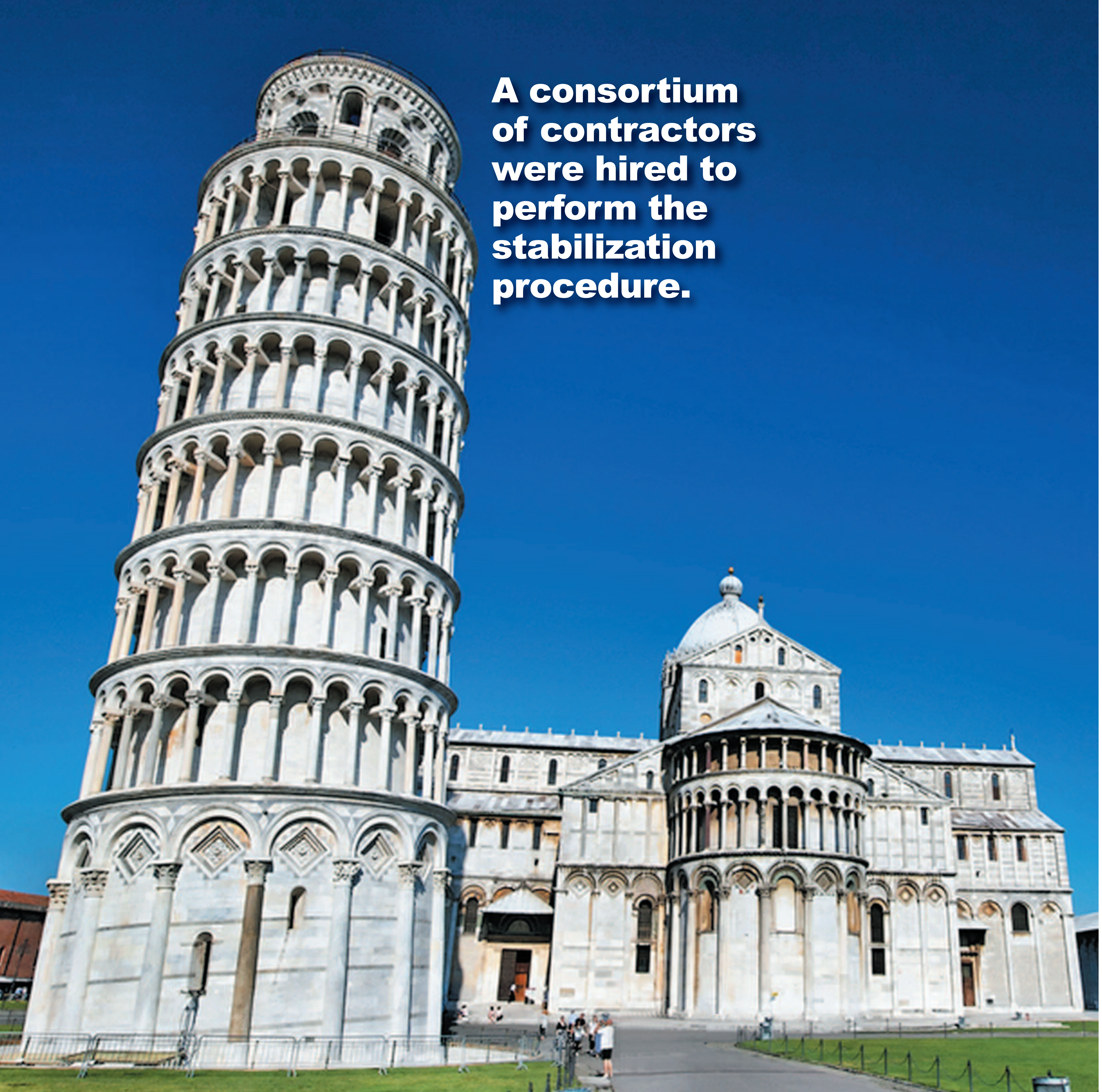

A consortium of contractors were hired to perform the stabilization procedure.

Propping Up The Leaning Tower of Pisa

By Federico Pagliacci and Vincent Jue

The following, article which comes to us from ADSC International Members Trevi S.p.A. and Soilmec, highlights the innovative repairs undertaken at the iconic, ***Leaning Tower of Pisa*** *in the early 2000s. I happened to be at the site towards the end of the project described as I was visiting Pisa on my way to a meeting of the International Society for Micropiles that was held in Venice, Italy. (Administered by the ADSC Planning Staff, ISM's most recent meeting was held in Krakow, Poland in early June of this year). At the time of my visit the "Tower" had just been opened to the public and Trevi's equipment was still on site. I'm not sure if the "Tower" is one of the "Eight Wonders of the World," but the fact that it is still standing, though on a dramatic tilt is a wonder indeed. When ascending the spiral staircase to the top one goes from leaning to the left to leaning to the right and back and forth until one reaches the observation level from which you can look out on the medieval town of Pisa. It is an impressive sight from an impressive structure. (Editor)*

Standing proudly within the Piazza dei Miracoli (Square of Miracles) in Pisa, Italy, the Leaning Tower of Pisa seems like a miracle given its seemingly gravity-defying tilt. However, the tilt of this world renowned architectural gem continued to increase over time until it was very close to collapse. A multidisciplinary group of companies were hired to save the Tower, while the eyes of the world watched.

