SEISMIC DESIGN OF THE KENTUCKY LAKE AND LAKE BARKLEY APPROACH SPANS

BRAD ROBSON

DAVID RUST

KYLE MCLEMORE

BIOGRAPHY

Brad is a Principal with Palmer Engineering Company and works in the Winchester, Kentucky office. He has a BSCE from the University of Cincinnati, an MSCE from the University of Colorado, and a PhD from the University of Kentucky. His wife finally said enough and made him get a real job.

David Rust is a Project Manager with Palmer Engineering also in the Winchester office. He earned a BSCE from the University of Cincinnati and an MSCE from the University of Kentucky. David is Engineer of Record on the Lake Barkley approach spans.

Kyle McLemore is a Structural Engineer in the Nashville office of Palmer Engineering. He holds a BSCE from the University of Florida and an MSCE from Vanderbilt University. Kyle led the seismic analysis efforts for this complex and challenging design project.

SUMMARY

New bridges over Kentucky Lake and Lake Barkley are in the United States’ most seismically active area in the East, the New Madrid Seismic Zone. Basket handle arches were chosen for the navigation spans with more than a mile of approach spans crossing the lakes. Because these structures will serve as a main route for evacuations and first responders, the Kentucky Transportation Cabinet (KYTC) designated them "essential" for seismic design. To remain functional after a large earthquake, site-specific hazard analyses, extensive field testing, and site-specific response analyses provided comprehensive input for structural design. Response spectrum analyses with linear foundation models were used in preliminary design to screen numerous approach span arrangements and narrow to viable alternates. Time history analyses determined the final layout which was then evaluated by accounting for nonlinear soil response, p-delta effects, potential plastic hinging, as well as the seismic dampers that were added to enhance performance.

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Location and History

US 68 / KY 80 crosses over Lake Barkley and Kentucky Lake in western Kentucky. These two bridges serve as gateways to the Land Between the Lakes (LBL) National Recreation Area (Figures 1-2). At more than 170,000 acres, the LBL is one of the largest undeveloped areas in the eastern United States.

The existing Eggners Ferry Bridge over Kentucky Lake (Figure 3) was constructed in 1932 across the Tennessee River and is 3348 feet long. In 1933 Congress established and President Franklin D. Roosevelt signed the Tennessee Valley Authority (TVA) Act to control flooding on the Tennessee River, provide navigable waterways, and generate electricity. The Kentucky Dam project to impound Kentucky Lake was authorized by Congress on May 23, 1938; construction began in 1938 and was completed in 1944. Consequently, in 1943 the bridge was temporarily closed and raised 22 to 25 feet to accommodate the lakewaters. Kentucky Lake is the largest TVA reservoir at 160,000 acres and the largest artificial lake in the eastern US by surface area.

In a similar fashion, the existing Lawrence Memorial Bridge over Lake Barkley (Figure 4) was constructed in 1932 across the Cumberland River and is 3045 feet long. Barkley Dam was authorized in the River and Harbor Act of 1954; construction began in 1959 and was completed in 1964. The transformation of the Cumberland River into Lake Barkley necessitated raising the Lawrence Memorial Bridge in 1963.

Originally built for lighter and narrower traffic, the existing structures have only 20 feet of clearance for the two lanes of opposing traffic. With recreational boaters, campers, and today's semi-truck fleet, incidents of mirrors slapping and accidents are not uncommon. Furthermore, the navigational clearance for barge and other lake traffic is substandard; Eggners Ferry Bridge provides approximately 350 feet of navigation width while Lawrence Memorial Bridge provides only 320 feet. The new basket handle arch spans will provide more than 500 feet of navigable width.

As two of the longest bridges in the Commonwealth of Kentucky, each represents a major investment in Kentucky’s transportation infrastructure. The sites are near one of our country’s most seismically hazardous areas; the New Madrid Seismic Zone (NMSZ). In the event of a major earthquake, this corridor across the two lakes will serve as an evacuation route and allow first responders to access areas between the LBL and the Mississippi River. Balancing cost and performance, KYTC designated these bridges as "essential" for seismic design to remain functional after a large earthquake.

