RION-ANTIRION BRIDGE
Gulf Of Corinth, Greece
Winner of DFI’s
2007 Outstanding Project Award
Rion-Antirion Bridge

AN OLYMPIAN EFFORT OVERCOMES EXTREME GEOHAZARDS

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This year’s DFI Outstanding Project Award is for the design and construction of the foundation scheme for the largest cable-stayed bridge in the world. In 1993, Gefyra, SA (a French/Greek consortium led by VINCI of Paris, France) was awarded a €750 million ($1 billion+ USD) Concession Contract to design, build, finance, operate and maintain a three-span cable-stayed suspension bridge connecting the Peloponnesse, Greece’s southernmost peninsula, with the mainland across the Gulf of Corinth. The contract extends over a 42-year period, 7 years for design and construction and 35 years for operation. The project was financed through a combination of public funds, private equity and bank loans. Alternative foundation concepts that were considered included traditional driven piles, deeply embedded caissons and soil improvement.

PROJECT CHALLENGES

The extreme technical challenges faced included:

- Weak foundation soils composed of soft alluvial deposits consisting of interbedded layers of granular and cohesive materials with thin layers and lenses of gravel and liquefiable sand pockets; rock is believed to be at a depth of 1,000 m (3,500 ft) or more.
- A very deep seabed exceeding 60 m (200 ft).
- The requirement to withstand the collision of 180,000-ton tankers traveling at 16 knots.
- Maximum wind forces of 250 km/hour (155 mi/hour).
- Design seismic forces corresponding to Richter magnitudes of 7.0+ with peak ground accelerations of 0.48 g at seabed.
- Design tectonic movements of 2 m (7 ft) in any direction between any two adjacent bridge pier foundations/pylons.

Considering subsurface conditions and local seismicity and water depths, foundation design and construction methods were the key drivers for this project. In large part, the success of the project is owed to the unprecedented partnering and collaboration between all partners involved fostered under the leadership of Jean Paul Teyssandier and Gilles De Maublanc of VINCI Group (France) who served as lead Concessionaire and General Contractor. The joint venture’s lead Greek partners were Elliniki Technodomiki/AKTOR and J&P/AVAX. Alain Pecker of Geodynamique et Structure (France) served as lead Geotechnical Consultant/ Designer while Buckland and Taylor (Canada) served as Design Checkers with Ralph Peck and Ricardo Dobry (U.S.) as Special Advisors on foundation issues, Langan International/Langan Engineering and Environmental Services P.C. (George E. Leventis, Gregory Biesiadecki and Diane Fiorelli) served as Technical Advisor on geotechnical, geodynamic and foundation/marine construction issues.

INNOVATIONS

The innovative foundation system, designed in response to the technical challenges, consists of three 90-m (300-ft) and one 80-m (270-ft) diameter piers; and includes the use of up to 30-m (100-ft) long, 2-m (7-ft) diameter steel inclusions to reinforce the weak foundation soils. These inclusions increase the shear strength sufficiently to withstand the seismic forces as well as hydrodynamic water pressures likely to occur during the design earthquake. Three of the four bridge pylons that support the main bridge deck are founded on deep bridge piers on top of the reinforced soil zone; there are 200 inclusions below each pier typically driven at spacings of 8 m x 8 m (±26 ft x 26 ft). A gravel layer isolates the inclusions from the piers to reduce transfer of the shear forces from the reinforced ground to the superstructure.

Centrifuge model tests validated the model concepts by providing information on the ultimate lateral bearing capacities of the foundation and its failure behavior. Three distinctive
failure mechanisms were predicted from the soil-structure interaction modeling: a sliding mode, a combined sliding/rotational mode and a rotational mode; while the centrifuge test results indicated two distinctive failure features: digging of the front toe into the soils and uplift of the tension side of the footing. The numerical models confirmed that the steel inclusions provided additional shear resistance in the soil and tended to act as load paths to transfer loads into deeper and stronger soil strata near their tips.

This foundation scheme represents the first implementation in geotechnical earthquake engineering of a concept known as capacity design principle, typically used in earthquake structural engineering; the gravel layer is equivalent to the “plastic hinge” and the “overstrength” is provided by the inclusions. Analytical and numerical methods, including limit analyses based on yield design theory and two- and three-dimensional non-linear finite element models were used to evaluate the behavior of the foundation system and optimize the spacing of the inclusions.