Stand Against Time

Built in stages over time, the construction of the Tower began in 1173. It wasn't completed until 1370. The Tower is composed of a 50.8 ft diameter cylindrical masonry body surrounded by loggias with arches and columns. The original height of the Tower was 197 ft. It now stands 183 ft on the south side and 186 ft on the north side. The Tower weighs approximately 14,500 tons.

Unfortunately, the massive weight of the Tower rests on soft ground consisting of three distinct layers. Layer A is approximately 33 ft thick and primarily consists of an estuarine mixture of silts, clays, and sands laid down under tidal conditions. At the bottom of this layer is a 7 ft thick layer of fine sand, which is in contact with the underlying clay. Layer B consists of layers of clay, medium or "Pacone" clay on the top, stiff clay and sand in the middle, and stiff clay at the bottom reaching down to an overall depth of approximately 131 ft. Layer C is dense sand that reaches to an overall depth of close to 230 ft.

This ground composition posed problems from the start, and the Tower began leaning even during construction. A key problem is the upper "Pacone" clay, which is very sensitive and loses much of its strength if disturbed. As a result, a depression approximately 7.2 ft deep developed under the Tower, centered towards the south side, near the top of Layer B.

Based on extensive measurements of the Tower foundations during the recent reconstruction efforts, the Tower is subjected to seasonal rotations due to ground water table fluctuations. Seasonal heavy rainstorms occur in September through

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December. The Tower's tilt increases after each heavy rain. The sharp rise in ground water levels during a heavy storm isn't symmetric. In effect, the water table during a storm slowly and temporarily boosts the land on the north side, pushing the

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Installation of complex monitoring equipment to allow continuous measurement of the Tower's displacements, rotations, stresses, temperatures and vibrations.

Tower to lean further south. Once this was discovered, a custom drainage system was installed to normalize the water table below the Tower.

However, the most significant increases in tilt occurred when people interfered in an attempt to stabilize the Tower. In 1935 workers drilled a network of angled holes into the foundation masonry and injected them with cement grout in order to seal the base from water. This work caused the Tower to suddenly shift to the south by 0.4 in. In the 1960s water was manually extracted from the subsoil to meet increased water demans due to several years of drought. This intervention caused the Tower to lurch further sideways, moving about 0.5 in.

These interventions confirmed how precarious and sensitive the Tower was. It was therefore clear that future restoration teams had to be even more cautious. In 1989 a similarly constructed bell tower in Pavia, Italy suddenly collapsed. This event prompted the closure of the Leaning Tower of Pisa. In 1990 the Italian Prime Minister formed the International Committee for the Safeguard of the Leaning Tower of Pisa in order to implement stabilization measures. The committee, chaired by internationally acclaimed geotechnical engineer, Michele Jamiolkowski, included geotechnical and structural designers, stone material specialists, restorers, and art historians.

Emergency Measures

A consortium of contractors, Trevi, Bonifica, Enel Hydro, Italsonda, and Rodio, were hired to perform the stabilization procedure. ADSC International Contractor Member, Trevi was involved in all of the temporary and permanent phases of the geotechnical work.

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The consortium faced the immediate risk of the Tower collapsing due to overturning, or to rupturing masonry. In order to meet the demands of the public and the government, the contractors faced the challenge of preserving the historical, architectural, cultural, and structural features of the existing Tower. As an example, permanent stabilization couldn't involve propping or visible support.

It quickly became clear that finding a long-term solution for the

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Construction of the removable concrete ring around the Tower foundation.

Steel cables sheathed in Teflon being positioned and tensioned around the first story cornice with a specially-designed device.

stability of the monument was going to take a lot of time and planning, and was going to require advanced computer modeling, large-scale field testing, continuous high-precision monitoring and control, and a good deal of patience.

While coming up with a permanent solution, it was necessary to take emergency measures to temporarily stabilize the Tower foundations.

The first step was to install a complex monitoring system to continuously measure many Tower parameters, including displacements, rotations, stresses, temperatures, and vibrations. In

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1993, once this was in place, 600 tons of lead weights were applied to the north side of the foundation to counterbalance the overturning tilt of the Tower. This was accomplished by building a post-tensioned, removable concrete ring around the base of the Tower, where the lead weights were stacked. In order to make the concrete ring adhere to the Tower, it was tensioned using 6-thread steel cables fed through cavities within the concrete. In 1995, the lead weights were increased to total 1,000 tons.

When completed, this post-tensioned concrete ring slightly reduced the inclination of the Tower, and more importantly stopped its rotational motion. However, these unsightly lead weights provided only a temporary solution.

