REMOTE MONITORING AND INNOVATIVE TECHNIQUES FOR THE
CONSTRUCTION OF THE NORFOLK SOUTHERN BRIDGE OVER COTTON RUN,
SEVEN MILE, OH

Lisa Hoekenga, PE, SE, Michael Baker International, (216)776-6814, lisa.hoekenga@mbakerintl.com
Brett Mattas, PE, SE, Michael Baker International, (614)538-7606, brett.mattas@mbakerintl.com

ABSTRACT
A storm event on May 24th, 2017 caused settlement of one of the piers of the Norfolk Southern Bridge CF-35.40 in Seven Mile, OH of more than one foot with a corresponding superstructure distortion. Norfolk Southern immediately installed timber cribbing and rip rap around the piers to restore service under reduced speeds. A structural monitoring system consisting of tilt meters and settlement gages were installed on the bridge with remote viewing capabilities while permanent improvements were developed. A replacement structure was designed to replace the existing structure utilizing accelerated bridge construction techniques. The 24-hour outage was executed on May 21, 2018, one year after the storm event.

INTRODUCTION
A large storm event came through Seven Mile, Ohio on May 24th, 2017. The mayor of Seven Mile, Vivian Gorsuch, described the storm as the worst flooding that the city has seen in 35 years McCrabb (1). The Butler County Emergency Management Agency estimated that the storm brought almost 5 inches of rain in two hours and local newspapers reported that U.S. 127 had been overtopped in several locations. Just downstream of the U.S. 127 bridge over Cotton Run is the Norfolk Southern bridge CF-35.40. The bridge spans over Cotton Run which flows into Seven Mile Creek in Seven Mile, Ohio.

The flash flooding through Cotton Run created a scour condition around the East Pier of the NS CF-35.40 resulting in settlement of the pier by more than a foot. The pier settled nearly vertically with no noticeable rotation suggesting that the settlement may have been the result of a bearing capacity failure after the scour removed the adjacent over burden material rather than removal of material from beneath the footing. The pier settlement resulted in movement and rotation of the two concrete box beam spans supported on the pier and ultimately a loss of support at track level.
Norfolk Southern personnel were on site soon after the storm to assess the damage and prepare an immediate response to restore service to this line. The bridge is located on the Northern Region’s Lake Division and supports one track carrying approximately 15-20 trains per day between Cincinnati and Richmond, continuing on to Muncie. This is a prime route for time-sensitive shipments between Detroit, Chicago, Fort Wayne and to the south through Cincinnati, so restoration of rail operations was needed as soon as possible. Norfolk Southern contracted with Fenton Rigging & Contracting and they mobilized immediately to install rip rap and stone in the scour hole and constructed a timber mat support around the East Pier to serve as a “catch bent”. Steel beams were used to brace the East Pier against the adjacent East Abutment and West Pier to provide lateral support of the pier. Additional ballast was added above the settled portion of the superstructure and the track realigned to reestablish service on the track.

EXISTING BRIDGE INFORMATION
The existing structure was a three-span concrete slab beam bridge supported on concrete piers and concrete gravity abutments. The record drawing on file for this bridge indicate the current substructure was built in 1926 and that the piers are founded on spread footings 8'-0" wide and 4'-0" deep (see Figure 3.

The bridge was built as a replacement to another structure with the new abutments located on font of and behind the previous abutments, maintaining approximately the same overall bridge length. The spread footing foundation for the pier proved to be insufficient for the hydraulic scour conditions of Cotton Run during the storm event. The foundation elements for the US-127 highway bridge just upstream had been retrofitted in 1983 with steel sheet piling around the piers and abutments during a planned superstructure replacement. This scour countermeasure likely prevented a similar failure of the highway bridge.

MONITORING SYSTEM
Bracing the bridge with a rip rap base, timber cribbing and steel rolled shapes (see Figure 4), provided additional resistance to complete collapse of the bridge if additional settlement or rotation of the pier occurred. However, additional settlement of the weakened soil beneath the pier footing could occur at any
time resulting in misalignment of the tracks. Additionally, another storm event might result in sudden failure of the weakened bridge. Because Norfolk Southern restored operations on the bridge at a reduced speed, they needed to be able to stop trains if additional settlement of the bridge occurred. Periodic surveying was considered and determined to be too costly and would be difficult to execute during storm events similar to the one that precipitated the scouring and undermining of the East Pier. More importantly, periodic surveying would not provide the required real time information necessary to justify a decision to suspend train operations if required. Ultimately, a monitoring system was selected to log readings of bridge movement at less than 5-minute intervals and transmit an alarm if large movements of the structure were detected. This monitoring system would provide real time warning to Railroad Operations, allowing them to halt trains over the bridge if the track and/or structure was further compromised.

