Use of Ground Penetrating Radar for Void Detection and Hydro-Geochemical Water Testing Results at the Cumberland Gap Tunnel

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ABSTRACT

Both Ground Penetrating Radar (GPR) surveys and Hydro-Geochemical Water Testing (HGWT) have been performed at the Cumberland Gap Tunnel to determine why the reinforced concrete pavement has settled in various areas throughout both tunnels. To date, approximately 7,300 total square feet of pavement surface has voids beneath it that range from 0.05 to 40 inches in depth. Both GPR and HGWT results indicate that approximately 0.75 to 1.5 cubic yards of limestone sub-base material leaves the tunnel in solution form on a monthly basis. Furthermore, HGWT results indicate that the ground water beneath the tunnels is calcium deficient. Thus allowing the water to dissolve the limestone sub-base. Approximately 500,000 to 1 million gallons of water flows through the tunnel’s ground water collection system on a daily basis.

Attempts to fix/shore-up the settled pavement areas were performed in 2002, 2007, and 2008. In 2002, UreTek foam was placed beneath approximately 2000 square feet of settled pavement for shoring purposes. In 2007, approximately 150 lineal feet of both pavement and backfill were removed and replaced with inert granite backfill material and a new reinforced concrete pavement. In 2008, approximately 51 cubic yards of cement grout material was placed beneath approximately 7,400 total square feet of settled pavement for shoring purposes.

There are several strategies outlined in this report to address both short-term and long-term remediation. However, there are certain strategies that may prevail over others. It is proposed that grout material should be placed beneath the pavement structure, at an estimated cost of $50,000 to $100,000/year, as a short term assurance measure. It is proposed that approximately 2,800 lineal feet of pavement and backfill material be removed in both tunnels and replaced with an inert granite backfill and a new 10 inch reinforced concrete pavement be installed for a long-term remediation (estimated costs $10,000,000).
INTRODUCTION

This is a summary report of the pavement settlement issues (distressed areas) and hydro-geochemistry (water quality testing) results from the recent Cumberland Gap Tunnel pavement inspection project. This report will briefly highlight the following:

a. History of the distresses incurred to the pavement structure
b. Quantify the settlement areas (void areas)
c. Explain the hydro-geochemical water testing results
d. Discuss the traffic impacts in the event that the tunnel would need to be closed for emergency repairs
e. Discuss future traffic impacts
f. Offer suggestions for short-term remediation efforts (maintenance)
g. Offer recommendations for long-term remediation efforts for the settled areas
h. Provide preliminary costs estimates for both the short and long term repair recommendations

BACKGROUND

The Cumberland Gap tunnel is a twin-bore-four-lane mountain tunnel that carries US 25E from southeastern Kentucky into Tennessee. It resides within the Cumberland Gap National Park, and carries an average annual daily traffic (AADT) volume of 22,500 vehicles bi-directionally per day. Approximately ten percent of the AADT volume is trucks, which predominately transport fuel and coal between the two states.

Both the design and construction oversight for the tunnel was performed under the direction of Eastern Federal Lands, a division of the Federal Highway Administration. The tunnel was completed in 1996 with an approximate total project cost of 260 million dollars.

Currently, the tunnel is maintained and operated by the Cumberland Gap Tunnel Authority (CGTA). The CGTA performs its duties as an over-site agency for the maintenance and operation of the tunnel under a joint contract with both the Kentucky Transportation Cabinet and the Tennessee Department of Transportation.

HISTORY OF DISTRESS

Distresses to the continuous-reinforced-concrete-pavement (CRCP) were first noticed in 2001 by the CGTA. These distresses consisted of multiple areas starting to settle in the southbound tunnel between stations 119+50 and 140+50. The magnitude of the pavement settlement was approximately 1-3 inches at that time. In efforts to bring the pavement structure back into proper elevation, it was suggested that an expansive foam material be installed beneath the pavement to lift the pavement back into proper elevation in the settled areas. This process worked with
limited success. The foam material only filled the void space between the concrete pavement and the aggregate sub-base. Therefore it was unable to lift the pavement into proper elevation.