In 1992 critical areas of the Tower were "hooped" with steel cables sheathed in Teflon and slightly pre-tensioned. These temporary strands were removed near the end of 2000 and replaced with more aesthetic, permanent circumferential wires using 4 mm stainless steel strands. The permanent hoop below the first story cornice is made up of 116 coils in four layers with an applied tensile force of 9 tons. The hoop at the base of the second story is comprised of 60 coils in three layers with an applied tensile force of 4.6 tons. A special device was developed to position and tension these wires.

In 1998 a system of temporary rigging trestles was put in place to help prevent any potential movement during restoration operations. Two sub-horizontal steel backstays were connected to the Tower at the third story utilizing two metal frames on the north side. The trestles were supported by 108 ft long micropiles that were drilled using a Soilmec SM-405 rig*. In the event of adverse movements of the Tower, this safeguard cabling could be tensioned to hold the Tower in place. The maximum force that could have been exerted by each of the backstays equaled a force of 150 tons. At most a 120 ton-force was applied.

Practice Makes Perfect

Given the importance and fragility of the monument, many possible permanent stabilization methods were investigated. Ultimately the method of

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Temporary rigging trestle used to attach a backstay to the Tower, to prevent potential movement of the Tower during restoration operations.

Soil excavation from under the Tower during the final geotechnical stabilisation.

soil extraction was selected, using soil extraction tubes installed adjacent to, and only beneath the north side of the foundation. This plan was arrived at by the application of physical models and advanced numerical analysis. The team determined that the soil extraction had to take place north of a critical line located about half a radius from the northern edge of the foundation. This was undertaken to maintain Tower stability.

A large-scale field test was performed in 1995-1996 in order to verify that it was truly feasible to extract soil without triggering a Tower collapse. In the Piazza, Trevi built a 23 ft diameter circular foundation of reinforced concrete at approximately 4.9 ft below ground. On top of this foundation Trevi built a structure composed of over 150 concrete blocks geometrically placed so as to simulate the Tower's pressure distribution on the ground. Instrumentation was installed in the concrete and soil to monitor settlements, rotation, contact pressure, and pore pressure during and after the soil extraction tests. The procedure had to allow for extracting soil with precise control and without causing vibrations.

For this delicate under-excavation work a drill that could advance without disturbing the surrounding ground was required. Trevi used the newly-developed Soilmec SM-405* drill rig with a hollow-stemmed continuous flight auger (CFA) housed inside a 7 in counter-rotating diameter casing instrumented with a probe sensor that was mounted onto the drill bit.

During soil excavation, the casing, auger and probe were advanced 64 ft at an inclined angle of 30 degrees with respect to ground level. The casing and auger were then withdrawn while counter-rotating thus creating an 18 qt borehole. During extraction, the probe was left in place so that the probe sensors could measure the controlled-collapse of the borehole which occurred a few minutes later.

This large-scale in-situ experiment demonstrated that the boreholes closed gently and that repeated extractions could be made from the same location. The experiment validated that soil could be safely extracted from beneath the Tower using their newly-developed equipment, drilling procedure, and communications plan.

Saving Pisa Tower

Trevi began limited excavation work under the actual Tower in 1999, using a Soilmec SM-450 rig to drill 12 boreholes lined with 8.7 in diameter casings within a 20 ft wide area. Each borehole started close to the monument and ended underneath it. The operation was slow and cumbersome with a maximum of two extractions per day. For the first few days of under-excavation, the Tower showed no discernable response but then slowly began to rotate northwards. After extracting 247 ft^3 of soil, 15% from under the foundation and 85% from the ground north, the Tower had rotated to the north by 130 in. At this time three lead blocks could be removed from the temporary concrete ring.

The success of the preliminary under-excavation led to soil extraction over the full width of the Tower

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Large-scale field test performed in the Piaaza.

The temporary post-tension concrete ring with lead blocks stacked on the north side of the Tower foundation. The backstay cables are also visible.

foundation that had begun in 2000. In preparation, 120 sensors were placed in, around, and outside the Tower. Telecoordinometers, GB pendulum, level meters, and inclinometers were placed on the central rotation axes of the Tower. Weather stations, thermometers, strain gauges, and external and internal stairwell deformometers were placed on the Tower perimeter.

Forty-one temporary extraction holes were then installed on the north side of the Tower at a depth of 64 ft, spaced 1.6 ft apart, and at an inclination angle of 30 degrees. The top section of each borehole featured an 8.7 in diameter fixed casing, 50.8 ft in length, followed by a lower borehole section with a 6.6 in casing. The lower borehole sections were beneath the Catino and Tower plinth. The Tower's northward rotation increased on average by 6 arc seconds per day brought about by the removal of approximately 127 qt of soil.

Upon completion, the Tower rotated toward the North by about 1,800" returning to the position recorded 200 years earlier. In addition, the uplift of the southern side of the foundation significantly reduced the bearing pressure applied to the stressed foundation soils.

The restoration was completed, the emergency measures removed, and the Tower reopened to the public in 2001. Experts expect the Tower to be safe for the next 200 or more years.

About the Authors

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