Figure 4 – Model of Bridge with Emergency Repairs

MONITORING SYSTEM
Geo Instruments, Inc. was subcontracted to install the monitoring system on the bridge, process sensor readings and maintain a project website that provided real-time data readings and graphs. The system was comprised of electrolevel tiltmeters, settlement gages, and a data logger fitted with a cellular phone connection. The data logger reported the instrumentation readings in addition to battery condition and temperature. The batteries were maintained by solar panels mounted on the enclosure. See Figures 5 & 6 for instrument locations.

Figure 5 – Placement of Tiltmeters on South Side of Bridge. North Side Similar.
RESULTS OF MONITORING
The monitoring was able to detect sudden movement events. Most movement was related to thermal expansion and contraction of the bridge. A typical sudden movement event is shown in Figure 7.

In this case the extremely low temperature resulted in rotation of span 1 and span 2 and corresponding rotations of the east and west pier. The movements recovered to their original position as the temperature warmed up. These movements were within the tolerances set up, so no alarm was generated.

The monitoring system detected continued settlement of the east pier during the time between the initial event and the final bridge replacement. Figure 10 summarizes the overall rotation of the tiltmeters on the spans. It can be seen that spans 1 and 2 show equal and opposite rotations as the east pier continued to settle. The total rotation was approximately 0.03 in/ft and 0.025 in/ft for span 2 and span 1 respectively. Span 3 showed much less rotation.
Figure 8 – Summary of Rotation of Span Tiltmeters in Y-Direction

Figure 9 shows the locations and directions of the total rotations shown in Figure 10 above. From the rotations and directions, it can be inferred that the east pier moved downward about 0.55 inches relative to the abutments.

Figure 9 – Average Net Rotations of Span Tiltmeters in Y-Direction

The settlement gauges were severely impacted by daily temperature cycles and solar radiation. However, as shown in Figure 10, a general trend can be discerned. The east pier appears to have settled almost 1 inch while the west pier may have settled up to 0.5 inches during the time between installation of the gauges and replacement of the bridge.
MONITORING SYSTEM LESSONS LEARNED
This monitoring system provided real time information to Norfolk Southern to allow them to continue to operate over the bridge with confidence. Over the 11 months that the monitoring system was in service, the design team learned several key lessons regarding the monitoring system:

- It is important to have a clear and accurate understanding of the relative motion that each tilt meter reports and which direction is reported as positive or negative. The readings from multiple tiltmeters should indicate an overall movement of the bridge that makes sense rather than being viewed as independent motions compared to an alarm level.
- The alarm could be triggered by a single reading of a single gauge exceeding its alarm level. Ultimately, each alarm had to be looked at carefully by the engineer and a decision made regarding the validity of the alarm no matter what time the alarm sounded. Future installations need to include sensor error handling in the alarm trigger before sounding the alarm.
- The problem with malfunctioning tiltmeters generating false alarms indicated a need to have a backup monitoring system that could be used to easily check the current condition of the bridge without traveling to the site. A web cam is recommended for future monitoring as an independent check of the tiltmeter system.
- The settlement gauges are susceptible to solar/thermal effects. There was no place to install the fluid reservoir and lines that were not in direct sunlight. The settlement gauges were used in conjunction with the tilt meters to evaluate false alarms, however, overall reliability of these gauges is low. Future installations of fluid driven settlement gauges need to consider placement of reservoirs and fluid lines out of direct sunlight.
- The monitoring system provided a level of confidence to continue rail operations on the partially damaged bridge in the interim period despite the false alarms.

BRIDGE REPLACEMENT TYPE STUDY
The Design Team mobilized immediately after learning of the bridge’s condition and set out to complete a site survey, geotechnical soil borings, and site investigation. Several options were investigated for the replacement of the existing bridge. The criteria used to evaluate the merits of the replacement options were as follows:

- The hydraulic opening for the proposed structure should not increase the 100-year flood elevation of Cotton Run.
- The replacement span should provide increased scour resistance for substructure elements.
- A maximum 24-hour track outage could be accommodated for construction of the replacement span.
- The replacement bridge should accommodate a single track operating at 60 mph.

The Design Team developed six (6) options for replacement of the bridge. Variations of each option were investigated for different construction methods.

