A rendering superimposed onto a photo of the Gulf of Corinth, above, shows the Rion-Antirion Bridge as it will appear when it is completed in 2004. Crossing a 2,500 m stretch of water, it will be the longest cable-stayed bridge in the world, featuring three main spans suspended from four piers.
The 90 m diameter foundation caissons were constructed two at a time to a height of 15 m before being towed to a wet dock for additional construction. Now in place, the caissons rest on soft soils that have been strengthened by inserting dozens of hollow steel pipes 25 to 30 m long into the seabed.

CROSSING

Unique soil-enhancing and foundation techniques, the longest cable-stayed deck in the world, and innovative seismic systems will enable the Rion-Antirion Bridge to connect the Greek mainland to the Peloponnese. By Jean-Paul Teyssandier
A million years ago the Peloponnese, Greece’s southernmost peninsula, was firmly connected to the mainland, and the Gulf of Corinth did not exist. Over the course of several millennia, however, the Peloponnese began to drift southward, creating the gulf that now nearly separates much of the peninsula—home to the city of Olympia, the site of the original Olympic Games—from the rest of Greece.

Today a slow and unreliable ferry system that transports vehicles across the gulf forms the main link between the northwestern part of Greece and the Peloponnese. Soon an extraordinary bridge will replace the ferry system, which carries roughly 10,000 vehicles each day but becomes inoperable in bad weather and high winds. The Rion-Antirion Bridge will reduce the time that it takes to cross the gulf from 45 minutes to 5 minutes and will not be affected by weather. It is hoped that the
Bridge will facilitate not only travel but also communications between the northwestern part of Greece and the peninsula, bringing economic benefits to both.

The Greek government determined in 1992 that a build/operate/transfer scheme would be the most appropriate form of project delivery for the bridge. A consortium led by the French design and construction firm Vinci Construction was awarded the contract in 1996 following negotiations that proved to be quite lengthy because of the novelty of this type of contract in Greece. The consortium devoted two more years to raising the necessary capital, and the contract took effect in December 1997.

When completed in 2004, the Rion-Antirion Bridge will be the longest cable-stayed bridge in the world. Crossing a 2,500 m stretch of water, the bridge will consist of a cable-stayed main bridge 2,252 m long and two approach viaducts. The main bridge will have two side spans 286 m long and three middle spans of 560 m (see figure on page 48). The main bridge will repose on four foundations 90 m in diameter—the biggest ever built for a bridge—that in turn will rest on the seabed. The deck will be suspended from cables anchored to the pylons atop these foundations.

The environment in which the bridge is being constructed combines a number of physical challenges and thus makes this project quite complex. Deep water (up to 65 m) combined with deep soil strata of weak alluviums and the possibility of strong seismic activity—including potential tectonic movements—posed formidable challenges to the bridge's structural engineers.

The seismic threat arises from the prehistoric drifts in the earth's crust that shifted the Peloponnesse away from mainland Greece. The peninsula continues to move away from the mainland by a few millimeters each year. As a result, several active faults exist in the area that can produce intense seismic activity. In the past 35 years, three earthquakes exceeding 6.5 on the Richter scale have occurred in the Gulf of Corinth.

In view of these threats, the contract specified that the bridge be able to withstand an earthquake with a 2,000-year return period. The response spectrum at the seabed level of this event would have a peak ground acceleration of 0.48g and a maximum acceleration of 1.2g for periods up to one second. Such a spectrum is more stringent...
than the one corresponding to the earthquake that struck Izmit, Turkey, in 1999, which measured 7.4 on the Richter scale. The bridge must also accommodate vertical and horizontal fault movements of up to 2 m. Although the bridge must be designed to withstand the impact from a 160,000 Mg tanker sailing at 8.2 m/s, as well as high winds, it was the seismic conditions that dictated the design.

The geotechnical conditions of the seabed exacerbated the challenge posed by the seismic loads. Soil investigations to a depth of 100 m below the seabed revealed no bedrock; in fact, based on further geological studies, it is believed that there is no bedrock even at depths of 500 m beneath the seabed. This meant that the bridge had to be founded on soil rather than rock. The soil consists of a cohesionless layer of sand and gravel extending from the mud line to a depth of 4 to 7 m in most locations. Beneath this layer, the soil profile, which is rather erratic and heterogeneous, includes strata of sand, silty sand, and silty clay. At depths beyond 30 m the soils are more homogeneous and consist mainly of silty clays or clays.