Three of the four piers (M1, M2 and M3) rest directly on a 3-m (10-ft) thick filter and gravel ballast layer placed over and around the soil reinforcing inclusions. At pier M4 the designers found it beneficial to increase the dredging quantities to reach a deeper gravel deposit and eliminate the inclusions. At piers M1, M2 and M3, the inclusions increase the shear strength of the in-situ soils without being connected to the pier base; the top of each inclusion is 0.75 m (2.5 ft) below the base of pier. The non-connection of the inclusions to the pier base limits the inertial shear forces that can be generated by the superstructure during seismic events. All piers act as gravity base structures free to slide during seismic events providing additional isolation of seismic forces. The internal hysteretic damping of the reinforced soil provides a large portion of the total available damping.

Similarly, and in order for the superstructure to be compatible with the bridge foundations, a continuous suspended deck was designed. Movements of the deck under earthquake conditions are controlled by a series of large dampers and fuses at the top of each pier and by highly sophisticated joint mechanisms at its two ends where the deck meets the approach viaducts.

**CONSTRUCTION METHODS**

New construction techniques were developed to accommodate construction of the piers in 60-to 65-m (200-ft) deep water. The steel pipe inclusions were installed using underwater hydraulic hammers from a specially designed tension leg barge kept in position by four 700-ton counterweights. A specifically designed and constructed “catamaran” with a gantry system attached to the barge allowed placement of the inclusions at their design locations and of the final gravel layer to leveling tolerances of ±5 cm (2 in). The entire operation was guided by GPS and quality controlled using high resolution sonar imaging.

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dry dock; about 250 m x 100 m (800 ft x 300 ft) was created for the construction of the pier bases.

In a departure from the tender phase concept, the original single dry dock was modified to accommodate the construction of two pier bases simultaneously. A costly floating front gate was replaced with a sheet pile supported dike, which allowed the dry dock to be sealed off and dewatered for the construction of the first two piers. When the first inland pier reached a proper height, the dike was removed and the pier was floated out to the wet dock; it was then replaced by the second pier which essentially acted as a “dam” (with additional sheet pile sealing walls on each side) allowing for the dry dock to be de-watered again. This cycle was repeated to complete all four pier bases.

A second staging area, the wet dock, was used to construct the submerged portion of the main piers prior to sinking them at their final locations. This second staging area was connected to the Antirion shore. The floating pier base was held in position by three steel mooring chains; one chain anchored on land, while the others anchored to single 2-m (7-ft) diameter steel piles driven into the seabed. A third staging area of approximately 15,000 sq m (160,000 sq ft) on the Rion side accommodated storage and prefabrication of reinforcing bars, offices, a warehouse and a service area for embarking on small boats. This staging area supported the construction of the Rion approach.

Construction of the foundation piers was performed by employing methods and equipment typically used for offshore gravity oil platforms. The pier base was constructed in the dry dock on the Antirion staging area using tower cranes, one of which was later fixed to the base and followed the pier shaft throughout its construction. When the dry dock concrete works were completed with approximately 18,000 m³ (24,000 cu yd) of concrete for each pier, the dry dock was flooded, the dike removed and the pier base towed to the wet dock using tugs. At the wet dock, the piers were moored in 60 m (200 ft) water depth. Construction of the pier shaft continued in lifts using sea water as ballast to control trim, freeboard and stability. Work at the wet dock proceeded to the height necessary for pier shaft stability and to extend above the water level after each pier was placed in its final position.

Prior to the tow out of each pier from the wet dock to its final position, the seabed had to be prepared to receive the pier foundations at each pylon location. This included relocating existing high-voltage electric cables that were resting on the seabed, excavating the upper soils and leveling the seabed at each pier location using a remotely operated dredging vehicle, placing the gravel ballast bed to very tight tolerances and installing the soil reinforcing pipe inclusions. The gravel ballast and the steel pipe inclusions were installed from a specially designed barge kept in position by four 700 ton counterweights and the principle of tension leg platforms. The barge and gantry system was equipped with a guiding pipe that allowed the driving of the inclusions using an underwater hydraulic hammer. After the seabed was leveled and the soil reinforcement installed, each 90 m (300 ft) diameter pier was towed to its final position and “sunk” into place by ballasting its hollow chambers with sea water. Positioning was controlled by GPS and was accomplished to within 5 cm to 35 cm (2 to 14 in) of each pier’s theoretical location.