In 2005, the Kentucky Transportation Center (KTC) conducted an experimental research project using ground penetrating radar (GPR) to determine if there were voids beneath the CRCP pavement in the distressed areas. This inspection determined that approximately 6,000 square feet of pavement surface between both the north and southbound tunnels had some type of void beneath it. These voids ranged from 2 to 40 inches in depth. Figure 1 below displays a 40 inch deep void located beneath the left driving lane of the southbound tunnel at approximately station 128+90. It can be inferred that the concrete pavement is essentially performing as a bridge in these void locations. Only because reinforcing steel was placed inside the concrete, is the pavement structure able to be in-service without complete failure today. Structural loading calculations indicate that the concrete pavement should only be able to span 6 feet before permanent deformation of the steel takes place. As seen in Appendix A, some of the void areas are spanning across both lanes (30 feet wide) and extending 1 to 70 feet in length.

![Figure 1: Forty-inch void beneath concrete pavement](image)

In April of 2007, a technical group was formed to study the pavement settlement issues at the Cumberland Gap Tunnel. This group consisted of representatives from the following: Kentucky
Transportation Cabinet (KYTC), Tennessee Department of Transportation (TDOT), Federal Highway Administration-Kentucky Division (FHWA), Federal Highway Administration-Eastern Federal Lands Division, National Park Service (NPS)-Cumberland Gap National Park, Cumberland Gap Tunnel Authority (CGTA), Kentucky Transportation Center (KTC), and the Kentucky Geological Survey (KGS). It was determined in that meeting that a significant amount of settlement was taking place in the southbound tunnel from stations 122+24 to 123+41 and that an investigative repair would be necessary to eliminate a potential pavement collapse and to gain a better understanding of the mechanisms which may have been causing this distress.

A new discovery was determined during this investigative repair. It was found that the ground water inflow into the tunnel backfill material beneath the concrete pavement was aggressive to calcite. The tunnel backfill material is a limestone material (approximately #57 size aggregate) that is rich in calcium. Figure 2 displays the ground water inflow into the repaired area. Approximately 500,000 to 1.2 million gallons of ground water flows beneath the tunnels on any given day depending on the rainfall events.

![Figure 2: Water inflow into the repaired area](image)

This limestone backfill material ranges from 4-6 feet in depth by design throughout both tunnels. The technical advisory group determined that the appropriate repair would be to replace the
excavated material with an inert granite backfill material. The backfill material consisted of a number 57 size aggregate, overlaid by a six inch layer of dense-graded-aggregate (DGA) separated by a geo-grid fabric. Next, a new 10 inch CRCP pavement was installed (Figure 3).

![Figure 3: Repair area with granite backfill and DGA prior to concrete pavement placement](image)

A more detailed summary of the hydro-geochemical water testing results will be provided in the hydro-geochemistry section of this report.

Another discovery made during the investigative repair was that the groundwater collection system is elevated approximately 2 to 3 feet above the invert of the tunnel (Figure 4). The ground water collection pipe can be seen in Figure 4 as the green pipe on the left side of photo.
Figure 4: Groundwater collection pipe location in relation to tunnel invert

For convenience of construction, the elevation of the groundwater collection system was constructed higher than the invert of the tunnel. Thus, the limestone backfill material throughout the tunnel was constructed to act as a natural drainage structure for the ground water in-flow to pass through. It has been presumed, after research of both design and construction documents, that no water test were conducted to measure calcium deficiency during either the design or construction phase of the tunnel.

In the spring of 2008, as a precautionary measure to avoid further settlement, both the KYTC and TDOT decided that the other void areas (approximately 7,460 square feet) needed to be filled with cementatious grout. Approximately 51 cubic yards of cement grout was placed into all known void areas at that time. As of August 2009, approximately 90% of the voids grouted in the spring of 2008 have reappeared and the repaired area with the granite backfill appears to be unchanged and performing well.

QUANTIFICATION OF SETTLEMENT (DISTRESSED AREAS)
The distressed areas started to appear in the southbound tunnel in 2001, just five years after completion of construction. The distress was first noticed by the Cumberland Gap Tunnel Authority during routine maintenance. In an attempt to monitor the progression of void growth, the Cumberland Gap Tunnel Authority asked the Kentucky Transportation Cabinet to involve the Kentucky Transportation Center in its use of its falling-weight deflectometer (FWD) and ground penetrating radar (GPR) equipment to monitor and evaluate void growth. As mentioned above, approximately 7,300 square feet of void space are present today. However, the voids are not as deep as they were in 2005 because of the grouting that took place in the spring of 2008. Preliminary GPR results obtained from the latest survey performed in August 2009 indicate that the void depths range from 0.5 to 6 inches deep depending on their location in respect to the hydro-geochemical data (Appendix A). Figure 5 outlines the time line of combined void growth for both tunnels. The green bar indicates the quantity of voids that were removed during the investigative repair in the summer of 2007. This figure demonstrates that even with the reduction in total void surface area of 1,419 square feet in August 2007, the total void space in December 2007 had surpassed the quantity from January 2007.

