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Computational Flow Dynamics

Modeling Tool Yields Cost-Effective Solution

By Jeff Keller, PE

The Little Blue Valley Sewer District provides wastewater collection and treatment for approximately 320,000 customers in Missouri's Jackson and Cass counties. The district provides this essential service for residences and businesses through an extensive interceptor sewer network serving over 270 square miles, pumping stations and a main wastewater treatment facility located east of Independence, Mo. Since the district's inception in the early 1970s, Burns & McDonnell has provided design and consulting services on a variety of treatment and conveyance projects.

Wet-Weather Storage Planned to Hold Peak Flows

As a part of a regional plan to assume operation of an existing sewer utility in Cass County, Mo., the district is providing wet-weather storage to temporarily store peak flows during storm events. Sewer systems typically experience high flows during storm events due to infiltration and inflow (I&I), where leaks in the system allow rainwater and groundwater to enter the pipe network. The planned excess-flow basin site was an existing pumping station with earthen basins available to hold wet weather flows temporarily until the storm events pass and the treatment plant has adequate capacity to treat the additional water. Prior to the plan for excess flow storage, this existing pump station pumped all flows into the upper extremities of the district's gravity collection system. These flows ultimately were received at the existing treatment plant.

Wet Well Sizing Presents Major Challenge

To transfer wet weather flows into the existing earthen basins, the existing pump station would be required to deliver 24.9 million gallons per day (MGD). However, the original design condition of the pump station was only 5.7 MGD. The significant increase in pumping rate posed a challenge, as the sizing of the existing concrete wet well structure was based upon the original duty point of 5.7 MGD, not the new delivery of 24.9 MGD. Traditional design approaches would have found the existing pump station wet well to be too small to accommodate the flow.

Wet well sizing is primarily driven by flow velocities in the wet well and pump operating time requirements. The higher pumping rate and velocities in this undersized structure would lead to eddies, vortices and other turbulence that entrap air in the water.

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Such entrained air can be drawn into the pump suction end where the compressible air bubbles can cause a condition known as cavitation, which damages pump impellers and other "wet end" internal pump components. Depending upon the severity of the cavitation, the effects can range from vibration, loss of efficiency, pump damage or catastrophic pump failure. (See Figure 1.)

Figure 1: Pump damage from improper hydraulics. (Courtesy Caltech)

The traditional solution to this sizing problem is construction of a larger wet well. However, this approach was hindered by site constraints, including the presence of other structures surrounding the deep well and the electrical conduit and piping on all sides of the structure. This congestion would have made the traditional approach very difficult and costly.

Computational Flow Dynamics Models Used to Find Solution

A more cost-effective solution was needed. Engineers devised the solution using a computational fluid dynamics (CFD) model, which provided a tool to develop design modifications to control turbulence and uniformly distribute the higher flows to multiple pumps. CFD modeling allows different fluid flow scenarios to be simulated. This digital modeling is performed in many industries to analyze various scenarios from combustion performance in automobile engines to spacecraft heating during atmospheric re-entry. CFD is occasionally applied in the wastewater industry to confirm scenarios such as optimum mixing in basins and fluid flow conditions in clarifiers.

How CFD Works

CFD models use complicated fluid mechanics equations applied to models where the water flow is broken into millions of tiny elements that sequentially relate to one another to replicate actual flow conditions. The sequence is repeated over all the elements in the model for thousands of discrete time intervals to create a dynamic representation of the fluid interactions that would be expected to occur in the real-life scenario. For this application, the CFD model could be used to test various flow control devices such as baffles, walls and ramps that could help reduce the potential for turbulence and uneven flows produced due to the high velocities in the wet well. Multiple CFD modeling firms were contacted to discuss the utility of this technique. Ultimately, the pump manufacturer was able to provide the modeling through a third-party firm that had previously performed CFD modeling for other pumping applications.