PIER PERFORMANCE

Settlements were estimated for each pier base. The vertical stress distribution was analyzed using 3D Finite Element analyses to model the specific characteristics of each pier, imposed load, pier diameter and foundation subgrade and to account for the length and spacing of inclusions. The stress distribution was computed to a depth of 120 m (400 ft) taking into account the unloading stresses due to excavation. Compressibility parameters of the soil were determined.
coinciding with the available CPT records. The direction cosines of the vector normal to the plane were computed to obtain the direction and magnitude of the maximum foundation tilt for each pier.

Inclusion installation records were kept during driving. Unlike typical piles, there were no driving criteria for the steel inclusions. Instead, hammer blows and total transferred energy were plotted with depth on an inclusion basis and most importantly on a quadrant basis for each pier. The intent was to identify potential weaker areas that could result in excessive settlement and/or tilt. After each pier base was in place, pre-loading of the piers was initiated by filling the hollow base chambers and the pier itself with seawater to apply the full design load. This method allowed a full-scale test to be performed and verified the behavioral characteristics of the underlying soil prior to construction of the superstructure. Settlement and tilt movements were monitored and recorded, so that they could be accounted for as the pylon superstructure construction progressed.

Settlement and maximum tilt of the foundation piers during preloading were typically less than predicted. Due to the lower than predicted settlements, the tops of piers M1, M2 and M3 are actually higher than designed; the difference in elevation being corrected within each capping slab below the bridge deck.

**CONCLUSIONS**

Foundation construction for a bridge spanning the Gulf of Corinth, founded in 65-m (200-ft) deep waters on marginal soils was not without risks. The key for the Contractor in mitigating these risks was identification, assessment of probability, and development of contingency and/or risk management plans. Risks due to construction cost overruns were mitigated by the fact that the Concessionaire and the Contractor were solely responsible for all design and construction methods and associated costs and had the foresight to heavily invest in the design and achieve a combination of minimum cost and practical time allocation.

The Contractor obtained critical highly specialized and often custom pieces of equipment at the start of the project to achieve the desired results. The availability and capabilities of this equipment were factored into the design. The risk of potential accidents that could result in short term or permanent loss of this equipment was covered by insurance policies.

Another form of risk was the shortage of skilled laborers for the unique type of work involved in this project and the strong labor unions in Greece. To mitigate these risks, the Contractor undertook a proactive approach by establishing an on-site training center and program designed to develop a skilled labor pool of foremen, gang leaders and laborers necessary to meet the project demands. The Contractor opted to train locally rather than import skilled labor due to the language advantages and the local workers’ good spirit and willingness to learn.

While proper training may have caused some initial delays in the early stages of construction, the long term benefit has been justified. Partnering among the various team members was key to achieving the desired end results. The Concessionaire fostered an unprecedented spirit of collaboration and focus to a common goal. The design and construction process was a remarkable experience that allowed significant challenges to been identified, solutions prepared and construction executed.

The Rion-Antirion Bridge was completed within budget and opened four months ahead of schedule to allow for the Olympic Flame to cross on August 8, 2004. The project set numerous world records including: longest cable-stayed suspended bridge deck 2,400 m (8,000 ft); deepest bridge foundations set at sea depths of 65 m (200 ft); largest bridge foundations – each pylon base is 90 m (300 ft) in diameter; first use of deep steel pipe inclusions to reinforce weak subsurface foundation soils; and most innovative foundation system of “floating” pier bases bearing on a gravel bed over reinforced soils. For these technical achievements the project was awarded the 2005 ASCE Outstanding Civil Engineering Achievement Award (OPAL). It was the first time that a project outside the U.S. has received the OPAL. The project has received widespread media coverage including specials on the Discovery and National Geographic channels.

Visit www.langan.com/rionawards to view a short video on The Rion-Antirion Bridge
RION-ANTIRION BRIDGE PIER FOUNDATIONS

Driving of 2m-dia. steel pipe inclusions from catamaran assembly for foundation pier base

Support material barge with gravel for isolation layer on the left

Catamaran with gantry and tension leg barge on the right