Figure 1: Project Location (Google Maps).

Figure 2: Project locations relative to New Madrid, Missouri (Google Maps).

Figure 3: Existing Eggners Ferry Bridge.

Figure 4: Existing Lawrence Memorial Bridge.

Seismicity

New Madrid, Missouri is the site of some of the largest earthquakes ever experienced by modern-day Americans, outside of Alaska. A series of large quakes, three of which are believed to be larger than magnitude 7.0, struck the region in the winter of 1811-1812. At this time, the area was the frontier of settled land so few people experienced the greatest effects of the quakes. Some who did reported the land rolling in waves while others reported temporary backward flow and waterfalls on the Mississippi River for several hours. Many landslides, fissures, sandblows, lateral spreads, subsidences, and uplifts were found after the great quakes. Reelfoot Lake near the Tennessee-Kentucky border was created after the land subsided from the earthquakes.

Seismic activity in the NMSZ did not end after the great quakes. As seen in Figure 5, a magnitude 6.3 quake occurred in 1843 followed by a magnitude 6.6 quake in 1895. The NMSZ is the most active seismic area in the United States east of the Rocky Mountains with numerous small earthquakes recorded each year. The faults are poorly understood because they are covered by approximately 200 feet of alluvium and are not present on the ground surface as other faults are, such as the San Andreas. The locations for the two bridge replacements are approximately 80 miles from the town of New Madrid.

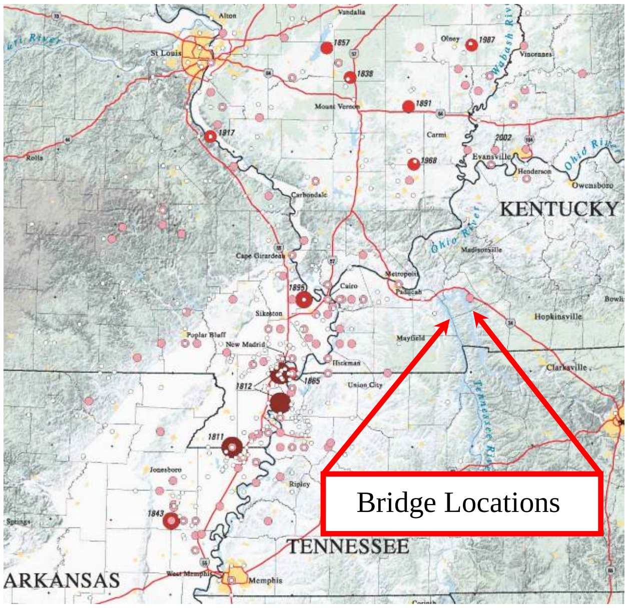

Figure 5: USGS seismicity of the New Madrid Seismic Zone (circle is proportional to magnitude).

Pre Design

Planning for replacement of the aging bridges over the two lakes in western Kentucky began over two decades ago. In 1995 FHWA approved the first environmental assessment for the project. After a few delays, in 2006 KYTC selected the team lead by Michael Baker International with major subconsultant Palmer Engineering to perform type selection, preliminary and final design services.

Public Involvement

A Citizens Advisory Committee provided the project team guidance. Additionally, a multitude of data was collected at public meetings through anonymous electronic polling. Public preferences for specific and general appearance were incorporated into final recommendations. During this months-long process, the project team refined engineering concepts and estimates so the final selection balanced the public interest for aesthetics and economy.

The broad public involvement process undertaken in the type selection study included presentation of renderings, gathering public preferences, and evaluating the economics of the many varied alternates.

On July 14, 2009 Governor Steve Beshear announced that Basket Handle Arch Bridges were chosen to be constructed over the navigation channels at Kentucky Lake and Lake Barkley. These signature ‘gateways’ to the Land Between the Lakes National Recreation Area would be the first of their type in Kentucky and some of the first for the country.