Existing Conditions Simulated

Burns & McDonnell, the pump manufacturer and the modeler developed the wet well geometry for the model that would represent the existing condition without any flow control structures in place. Alternative scenarios were then evaluated using differing water depths and pumping combinations. The final model showed that the wet-weather flow was conveyed into the wet well in an unbalanced manner, resulting in the bulk of the flow landing near one side of the pump station, creating highly turbulent conditions on one side and potentially starving the pump on the other side of the wet well. Without improvements, the cavitation of one or more pumps was likely, with resulting dire consequences. (See Figure 2.)

The final solution included a combination of a flow distributing baffle wall in the wet well and flow guide vane located in the entrance to the well.

Control Structures Designed and Evaluated

Additional modeling runs evaluated multiple flow-control structures to determine what type of structure would provide uniform, laminar flow to all pumps. The final solution included a combination of a flow distributing baffle wall in the wet well and flow guide vane located in the

Jeff Keller, PE, is a project manager in the Burns & McDonnell Infrastructure Group in Kansas City. He received his bachelor's and master's degrees in civil engineering at Kansas State University.

For more information, please email jkeller@burnsmcd.com.

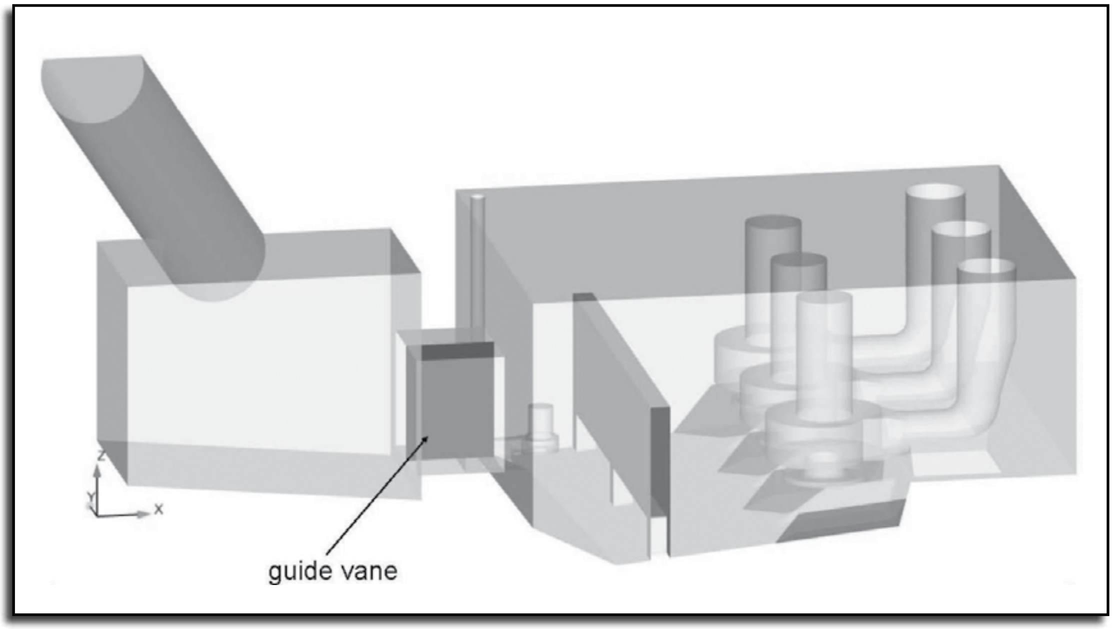

Figure 2: Final configuration of wet well with baffle wall and control vane. (Courtesy ITT)

entrance to the well. The wall includes slotted openings at the bottom of the wall to promote uniform flow towards the pump intakes. The guide vane redirects and centers the flow.

Concerns with debris building up on the guide vane precipitated the design of a guide vane shaped more like a sharks' fin, where debris can slide over the vane and continue into the wet well.

Modeling results indicated that these modifications would mitigate most potential problems and allow the small wet well to convey the very high flows needed in this application.

The result is a design for pump station modifications that capitalizes on the infrastructure already in place, saving an estimated $700,000 compared with building a new wet-well structure. The project is scheduled to be built in 2012-2013 with startup in late 2013. The renovated facility will allow the new conveyance system to manage wet weather conditions without swamping the new wastewater treatment plant, which ultimately receives all the collected flow. With new electronics, pumps and SCADA equipment, the renovated facility should continue to serve the district for many years as it expands service into other areas of western Missouri.