![Figure 5: Total square feet of void surface areas](image-url)
HYDRO-GEOCHEMISTRY RESULTS

After the investigative repair was completed in 2007, the technical group decided that a much broader hydro-geochemical water-chemistry testing study was needed. This study was conducted to validate the extent of the calcium deficient water entering into the tunnel. Laboratory tests have confirmed that water samples that have a calcium deficiency less than 0.10 will start to dissolve limestone material.

Approximately 120 water-sampling wells were drilled and instrumented in both tunnels during the fall of 2008. As shown in Figure 6, the geological composition of the rock material from stations 140+50 to 160+00 (Tennessee portal) consists of limestone composition while the composition from the Kentucky portal to station 140+50 is sandstone.

![Figure 6: Geologic map of Cumberland Gap Tunnel](image)

Water samples obtained between stations 140+50 to 160+00 appear to be chemically balanced with respect to calcite. Thus, there was no noticeable chemical breakdown noted in the limestone backfill beneath the pavement in this area. The water is apparently naturally aggressive in this location and is using the native formation of limestone to balance itself with respect to calcite. This gives rational to the presence of the cave systems located in these areas. However, the remainder of the tunnel has a different geological composition (i.e. siltstones, mudstones, sandstones, etc.) that is incapable of chemically balancing the water with respect to calcite before entering the limestone road-base aggregate. In these locations (stations 119+50 to 140+50) water samples collected and analyzed by KGS appear to be aggressive with respects to calcite. Figure 7 summarizes the hydro-geochemical water-testing data. Figure 7 demonstrates that 84% of the southbound and 77% of the northbound water samples are aggressive to calcite.
Therefore, the majority of the ground-water samples between stations 119+50 and 140+50 have the potential to chemically dissolve the limestone aggregate backfill. This material then exits the tunnel in solution through the ground water collection system on a continual basis. Preliminary results of the amount of material leaving the tunnel in solution have been quantitatively compared between mass-flux models, ground penetrating radar results, and visional calculations during the grouting process. These preliminary results estimate that approximately 0.75 to 1.25 cubic yards of limestone material are being removed in solution from beneath the concrete pavement on a daily basis. This also translates into approximately 70 to 150 square feet of new void space opening up beneath the pavement surface on a monthly basis.

**TRAFFIC IMPACTS FOR DIVERTED TRAFFIC**

Considerations were made for the impacts imposed on the traveling public (approximately 22,500 AADT) during the repair conducted in 2007. These considerations for complete traffic diversion can also be used to guide future repairs and or emergency maintenance repairs (Table 1). All dollar values have been adjusted using the 2007 consumer price index published by the Bureau of Labor Statistics.
Table 1: Diversion routes and daily user costs 2007 dollars

<table>
<thead>
<tr>
<th>Route Description</th>
<th>Distance</th>
<th>Time</th>
<th>User Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Via La Follette, TN and Williamsburg, Ky</td>
<td>130 miles</td>
<td>3 hrs 6 min</td>
<td>$1,197,096 (daily)</td>
</tr>
<tr>
<td>Via Pennington Gap, VA and Harlan, Ky</td>
<td>110 miles</td>
<td>2 hrs 50 min</td>
<td>$1,071,085 (daily)</td>
</tr>
</tbody>
</table>
However, no complete diversion of traffic was necessary to the general population of traffic during the repair. Only wide load cargo vehicles were subject to the complete diversion routes as mentioned above. During the construction phase of the repaired area, the southbound traffic was diverted over to the northbound tunnel, with traffic running bidirectional in the northbound tunnel. No noticeable delays in traffic were experienced in the northbound tunnel despite the reduced travel speed of 25 mph.