Given the nature of the soils, liquefaction did not appear to be a problem to the design team. However on the mainland the first 20 m are seen as susceptible. This led the engineers to design very deep pile foundations for the approach viaduct on the Antirion side.

To develop a foundation scheme that would be appropriate for the main bridge given these soil conditions, such alternative concepts as pile foundations, deeply embedded caissons, and soil substitution were investigated to determine their cost, feasibility, and technical soundness. This analysis showed that a shallow foundation was the most satisfactory solution as long as the top 20 m of soils could be improved to the point where the shear strength would be sufficient to withstand the large seismic forces as well as hydrodynamic water pressures likely to be experienced by the bridge during an extreme seismic event. The upper layer of soil was therefore reinforced using an approach developed expressly for this project that used what are referred to as inclusions. These inclusions—hollow steel pipes 25 to 30 m long and 2 m in diameter—were driven into the upper layer of soil at a regular spacing of 7 to 8 m (depending on the pier). Some 150 to 200 pipes were driven at each pier location, and the area was then covered with a 3 m thick gravel layer. It is on this layer that the foundations rest. Inclusions were not required under the pier closest to the Antirion shore because a thick layer of gravel already existed at that location.

Although the inclusions resemble pile foundations, they do not behave as such. Since no connection exists between the inclusions and the foundation base, the base can move upward and slide laterally with respect to the soil. To validate this innovative type of soil reinforcement, extensive numerical studies and centrifuge model tests were conducted at the Laboratoire Central des Ponts et Chaussées, a facility operated by the French government for research in civil engineering, transportation, and environmental engineering. These tests established the soundness of the foundation design.

Each foundation base, which will rest on the reinforced soil, consists of a 90 m diameter caisson made of reinforced concrete. Because of their size, the caissons are strengthened by 32 radial beams, each 1 m thick. The radial beams decrease in height from 13.5 m at the center of the caisson to 9 m at its edge and are 26 m long (see illustration on page 49). Above the base, a conical concrete shaft with a diameter that tapers from 38 m at the bottom to 27 m at the top forms the upper part of the underwater foundation. Its height will vary from 37 to 53 m, depending on the water depth at each pier location. Above sea level, an octagonal pier shaft rises 28 m in the case of the two center piers and 6 m in the case of the two end piers. The pier shaft is topped by an inverted pyramid 16 m high that supports a square base 40 m on a side. Four legs made of high-strength reinforced concrete, each 4 m square, rise from this square base. The four legs angle toward each other and are joined together at their tops to impart the rigidity necessary to support the asymmetrical service loads and seismic forces. The tops of the legs are rigidly embedded in a pier head that is 35 m high and comprises a steel core connected.
The dry dock near the construction site, above, measures 200 m long, 100 m wide, and 14 m deep. Two caissons were constructed at a time, with the one located in the foreground helping to block the seawater. Once this first caisson was completed, it was towed to the wet dock, the second caisson was moved into the foreground position, and construction of a third caisson was begun.

to two vertical concrete walls that are 2.5 m thick. Each pier forms a monolithic structure extending up to 230 m from the bottom of the sea to the top of the pier head.

These foundations are very large and quite costly, but only a few are required because they can support long spans. Initially a suspension bridge with a span of about 1,500 m was investigated, but a solution involving multiple cable-stayed spans was found to be more economical. However, accommodating the 2 m tectonic movements that are possible between adjacent piers proved to be a very difficult challenge. Finally the design team found that the best solution was to adopt a continuous deck that would be 2,252 m long and fully suspended from the pylon heads. This would create an isolation system efficient enough to significantly reduce the effect of the seismic forces on the deck and would impart enough flexibility to accommodate relative movements between piers.

The deck will be 27 m wide and will carry two traffic lanes in each direction. This composite steel structure will have two 2.2 m high longitudinal steel plate girders—one on each side. Transverse plate girders that also are 2.2 m high will connect the longitudinal girders every 4 m in the longitudinal direction. This steel structure will be topped by a 0.25 m thick concrete slab.
The stay cables are anchored to the pylon heads in two rows and incline in a fan shape to the sides of the deck, where they are anchored. The cables use a system designed by a subsidiary of Vinci, Freyssinet International. Each galvanized strand in the system is protected by its own polyethylene sheath. The thickest cable comprises 70 strands, each 15 mm in diameter.