Transmission Line Foundation Design

Innovation Helps Save Time and Money on Fast-Tracked 345-kV Transmission Line Project

By Don Cannon, PE, PhD, Brad Gardner, PE, Josh Jordan, PE, and David Hancock, PE

Burns & McDonnell completed fast-track design and construction of a 120-mile, single-circuit 345-kV transmission line as part of a project connecting wind energy in western Oklahoma to electric load in central Oklahoma. The highly compressed schedule allowed just 24 months from receipt of notice-to-proceed to placing the line in service.

Meeting this schedule required selecting the line route, obtaining route-inspection authorizations (RIAs) for survey and geotechnical investigation, acquiring easements, performing the survey and geotechnical investigation, obtaining necessary permits, designing the transmission line and completing procurement and construction, all within the two-year period. To meet the schedule, design had to begin before access to private property was available but couldn't be finalized until full access was obtained to all the easements. The design team found a way to control costs despite the rework involved due to the overlapping schedule.

Transmission Line Design Allows Flexibility

The owner had not constructed a 345-kV transmission line in several years and had limited 345-kV standards available for the design. So the first task was to develop updated standards for structures and hardware assemblies. A preliminary study of structure and foundation options led to the selection of a delta configuration, single circuit, monopole structure for the line. (See Figure 1.) Due to the short schedule for the project and the lack of information regarding soil profiles along the 120-mile corridor, drilled piers were selected for the foundations. This choice allowed structures to be ordered before subsurface conditions were known, which would not have been possible with direct-embedded poles. It also allowed more flexibility to develop economical foundation designs as soil profile information became available along the route. Finally, it allowed the construction contractor to begin construction of foundations as soon as anchor bolt cages were delivered rather than waiting for structure deliveries, which typically occur later.

Figure 1 : Monopole structure.

The transmission line design required a total of 654 monopoles, including 570 tangents, 21 heavy tangents, 36 angles and 21 dead ends. Therefore, 654 drilled-shaft foundations were designed and constructed to support these 345-kV monopole structures.

Geotechnical Investigation Includes Borings at One-Mile Intervals

The design schedule required that the team be ready to issue the first batch of drilled shaft foundations for construction in November

2008. When the geotechnical scope of work was being prepared in April and May 2008, the final alignment for the transmission line had not been selected but had been narrowed to a preferred route and an alternate route. Of the two routes, only about three miles of the 120-mile alignment were included in both. In addition, the team had to proceed with establishing boring locations under the assumption that access to private parcels would likely not become available until late June or later, after the investigation needed to be well under way.

The original geotechnical exploration scope included 190 borings along the preferred route alignment, generally at angles, dead-ends and tangent locations at intervals of one mile or less. Approximately 99 of these borings were targeted for locations along city, county and state road rights-of-way. These public right-of-way borings were primarily limited to the tangent segments of the alignment with the exception of a few locations where angle and dead-end structures happened to be located near a road right-of-way.

Investigation Completed As Authorizations Received

The geotechnical field investigation began in June 2008, with the construction contractor mobilizing two drill rigs to the project. These two rigs were able to complete the initial 99 borings, with total drilling length of 3,865 feet, three weeks later. At that time, the right-of-way agents were beginning to obtain RIAs from landowners granting permission to gain access to their respective properties to complete the geotechnical borings. As with most other aspects of the project, RIA acquisition began near the center of the transmission line alignment and proceeded east and west simultaneously.

With the acquisition of RIAs along various portions of the alignment, the geotechnical investigation gradually continued. An additional 70 borings were completed by mid-November 2008, which required three additional drill rig mobilizations. During this time there were some final adjustments to the transmission line alignment that resulted in the addition of 15 borings to the geotechnical investigation program, bringing the final total to 205 borings for the entire transmission line. The final 36 borings could not be completed until after construction had begun due to delays in RIA acquisition of the affected parcels.