The survey data, along with FEMA floodmaps was used to develop a hydraulic model for the watershed and bridge opening. The bridge is located on the Flood Insurance Rate Map (FIRM) for Butler County, Ohio. The length of Cotton Run is not within a detailed study area and has no published base flood elevations. The downstream end of Cotton Run is subject to backwater from Seven Mile Creek, which is in a detailed study area subject to inundation by the 100-year flood with published peak flows and base flood elevations. Therefore, the 25-year storm event with the 100-year backwater from Seven Mile Creek and the 100-year storm event with the 25-year backwater from Seven Mile Creek were analyzed in accordance with accepted methods for coincidental occurrence frequencies. This analysis was done to ensure there were no increases between the existing and proposed conditions.

An existing conditions HEC-RAS model was developed based on a detailed field survey and aerial topography of Cotton Run and its overbanks in the project area. The bridge was modeled using internal cross sections. These cross sections were modified to approximate the existing channel geometry prior to the pier settlement and temporary remediation measures.

The type study options were analyzed within the hydraulic model to determine if they would affect the 100-year flood elevation. Options that raised the 100-year flood elevation were eliminated from consideration. Each of these options were evaluated against the design criteria and ultimately the following options were eliminated:

Option 1 – ELIMINATED - Rehabilitation of the existing substructure and replacing the superstructure with new concrete box beams. The presence of the emergency response rip rap around the East Pier made the installation of a deep foundation to support and stabilize the pier difficult. This option would still leave the bridge with the original substructure elements which were nearing the end of their service life. Finally, it was estimated that this option would require at least a 40-hour track outage, which was not feasible for the railroad operations.

Option 2 – ELIMINATED – Replacing the piers with drilled shafts installed on either side of the existing piers and a straddle bent cap spanning between them. The superstructure would be replaced with concrete box beams. This option was estimated to be the least expensive, however it was also estimated to require a 36-hour outage to install the large pier straddle bents and superstructure. Significant concern about the ability to install drilled shafts through the rip rap at the East Pier while not causing further movement in the East Pier also contributed to the elimination of this option.

Option 3 – ELIMINATED – Four adjacent concrete box culverts. The Design Team could not develop a feasible arrangement of boxes within the limits of the existing abutments that did not increase the 100-year flood elevation. In addition, the time required to install the culverts was considerably more than the prescribed 24 hours.

Option 5 – ELIMINATED – Two-span bridge replacement. This option was investigated using two different construction methods; slide-in of the superstructure during a track outage and building the bridge adjacent to the existing bridge with a temporary track shift onto the new adjacent bridge and then completing substructure construction in place of the existing bridge where the new span could slide into a final position on the existing alignment. The first construction method (the slide in) was found to be somewhat cost effective but would require more than a 24-hour outage to install. The second construction method required less outage time but was considerably more expensive.
Option 6 – ELIMINATED – This option would build a new permanent alignment adjacent to the existing bridge. The new alignment would be supported by a new bridge built adjacent to the existing bridge. This option was estimated to require very little track outage, only enough time to cut and throw the tracks onto the new alignment. However, the cost associated with this work (including additional retaining walls and/or potential ROW purchase) was much higher than other alternatives.

THE BRIDGE REPLACEMENT DESIGN
The design team ultimately selected Option 4 – Replacement with a new single span bridge that was to be installed during the 24-hour track outage. This single span option utilized a through plate girder span, which reduced the structure depth and brought the bottom of steel elevation up as high as possible. New abutments would be installed in front of the existing abutments and following the removal of the existing piers would provide the required hydraulic opening and have no effect on the 100-year flood elevation of Cotton Run. The replacement bridge was estimated to cost approximately $2 Million and was designed to be constructed around the existing bridge, with prefabricated and pre-erected elements installed during the prescribed 24-hour track outage.

The new abutments are founded on two 5-foot diameter permanently cased drilled shafts. The drilled shafts were located just outside of the existing concrete box beam superstructure to allow for construction during continued rail operations. A precast abutment seat was placed on top of the drilled shafts after the existing superstructure had been removed during the track outage.

A cast-in-place concrete web wall was formed between the drilled shafts and cast-in-place concrete wingwalls were built between the drilled shafts and the existing abutment. The gap between the precast seat and the existing abutment was filled with precast wingwall panel that could be installed after the seat was positioned. The box created by the web walls and wingwalls was filled with flowable fill up to the top of shaft elevations.