Geotechnical Investigation

Although only about 8 miles apart, the subsurface conditions of the Kentucky Lake and Lake Barkley bridge sites are very different. In 2009, KYTC selected a geotechnical team lead by H.C. Nutting (now Terracon) with major sub-consultant Florence & Hutcheson, Inc. (now HDR, Inc.) for final design services. The geotechnical team built on previous geotechnical investigations and formulated an extensive field exploration program.

Many soil borings, rock core borings, standard penetration tests, cone penetration tests, seismic cone penetration tests, cross-hole seismic tests, surface seismic tests, and suspension p-s velocity logging tests were performed in the field. Complimentary laboratory testing was also carried out in order to characterize the causeways, lakebeds, and soil profiles for site-specific seismic response analyses (5).

Kentucky Lake is up to 70 feet deep in the former Tennessee River channel and 25 to 30 feet deep in the former riverbank areas. Depth to bedrock was determined from surface seismic testing and borings confirmed rock at about 250 to 260 feet below summer pool. Large diameter steel pipe piles were chosen for the foundations. Structural demands resulted in concrete filled 6-foot diameter piles with wall thickness of two inches. To lessen risk associated with deep driving of the large pipe piles, which includes a layer of bedded chert, a load testing program was undertaken prior to bid (4).

From results of the load test program, it was determined that the piles should be driven open-ended with a constrictor plate inside to force the piles to plug. Ideally, the position of the internal constrictor plate would force the piles to plug as the tip penetrated the hard chert layer. One of the world's largest hydraulic pile hammers (IHC S-800 double-acting hydraulic hammer with a ram weight of 88.15 kips and a rated energy of 590 kip-ft) was used to drive the piles deep enough to achieve the required vertical and lateral capacities.

At Lake Barkley, hard limestone is approximately 90 to 100 feet below the water surface for most of the length of the crossing. Water depth is about 55 feet in the former Cumberland River channel and 5 to 20 feet deep in the former riverbank areas. Because of the shallower depths to hard rock, drilled shaft foundations were chosen for Lake Barkley. Approach spans will have 7-foot diameter drilled shafts socketed into rock with permanent steel casings. Voids were encountered during the exploratory drilling in this karstic region. Techniques for remediating voids during construction were devised and included in the bid documents.

Seismic Design Criteria

AASHTO (1) provides specific provisions for bridges classified as regular, and provides general guidance for critical and essential bridges. Because of their importance for emergency response to a major seismic event, these two bridges are more important than regular bridges. Therefore, KYTC adopted the following seismic design criteria for the project:

- Design Earthquake: 7% probability of exceedance in 75 years (1000 year return period)
- Seismic Operational Classification: Essential (i.e. at a minimum should be open to emergency vehicles and for security/defense purposes immediately after the design earthquake).
- Seismic Design Category D: due to the potential for liquefiable soil and lateral spreading, and some of the 1-sec design spectral accelerations.

Additional performance objectives for the project:

1. No collapse during the design earthquake.

2. Open to emergency and evacuation vehicles (one lane in each direction) immediately after the design

earthquake - temporary measures to cross deck joints could be needed after the design event.

3. Column displacement ductility ratio (seismic displacement divided by yield displacement) is limited to 3 for the design event (i.e. repairable damage due to concrete cracking, reinforcement yielding, and minor spalling of concrete cover at hinge regions).

4. If columns remain elastic at the demand displacements, the forces used for capacity design of components is taken as 1.2 times the elastic forces.

5. Arch elements, piles and pile caps shall perform within the elastic range.

6. Following the design earthquake, bridge can be restored to full functionality with full load capacity after minor to moderate repairs.

The latest seismic analysis and design methods to assess liquefaction potential and seismic stability for both the causeways and the bridge were used by the project’s geotechnical team. Likewise, structure design followed the latest recommendations contained in the AASHTO Guide Specifications for LRFD Seismic Bridge Design (1).