Foundation Design Memorandum Format Speeds Preliminary Design

To accelerate the delivery of design recommendations, the engineering team worked with the contractor to establish a "Design Memorandum" format that summarized all pertinent subsurface and foundation design information for each boring location on one 11-by-17-inch sheet. The memoranda included the final boring log with laboratory testing summaries at the applicable depths, axial and lateral loading drilled-shaft design parameters, groundwater data and field resistivity results.

The initial package of design memoranda was delivered in early October 2008, which coincided with the availability of the first package of foundation design loads from the pole manufacturer. Subsequent memoranda were delivered as the borings and laboratory testing were completed.

Preliminary Designs Developed with Limited Information

During the initial phases of design, the team was asked to design foundations through stretches of the alignment where subsurface information was limited because right-of-entry had yet to be obtained. Preliminary designs were needed to allow construction crews to order the reinforcing steel in time to deliver it to the site before foundation construction.

Based on a review of the surrounding topography and nearest available subsurface information, the team completed preliminary designs that could quickly be confirmed or modified once subsurface information was collected in closer proximity to the respective foundations. These designs were based on maximum ground line reactions provided by the pole manufacturer, which were based on structure design loads for maximum wind and weight span conditions.

Site-Specific Foundation Resizings Cut Cost

After construction was under way and several foundations had been installed, the client asked Burns & McDonnell to look for ways to save money on foundations. The most obvious way to save on large drilled shaft foundations was to perform site-specific designs. This was accomplished by obtaining the ground line reactions from the actual loading on the structure in the PLS-CADD™ model, then using these site-specific reactions to perform the foundation design. These site-specific reactions were smaller than the design reactions provided by the pole manufacturer. In some cases this allowed foundation sizes to be reduced, providing cost savings to the client.

The savings from this design modification alone were significant. In fact, 354 of the foundations were designed and built for site-specific loads at an average estimated savings of $2,000 per foundation, or a total of $700,000 of savings to the client. Site-specific foundation design required more time and effort on the part of the engineer, but the construction cost savings to the owner was worth it. However, this approach also reduces the design cushion and may limit the potential for future low-impact line upgrades. The team provided the client a detailed record of all the structures with site-specific foundations so they would have this record for future line capacity assessments.

Variable Subsurface Presents Additional Challenge

As construction proceeded, it didn't take long to discover that the foundations often required a quick redesign based on the actual subsurface conditions that the drilling crew encountered. Unlike the resizings, these redesigns caused lost time and money during construction and needed to be eliminated.

The subsurface conditions encountered along the alignment generally consisted of residual clayey and sandy soils weathered from the underlying shale and sandstone bedrock. Alluvial soils were encountered in the vicinity of stream and river crossings. The problem arose because depths of the shale and sandstone varied widely throughout the alignment. Bedrock was encountered near ground surface in some boring locations, while in other locations it was not encountered within the depths of exploration, which typically ranged from 35- 65 feet below existing grade. In addition, topography varied significantly over short distances, so it was difficult to predict soil conditions along portions of the alignment where borings were spaced at intervals of up to one mile.

Crew Downtime Threatens to Drive Up Costs

A product of highly variable terrain, unplanned field redesigns were expensive to the client. In addition to the schedule delays caused when variable subsurface conditions forced on-the-spot redesigns, crew downtime impacted costs.

Crew downtime occurred when foundation construction crews encountered soil conditions in the field that were different than what was assumed during the design, based on the information available at the time. The difference encountered most often was in the depth to bedrock. If a drilled shaft was designed to encounter bedrock at 12 feet below grade, but the drill rig actually encountered bedrock at 16 feet, a redesign was required.

Geotechnical and structural engineers understood the cost of crew down time and developed an efficient process for field redesigns. Geotechnical redesign, structural redesign, drawing revision, and quality review were typically handled in about an hour, including communications (phone and email). However, at $2,000 per foundation crew hour, the cost of this downtime added up quickly. After a redesign was done, the foundation crew would also often have to modify the rebar cage (See Figure 2), which cost the project additional time and money.

After approximately 30 field redesigns it was obvious that something had to be done to improve the situation and reduce costs.