Because it will be suspended, the deck will be free to accommodate all thermal and tectonic movements in the longitudinal direction. In the transverse direction the deck will behave like a pendulum, and its movements during a large seismic event will be buffered by four hydraulic dampers connected to each pylon base. The capacity of each damper, whether in tension or compression, is approximately 3,500 kN. The dynamic relative movement allowed between the deck and the pylons during an extreme seismic event will be approximately 3.5 m, at velocities up to 1.6 m/s. However, an additional system had to be designed to keep the deck in position during strong winds. Here a horizontal strut with a capacity of 10,000 kN connects each pylon base; during a strong seismic event, the strut will break, thus activating the dampers. A prototype test for these dampers was recently performed by the California Department of Transportation at a testing facility operated by the University of California at San Diego, and the results validated the concept.

The connection with the approach viaduct at each end of the main bridge must accommodate the large movements of the cable-stayed deck that will be caused by thermal, tectonic, and seismic forces. Under service conditions the longitudinal movements may reach 2.5 m but the transverse movement will be negligible. Under extreme conditions, movements of up to 5 m could occur in either direction. For this reason, the ends of the cable-stayed deck are supported by a 14 m high vertical steel frame that can accommodate uplift loads and longitudinal deck movements. The connection between the deck and the steel frame is similar to that between the deck and pylon bases, with two dampers and a strut device.

At present all of the foundations are in place and construction of the first pylon is under way. Dredging the seabed, driving the inclusions, and placing and leveling the gravel layer in water 65 m deep were major marine operations and required special equipment and procedures. A custom-made tension-leg barge designed along the same lines as the fixed tension-leg platforms common in the oil industry was used, the greatest difference being that the barge could be moved from location to location. Dead weights lying on the seabed and tied to vertical anchor lines provided stability for the barge, which deployed the pile-driving and gravel-placing equipment. Once the marine work at one location was completed, the weights were raised and the barge was moved into the next position.

The construction methods used for the foundations were those commonly employed in building offshore concrete platforms: Each foundation base was constructed to a height of 15 m in a dry dock and then towed and moored to a wet dock. Here the foundation was completed with the construction of the conical shaft and then towed to its final position in the gulf and lowered into the water.

A number of features made the construction process for these foundations quite exceptional. The dry dock, established near the site, is 200 m long, 100 m wide, and
Since bedrock could not be reached, some 150 to 200 steel pipes were driven into the sand and gravel at the bottom of the gulf to stabilize the soils. A 3 m thick layer of gravel was then applied, and it is on this gravel layer that the caisson foundations rest. The caissons are strengthened by 32 radial beams, each 1 m thick, which can be seen in the cutaway view above.

14 m deep, and it accommodated the simultaneous construction of two bases. Once the construction of the first of the two bases was completed and towed to the wet dock, the partially constructed second base was floated into the spot previously occupied by the first base and used as a closure for the dry dock. This allowed the water inside the dock to be pumped out so that the second base could be completed and the construction of the third could begin.

During the construction of the conical shaft at the wet dock the foundations remained afloat and moored, and their balance was quite sensitive to wind and currents. The 32 compartments created in the foundation bases by the radial beams were used to keep the foundations perfectly vertical through a differential ballasting system controlled by computer on a 24-hour basis. Once in their final position, the foundations were filled with water to accelerate settlement, which was significant (between 0.2 and 0.3 m). This preloading was maintained during the in situ construction of the pier shafts and pyramids so that corrections could be made for differential settlements before construction of the pylon leg began.

The steel core of the pylon heads will be lifted into position by a large floating crane with a height of up to 170 m. The steel deck structure is being fabricated in the United Kingdom by Cleveland Bridge and Engineering Company, Ltd., based in Darlington. Deck segments 12 m long and 27 m wide—including the concrete slab—will be assembled on-site. The deck will be erected using the balanced-cantilever technique: each segment will be transported and lifted by the floating crane, bolted to the segment that is already in place, and then connected to two new cables.

The Rion-Antirion Bridge exhibits exceptional features in its design and construction, many deriving from the seismic resistance requirements. This $750-million project is being funded by the shareholders of the concession company GEFYRA S.A. (composed of VINCI Group and several Greek contractors), a loan to GEFYRA from the European Investment Bank, and a subvention from the Greek government. With construction of the foundations completed and the erection of the first pylon under way, the project is on target to meet its completion date of December 2004.

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PROJECT CREDITS

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The main bridge will have three 560 m long middle spans and two 286 m long side spans, as well as a 392 m long approach structure on the Rion side, shown on the left side of this elevation, and a 239 m long approach structure on the Antirion side. Deep pile foundations were used under the pier closest to the Antirion side, where a layer of gravel raised concerns over possible liquefaction in the event of a strong earthquake.