Approach Span Arrangements

After tentative approval by the US Coast Guard for the navigation spans' pier locations, approach spans were developed. With no obstructions between the causeways and the navigation spans, possible approach span arrangements were nearly endless.

Three historically economical superstructure types were studied: welded steel plate girders, prestressed concrete girders built in span-by-span construction, and spliced prestressed concrete girders that extend the span lengths available for concrete girders. A total of 25 alternates (9 span-by-span PCI, 4 spliced PCI, 12 steel plate girders) were evaluated for Kentucky Lake in preliminary design. They included a range of span lengths in order to assess whether particular combinations of type and spans resulted in poor or superior seismic performance. A similar preliminary range of alternates were examined for the Lake Barkley approaches.

Possible approach span arrangements were determined from historically efficient span ratios - for bridges without seismic or vessel collision loads, or the deep foundations needed at these sites. Deep foundations constructed in lakes were known to be more expensive than typical land-based foundations. Likewise, bridge foundations that must resist barge impacts and high seismic forces are also more expensive than normal. Therefore, optimizing the layout and size of foundations for each alternate was necessary to determine the overall best option to carry forward into final design.

The design team determined that a waterline pile cap would be much more economical than constructing footings in cofferdams. With initial parameters set, determining efficient and cost-effect approach spans required extensive investigation of extreme events which controlled foundation sizes.

Pier heights vary considerably across the lakes and have a significant influence on the stiffness and distribution of loads (particularly for extreme events) to each structural unit and each unit's substructures.

Seismic Design

Preliminary

Because of the many possible approach span configurations to be assessed, relatively quick multi-mode response spectrum analysis (RSA) was used. Models were created in CSI Bridge and SAP 2000 (2) which consisted of a spine model for the superstructure with each pier modeled as a frame. Effective (cracked) stiffness was used for the columns and pier caps as can be determined from the figures in AASHTO (1) based on axial load and expected reinforcing ratios. At this preliminary screening stage, foundations for the alternates were modeled as a six degree of freedom, linearized spring at each substructure (Figure 6).

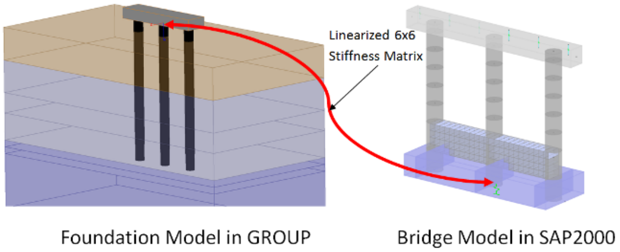

Figure 6: Capturing nonlinear soil response in GROUP for linear springs in SAP 2000.

Due to the inherent linear nature of the RSA method, the complex nonlinear foundation responses needed to be linearly approximated. A stand-alone program GROUP (3) was utilized to model the nonlinear effects of the pile and drilled shaft groups: p-y lateral soil response, t-z and q-z vertical soil response, shadowing effects, and additional drift and loading due to p-delta effects. An iterative process was needed to hone in on the correct secant stiffness to input for each of the three displacements and three rotations at each substructure. The process consisted of the following:

- Assume an initial 6 x 6 stiffness matrix for each pier foundation
- Run multimode RSA in CSI Bridge / SAP 2000
- Iterate applied forces in GROUP model of the foundation such that the resulting pile cap displacements closely match the peak displacements from a complete quadratic combination (CQC) of individual peak modal responses of the SAP model
- Calculate the linear (secant) stiffness for the displacements & forces in GROUP
- Update the finite element model with new 6 x 6 foundation stiffnesses
- Repeat RSA analysis and foundation stiffness process until convergence (i.e. until displacements used in GROUP to generate foundation stiffnesses matched the peak foundation displacements from the RSA analysis)

To initially explore the possible benefits of seismic isolation bearings and seismic dampers, linear damping elements (represented as a linear spring and an increase in modal damping) were included in a series of alternates.