The precast concrete abutment seats were designed to span between the drilled shafts and detailed with voids to fit over high strength threaded rods that were embedded in, and extended up from, the drilled shafts. The seats were designed for either a superstructure crane lift into place or a slide-in placement. Due to the girder bearings being centered nearly over the drilled shafts, the slide-in alternative was the
controlling design case for the seats. The threaded rods were tightened down, and the voids were grouted during the 24-hour track outage. Because the existing foundations were spread footings whose scour caused the initial emergency situation, the new drilled shafts were designed to resist all forces ignoring the contribution of the existing abutments.

The new superstructure is a single 52'-0" span through plate girder bridge. The girders were comprised of a 60" deep and 5/8" thick web and 20" x 1 5/8" flange plates. The girders were spaced 20'-0" apart which was just inside of the drilled shaft center to center spacing of 24'-0". The drilled shaft spacing was determined to allow for installation around the existing superstructure. A 4'-0" deep abutment seat on top of the drilled shafts allowed for shear transfer of the girder reaction load directly to the drilled shafts without having to design the abutment seat for large moment forces.

USE OF 3D VISUALIZATION

The abutment seat directly over the drilled shafts included reinforcement as well as anchor bolt sleeves and formed voids for threaded rods. The crowding around this connection was verified for minimum cover and spacing using Trimble Sketchup as shown in Figure 12.

Figure 12 – Precast Seat-to-Drilled shaft connection showing reinforcement and hardware ducts

By constructing a relatively fast model of both proposed alternatives and the existing bridge, 3D visualization was further used to discuss and modify design alternatives including the abutment seat to drilled shaft connection, superstructure details and the existing to proposed abutment interface. This could all be done in real-time with engineers in remote offices to quickly understand, discuss, and reconfigure new options.

BRIDGE REPLACEMENT TIMELINE

Storm Event to Full Replacement

The emergency nature of this bridge replacement project drove the design and construction schedule. Below is a summary of key timeline elements for the ultimate replacement of the bridge.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/24/2017</td>
<td>Storm and scour event</td>
</tr>
<tr>
<td>5/26/2017</td>
<td>Remedial repair measures installed and rail operations resume at reduced speed</td>
</tr>
<tr>
<td>6/05/2017</td>
<td>Replacement Type Study begins</td>
</tr>
<tr>
<td>6/28/2017</td>
<td>Replacement Type Study complete</td>
</tr>
<tr>
<td>7/01/2017</td>
<td>Monitoring System goes live</td>
</tr>
<tr>
<td>8/10/2017</td>
<td>90% Plans complete</td>
</tr>
<tr>
<td>8/14/2017</td>
<td>Permit submitted</td>
</tr>
</tbody>
</table>
24-HOUR TRACK OUTAGE FOR BRIDGE REPLACEMENT
On Monday, May 21, 2018, nearly one year after the storm event that damaged the original structure, Norfolk Southern ceased operations for 24 hours to allow for removal of the existing bridge and construction of the remainder of the abutments and the superstructure. The construction schedule called for 18 hours of track outage, with an additional 6 hours as a safety net. Complications encountered during removal of the existing concrete box spans consumed the 6 hours of float and left the remainder of scheduled work items during the outage to be completed without much "wiggle room". The failure of the pier resulted in the concrete spans rotating and locking into one another, which ultimately proved to be very difficult to unlock. The Contractor, McHugh Construction, worked to free the spans and remove them one at a time.

Once the existing spans were removed, the new precast concrete seats and backwalls were installed. The top of the drilled shafts received a layer of leveling grout and the precast seats and backwalls were lifted and set into place over the threaded bars. The threaded bar voids in the precast seat were grouted and the rocker bearings were installed. Simultaneously, precast concrete panels were placed between the back of the new backwall and the front face of the existing abutment.

The through plate girder superstructure had been assembled nearby prior to the outage. During the outage, a crane picked up the nearly 156 kip superstructure and lowered it onto the new bearings. With the new superstructure set, the void behind the backwall was backfilled, new ballast was placed on the bridge deck, and the track panel was laid on top of the new span. Norfolk Southern’s track crews quickly took over the construction at this point to reconnect the rails, tamp the ballast and reset the rail alignment as needed.

CONCLUSION
The solution implemented by Norfolk Southern proved highly effective in responding to a difficult emergency imposed by the extreme flooding event. The temporary cribbing and comprehensive monitoring system allowed Norfolk Southern to resume operations after the flood while maintaining confidence in the safety of the bridge. The Accelerated Bridge Construction techniques, using prefabricated elements, allowed Norfolk Southern to replace the structure with only a 24-hour closure of service on this critical rail artery. The bridge used proven construction and design techniques which resulted in a cost-effective solution with minimal disruption to rail service. These techniques could be applied to other emergency bridge response scenarios.

REFERENCES