Figure 8 displays the maximum work zone capacity of 1,300 vehicles-per-hour-per-lane (vphpl), ref. 2001 Highway Capacity Manual that can be processed in a single lane on an hourly basis without backups. The hourly traffic distribution for the 22,500 ADT can also be found in Figure 8, which identifies that the traffic would have to increase by an approximate 30 percent before backups would occur.
Figure 8: Single lane work zone capacity vs. hourly traffic distribution US 25 East Cumberland Gap Tunnel

FUTURE TRAFFIC IMPACTS

With the near completion of US 25E widening project from Harrogate, Tennessee to I-81 near Morristown Tennessee, it is conceivable that the traffic flow on US 25E will increase throughout the Cumberland Mountain Region in the near future. Once this construction is completed in late 2010, a driver will be able to reduce their driving time by an approximate 45 minutes when traveling from I-81 to I-75. With this reduction in travel time between the two major interstates, it is highly probable that the total volume of vehicles passing through the Cumberland Gap Tunnel will increase. Consideration should be given to construction scheduling in an effort to avoid excessive delays as traffic volumes increase. In addition, consideration for diverting traffic during the NASCAR racing season hosted in Bristol, Tennessee, also needs to be reviewed prior to scheduling of construction.

SHORT TERM REMEDIATION (MAINTENANCE)
Table 2: Short term remediation estimates for the settled areas may consist of the following

<table>
<thead>
<tr>
<th>Maintenance Item</th>
<th>Construction Costs provided by KYTC Division of Highway Design</th>
</tr>
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| Grout all void areas on annual basis (consideration needs to be made for potential damming the ground water over repeated grouting sessions) | $1300/cubic yard. (includes coring, ground penetrating radar, and placing grout)  
Total annual costs $40-70K depending on void depth/growth                                                                                       |
| Remove concrete pavement (major settled area) northbound tunnel approximately 1,500 square feet and backfill with concrete (consideration needs to be made for potential damming the ground water for full depth concrete) | $150/square yard  
Total cost $25,000                                                                                                                       |
| Micro-piles, spaced 6 feet on center in void areas                                | $35/square feet (approximate areas 7300 square feet)  
Total Costs: $255,500                                                                                                                       |

LONG TERM REMEDIATION

Based on the findings from the investigative repair, the hydro-geochemical water-chemistry data, and the continual growth of the void areas, it is of opinion that both the pavement and backfill material should be completely removed and replaced starting at approximate station 140+50 and proceeding to the Kentucky portal. It is also believed that a trench be excavated out in the invert of the tunnel to allow a majority of the ground water to channel through the tunnel (Figure 9). This trench would have to be of sufficient depth and width to lower the water table beneath the tunnels’ concrete sidewall structure. All backfill material must be inert granite material, and the paved surface would be a CRCP pavement (Figure 9). An approximate construction cost of $10,000,000 has been estimated by the KYTC Division of Highway Design based from recent unit-bid-pricing to perform such tasks. However, this estimate may vary depending on the economic climate and contractor availability.
Figure 9: Conceptual long-term fix design--not intended for construction purposes.

CONCLUSIONS

The concrete pavement structure at the Cumberland Gap Tunnel has been showing signs of pavement distress since 2001. The primary distress observed has been vertical displacement (settling) throughout various areas of both the north and southbound tunnels. To date approximately 7,400 square feet of continuously reinforced concrete pavement (CRCP) has voids beneath it. These voids range from 0.05 inch to 40 inches in depth.

In 2007 an investigative repair was conducted in the southbound tunnel to repair the most severely damaged section and to provide insight into the potential cause of the settlement issues.
From this investigation, it was determined through hydro-geochemical water-chemistry testing that the ground water in-flow throughout both tunnels is aggressive to calcite. Therefore, the 4-6 feet of calcium rich limestone backfill material placed beneath the concrete pavement is dissolving and leaving the tunnel through the ground water collection system on a daily basis. The calculated rate of removal has been estimated to be between 0.75 and 1.5 cubic yards per month or approximately 70 to 150 square surface feet of new void area is opening up beneath the concrete pavement on a monthly basis.

It has been proposed by a technical advisory group that the concrete pavement and limestone backfill material be removed from station 140+50 to the Kentucky Portal approximately 2,800 lineal feet in both tunnels. This removed material would be replaced by an inert granite backfill material and a new 10 inch continuously reinforced concrete pavement (CRCP). Preliminary construction estimates taken from previous unit-bid-pricing of the investigative repair, estimate that the repair will cost approximately $10,000,000. It is also proposed that annual maintenance be performed in the settled areas in efforts to avoid any potential pavement collapse until a long term fix is put into place. An approximate annual maintenance cost would be from $50,000-$100,000 per year.
APPENDIX A: Void and Water Well locations on strip map of tunnel.