The geotechnical team provided response spectra for each differing soil zone along the length of each bridge. These response spectra were developed through a response analysis enveloping six different potential earthquakes, three scaled from recorded events, and three synthetic earthquakes representative of the sites. Each of the six earthquake records had three orthogonal components (two horizontal and one vertical) (7, 8) and were used to develop the site-specific responses (Figure 7).

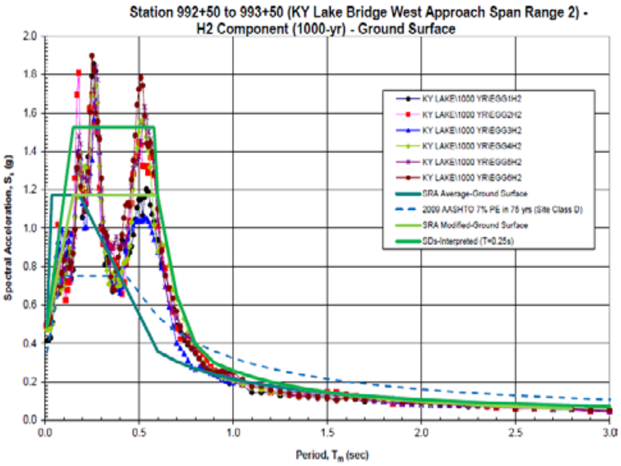

Figure 7: Typical Enveloped Response Spectra.

Final Design

After RSA was used to narrow the number of alternates, nonlinear time history analyses were conducted. At this stage, CSI Bridge allowed for discrete nonlinear links to be included in the seismic analysis through its Fast Nonlinear Analysis (FNA) method (9). Taking advantage of this in a modal superposition type analysis is much faster computationally than direct time integration. Seismic isolation bearings and seismic dampers were now able to be assessed more directly using true velocities and displacements instead of the approximate method used in response spectrum analysis.

Through much analysis and collaboration with Michael Baker's arch design team, it was determined that the Kentucky Lake Bridge would benefit by using longitudinal seismic dampers to connect the approach span units to the abutments and also to the arch piers. Likewise; seismic dampers were found to be beneficial in the longitudinal direction for the Lake Barkley Bridge, but most effective at the abutment expansion joints.

Once the determination was made to use dampers, the final span arrangements were selected and the seismic models were increased in complexity. All piles and drilled shafts for the piers were modeled with nonlinear springs to simulate the soil response (6). For this stage, the sub-structuring method of using GROUP for foundation response was not necessary as all effects were included in the global CSI Bridge model. However, the design team was still able to take advantage of the FNA analysis method since the nonlinear soil springs, dampers, and potential plastic hinges could be modeled with discrete link elements.

Ground displacement time history inputs were used so that phasing due to wave propagation as well as soil response variations at different substructure locations could be captured. While ground displacements provide significant advantages when analyzing structures that cover large horizontal distances, they require very high modal participation ratios in order to accurately capture the response and thus require larger numbers of modes and an increased computational effort.

The nonlinear soil elements used in final design consisted of multi-linear elastic springs. The final structural configuration for Kentucky Lake was checked using multi-linear plastic elements that included Takeda damping and gapping properties. Due to the increased number of nonlinear soil elements needed to characterize the soil response, it was not computationally feasible, within the limits of the software, to use plastic soil elements for the Lake Barkley model.

Despite the advantages of FNA, the size and complexity of the finite element models required significant computational effort. Care was taken to reduce the number of nonlinear elements such that the computational burden was reduced, and numerical stability was increased without compromising the validity of the models. Models were verified using parallel modeling techniques in which Michael Baker and Palmer Engineering ran full system models independently and compared resulting forces, displacements, and mode shapes. Consistent with traditional model building practice, nonlinearities were added to the model gradually so that their effect could be seen and numerical problems could be more easily detected. Additionally, spot checks were performed throughout the design process to search for signs of numerical instability such as force discontinuities or unsatisfied boundary conditions.