The Solution

By January 2009, it was clear that structure-specific subsurface information was needed to completely avoid last-minute redesigns. But performing full soil borings at each structure location would be time-consuming and expensive, essentially eliminating all of the cost savings obtained from the site-specific foundation designs previously discussed. An alternative and lower-cost method to improve

Don Cannon is a project manager in the Burns & McDonnell Houston office. He received his bachelor's and master's degrees in civil and structural engineering from the University of Tennessee.

Brad Gardner, PE, is a senior geotechnical engineer in the Burns & McDonnell office in Kansas City. He received his bachelor's degree in geological engineering from the Missouri University of Science and Technology.

Figure 2 : After a field redesign, a foundation crew member prepares to cut off a rebar cage to shorten it as required.

Josh Jordan, PE, is a senior civil engineer in the Burns & McDonnell Houston office. He received his bachelor's degree in civil engineering at Mississippi State University and his master of business administration degree from the University of St. Thomas.

David Hancock, PE, is an associate civil engineer in the Houston office. He received his bachelor's degree in civil engineering at Texas A&M-College Station.

For more information, please email: dcannon@burnsmcd.com, bgardner@burnsmcd.com, jjordan@burnsmcd.com or dhancock@burnsmcd.com.

knowledge of the subsurface conditions at each structure locations was needed to reduce last-minute redesigns during construction.

The solution was to have the contractor complete an auger probe at every foundation that was assumed to include bedrock embedment. The logic was that an inexpensive auger probe would reveal the actual depth to bedrock before building the first rebar cage or even before the foundation crew arrived on site. The auger probes also allowed the team to validate or modify design soil profiles, including types of soils and depth to groundwater, for structures that did not have a boring nearby.

At each auger probe location, the contractor proceeded to the depth at which bedrock was expected based on the current foundation design. At that depth, a standard penetration test (SPT) was performed to identify whether bedrock was present. If bedrock was not present at that depth, the probe was extended and SPT sampling performed at 5-foot intervals until bedrock was encountered, or to a maximum depth of 40 feet.

Aerial Imaging Used to Manage Probe Access Issues

As with the primary geotechnical investigation activities, completion of auger probes had to be closely coordinated with the ongoing land acquisition process. In many locations, auger probes could not be drilled until construction access to an area was completed, which included culvert installation to allow equipment to cross roadway ditches, gate installation along existing fence lines, and tree clearing. If auger probes were not sequenced effectively, completion of some probes might not take place until just before foundation construction.

In an effort to stay ahead of foundation construction in as many areas as possible, aerial images were initially used to identify the probe locations where tree clearing would not be required. To the extent possible, these locations were given higher priority for gate and culvert installation which facilitated quick access for probe completion well in advance of foundation construction.

The results of these auger probes were then used to update foundation designs before construction of each respective foundation began. In some cases this resulted in reduction of foundation depth and in others it resulted in increases in foundation depth. But in all cases it reduced the likelihood of design changes during construction and the resulting crew downtime and rework.

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This auger-probe approach was applied to about 250 foundation locations. For about half of these auger-probed foundations, the team was able to redesign the foundation before construction. This resulted in average savings of about $2,450 per foundation, or about $300,000, due to avoidance of crew downtime. At a cost of $300 per auger probe, or about $75,000 total, the net savings from auger probes was about $225,000.

Cost Savings Summary

Applying site-specific foundation designs for about half of the structures resulted in total savings of about $700,000 for the client. Another $600,000 of cost savings might have been possible if site-specific foundation designs had been performed for another 300 structures. Therefore, the total potential savings for site-specific foundation design for this project is an estimated $1.3 million.

Using auger probes to redesign foundations using better subsurface information resulted in a net savings of about $225,000. An additional net savings of about $180,000 may have been possible if this approach had been taken for the remaining foundation locations that were not at soil boring locations, bringing the total potential savings from supplemental auger probes to an estimated $400,000 for this project.

The actual total savings delivered to the client through using auger probes to avoid crew downtime and performing site-specific foundation design was approximately $925,000. Had these methods been applied across the board from the start of the project, an estimated total potential savings of $1.7 million might have been possible.