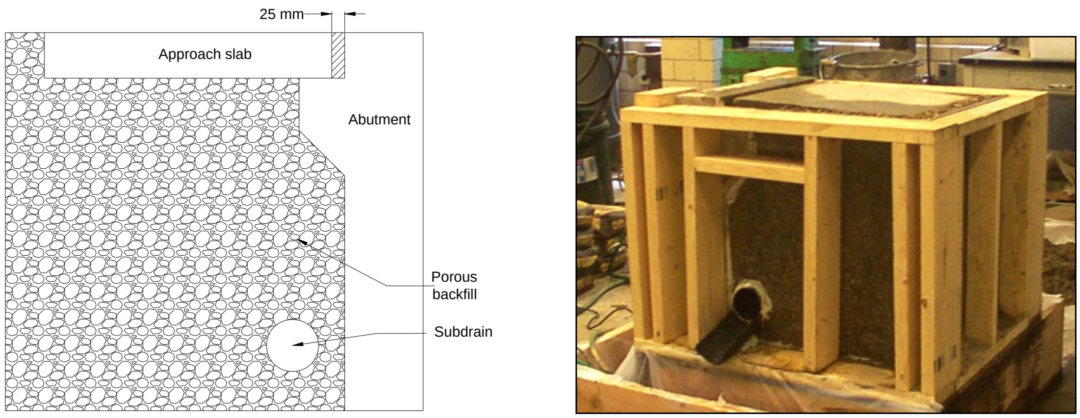

Figure 9. Using porous fill material behind the abutment

SUMMARY AND CONCLUSIONS

Bridge approach settlement and the formation of the bump is a common problem in Iowa that draws upon considerable resources for maintenance and creates a negative perception in the minds of transportation users. This study was undertaken to investigate the causes of bridge approach settlement in Iowa and develop simple concepts to improve drainage and reduce erosion.

An extensive field investigation was carried out in all six Iowa districts to document various bridge approach problems. Poor drainage and severe soil erosion were observed at approximately 40% of the inspected bridges and is primarily due to ineffective subdrain and end drain systems and water infiltration through insufficiently sealed expansion joints. Currently, Iowa DOT does not require the expansion joints to be fully sealed, which is primarily due to a lack of a suitable joint sealing system for Iowa’s harsh environmental conditions.

Soil erosion under approach slabs is attributed to the use of erodible granular backfill and void formation caused by soil collapse upon saturation. Limiting the percentage passing the No. 8 sieve to 60% reduces the granular soil erodibility. Soil collapse is highest when the granular backfill is placed within the bulking moisture content range (3% to 7%), while porous backfill does not collapse at any moisture content. Void development creates a path for infiltrated water to further erode the backfill. If not remedied, erosion may lead to exposure of H-piles supporting the abutment, failure of the concrete slope cover in the embankment under the bridge, and faulting of the approach slab pavement.

To develop simple alternatives to improve drainage and alleviate erosion, a one-fourth scaled model was constructed in the laboratory. The model evaluated different backfill materials and drainage techniques based on practices of other states and concepts developed by the authors for achieving optimum performance. Settlement, void formation, and maximum steady state flow were recorded and used for evaluation of each BADM test. Of thirteen different experiments, three drainage systems performed best. These details are (1) using geocomposite drain with granular backfill reinforcement and moisture content above bulking; (2) using tire chips behind the bridge abutment; and (3) using porous backfill material. Using geocomposite drain with backfill reinforcement eliminated settlement and void formation and increased the maximum steady state flow by 12 times when compared to the value measured from the Iowa DOT drainage detail. Using tire chips behind the bridge abutment eliminated settlement and void development and resulted in the highest maximum steady state flow. However, this drainage detail may require complex construction. Using porous backfill as a substitute for granular backfill eliminated settlement and void development. Furthermore, the maximum steady state flow was three times higher than the value recorded for the Iowa DOT drainage detail. Using porous backfill can be easily and successfully applied in the field due to its erosion resistance and simple construction sequence.

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