To envelope all possible conditions, the most flexible and the stiffest design conditions were subjected to all six earthquake time histories, with each of the horizontal components rotated in both of the primary structural directions (longitudinal and transverse) as independent cases. Also, the maximum phase delay due to wave passage was assessed in each longitudinal direction. The most flexible model assumed areas with potential liquefaction did liquefy, includes shadowing effects of the pile group, assumed half of the potential scour has occurred, and also deducted thickness from the pipe pile or permanent casing wall to account for corrosion. The stiffest model does not include any of those four effects. Figure 8 shows the first four natural modes for Kentucky Lake.

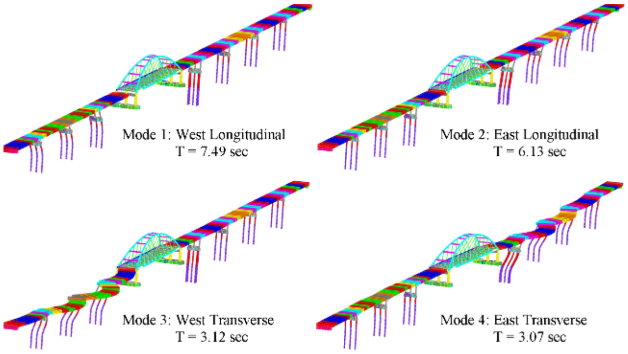

Figure 8: First four mode shapes of the Kentucky Lake Approach Spans.

Pier capacities were determined through pushover analysis which accurately tracks concrete and steel behavior through yield, plastic deformation, and on to collapse. Pushover analysis also ensured that the pipe piles and drilled shafts would not develop plastic behavior prior to column hinging. This would be undesirable since the foundations are below water and not readily inspectable. Figure 9 shows a typical pushover model with the colored dots indicating the locations of hinging at this intermediate load.

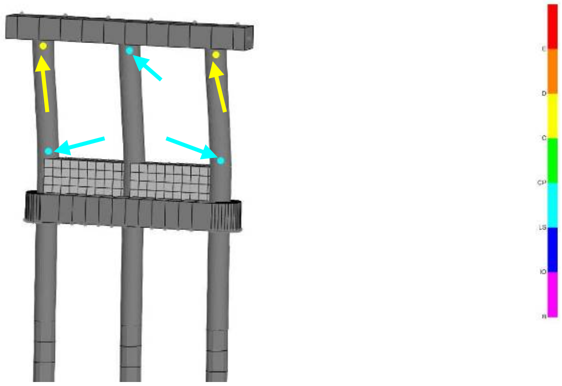

Figure 9: Pushover Analysis (colored dots = plastic hinge formation).

At the conclusion of the nonlinear time history analyses, the design team found that the relatively flexible piers coupled with longitudinal seismic dampers produced fully elastic behavior during the design event. As extra protection, reinforcement was detailed for ductile behavior in the potential column plastic hinge zones. Although not quantified, the bridges should be capable of resisting earthquakes with longer than 1000 year return periods. These new lake bridges are currently under construction (Figure 10 & 11). When completed, the LBL will have signature gateways that have been engineered for the unseen hazards beneath the surface.

Figure 10: Kentucky Lake approach girders.

Figure 11: Lake Barkley trestle bridge installation.

Benefits of Steel Superstructures

Both lake crossings have steel girder approaches with basket-handle arches over the navigation channels. Kentucky Lake's approaches have 129" web depths and spans of 336'-365'-365'-336' on the west and 292'-354'-354'-354'-292' on the east. Lake Barkley's approaches have 102" web depths for spans of 224.75'-270'-270'-270'-290'-250'-224.75' on the west and 211.25'-255'-255'-255'-255'-211.25' on the east. For these 1.19 miles of bridge, steel proved to be versatile and efficient for load resistance and also to mitigate site challenges.

At Kentucky Lake, the western bank of the former Tennessee River (now submerged by Kentucky Lake) was found to be susceptible to lateral spreading during a seismic event. Although options were explored to design the large diameter pipe piles to resist that lateral spreading force, the design team quickly decided that the best, more certain solution was to span over the area. Steel plate girders easily accomplished this with a tail span of 336 feet. The other spans were proportioned to take advantage of the girder depth required to span the problem area, resulting in an efficient four-span structural unit.

One project risk at Kentucky Lake was the deep embedment needed for the six-foot diameter steel pipe piles. Since one of the world's largest hydraulic pile hammers was required to achieve design depths, KYTC viewed fewer piles as a lower chance of installation problems. With fewer spans and foundations, the longer-span steel alternate resulted in lessened risk for bidders and the owner.

At Lake Barkley, hard limestone bedrock is relatively shallow below the lake. The region is known to have karst formations and many voids had been found along the new bridge's alignment. Several particularly large voids were discovered only a few months prior to bidding. Based on the best available subsurface data, the geotechnical team recommended relocating pier five by 20 feet, ahead-station.

Final design of the seven-span west unit was already well underway. It had been presented in the 60 percent plan set with the inner five spans set at 270 feet each. Span five was extended to 290 feet, span six reduced to 250 feet, and the structural unit was quickly redesigned for the letting. Because the spans were steel, the extra 20 feet of span could be accommodated with the 102" deep webs by merely thickening flanges at some locations. This might not have been possible without changing beam depth if prestressed concrete I-beam approach spans had been under design. Any change to beam depth would have also cascaded into changes to the substructures.

As with Kentucky Lake, Lake Barkley also had risk below the water – here it was due to known karst formations. Known and unknown voids meant added risk for a contractor during installation of the drilled shaft foundations. KYTC again favored alternates with fewer deep foundation elements, an advantage the longer steel spans provided.

Conclusions

Two lake crossings ($284 million) are under construction in one of the most seismically hazardous areas of the US. In addition to the main navigation spans, over a mile of approach spans were designated "essential" for seismic design. An extensive geotechnical effort was undertaken to provide the structural team the best possible information for seismic design. With deep foundations in a marine environment, the design team expected efficient seismic design to be a key for cost containment. Through rigorous seismic analysis the global structural performance was optimized and substructure cost minimized, keeping the projects within budget.

Model complexity and analysis rigor were increased each step of the design. In preliminary phase, numerous approach span possibilities were evaluated with simplified (linear) models and multimode response spectrum analysis. A sub-structuring approach was taken to approximate the nonlinear foundation response with linear springs.

In final design, piles, soil springs, and seismic damper elements were explicitly modeled. Nonlinear time history analysis was performed to more accurately capture expected displacements, to allow inclusion of velocity-dependent seismic dampers, and to account for nonlinear soil response directly. These nonlinearities were able to be included through judicious use of discrete nonlinear links and the Fast Nonlinear Analysis method.

Although conventional plastic column behavior was envisioned when project design criteria was adopted, the comprehensive seismic analyses allowed the design team to provide our client with a more robust design. Pier flexibility and displacement control provided by the longitudinal dampers resulted in elastic response for the design earthquake, with ductile details for greater quakes.

In addition to efficient load resistance and lighter weight girders, steel superstructures also allowed the design team to span problem areas, reduce risk in foundation installation, and facilitate rapid design changes only months before the letting.

Acknowledgment

Selected in 2006, the consultant final design team was led by Michael Baker International, with Palmer Engineering as a major subconsultant. Final geotechnical services were provided by Terracon, with ICA Engineering as a major subconsultant. Activities were directed and overseen by the Federal Highway Administration and many Kentucky Transportation Cabinet personnel in District 1 and Central Office. A true collaborative effort from all the stakeholders, administrators, owners and design team participants delivered these two bridges which will serve the traveling public for many decades.

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