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The Tower of Pisa: an engineering miracle, yesterday and today

Due to its prominent lean, the Tower of Pisa is a monument that attracts tourists but precisely because of this lean, it is also at risk. *GDI* takes a look at the work of one of Soilmec's employees – Alessandro Ditillo – who was involved in a piling project to protect the UNESCO World Heritage Site

For almost 900 years, the miracle of engineering that is the Tower of Pisa has been challenging the natural laws of physics, fascinating everyone fortunate enough to see it. Today, however, the Tower of Pisa is no longer in the critical condition it was in 20 years ago and this was made possible thanks to the brilliance of some great minds and solid teamwork that succeeded in turning the clock back by a century, making the Tower safe for future generations.

In 1998 Alessandro Ditillo was a young engineer who had graduated only a few years previously and immediately been offered a position at Soilmec - a successful company that was well-known in the world of ground engineering for building hi-tech, cutting-edge machinery. His job at that time was to supervise some auxiliary work being carried out on the Trevi "Tower of Pisa" site.

Trevi, a company that like Soilmec was part of the namesake group, had been appointed to carry out drilling work on the Tower, as well as some additional support work, as part of the consortium entrusted with carrying out consolidation and restoration work on the Tower of Pisa.

Ditillo says of his time at the Tower of Pisa: "Working on the project was like a sort of time machine but one that used methods and machinery that had never been thought of before."

Established in 1990, the companies in the consortium created to consolidate the Tower of Pisa were Bonifica, Italsonda, Rodio and Trevi (including Soilmec), all working towards making the monument safe under the guidance of an international committee of 14 experts in different fields coordinated by Professor Michele Jamiolkowski.

One of the first jobs allocated to Ditillo was to check the structure of the anchoring stands that would have to support the loads from the Tower support staying.

The system adopted by the consortium involved in the Tower of Pisa project consisted of using an under-excavation technique

A Soilmec SM-405 being used for part of the under-excavation work on the Tower of Pisa

The history of the Tower's lean

During the first stage of construction, the Tower tilted towards the north. When construction work recommenced, the Tower started to tilt southwards and the inclination continued. The inclination then accelerated greatly due to the excavation of the catino. Then the inclination proceeded basically at the same rate. In 1911 a modern monitoring system was put in place.

The collapse, in 1989, of Pavia Cathedral's thirteenth-century civic tower combined with the Ministry of Public Works proclaiming the scarce safety margin of the Leaning Tower, which caused it to be closed to visitors in January 1990, prompted the Italian Prime Minister to appoint an international committee to consider the problem.

The international committee appointed a consortium of five Italians companies to take care of the executive design and the execution of temporary and long-term structural and geotechnical interventions. The consortium managed 203 separate activities within the project for a total amount of about €26 million (US$30 million).

on the Tower while at the same time, merely as a precautionary measure, this would be backed up using a double cabled stayed support that would be wrapped around the Tower at the height of the colonnade of the second order and, passing above the roof of the Opera del Duomo, and anchored to the ground using two stands.

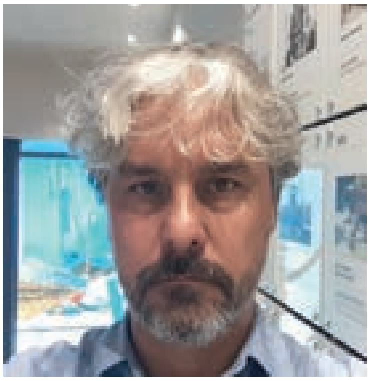
The project was basically divided into two main phases; the first consisted of the consolidation of the structure of the tower in elevation, by injecting cement mortar, fitting stainless steel bars and applying circumferential steel rods around the external façade.

The second step envisaged stabilisation of the Tower through excavation work, thanks to which a sexagesimal rotation of 0.5 degrees would be obtained. This work resulted in the Tower being returned to the angle of inclination it had at the start of the 19th century.

Examples of 3D CAD design and calculation of the finished elements for these structures were not easy to find in previously published work, but Ditillo managed to model this complicated system with the help of Professor Bertero, who patiently explained how the rods at the base of the support platform would behave and how to incorporate them in a model. This meant that for the first time he was able to develop a complete virtual model - consisting of soil, rods, support platform and stands - and to analyse the effective behaviour of the structure when subjected to the loads envisaged.

Twenty years on, all this seems normal and ordinary, but at the time the calculation capacity of computers and the software available were so poorly developed that everything was much more difficult and complex. Ditillo would launch his calculations of structures on Friday afternoon so that when he got to work the following Monday morning all the simulations would be complete. Today, this would probably only take about 10 minutes and the number of iterations for the subsequent optimisations would not be a problem. However, in those days, the race against time to straighten the leaning Tower of Pisa and secure it as quickly as possible demanded prompt and correct actions.

Furthermore, the figures were also out of the ordinary. Used to working with 10-19mm ropes for the movements required by the micropiling machines, with values of just a few thousand kilograms of weight at play, the normal load now had to sustain a force of 1500kN and an exceptional load in extreme conditions of 2000kN using 56mm diameter cables. Touching such things first-hand and seeing them being installed



Alessandro Ditillo worked extensively on the project to straighten the Leaning Tower of Pisa

during the assembly phase, further highlighted the importance and uniqueness of the work being carried out.

There was great confidence in the operation and nobody ever truly feared something might collapse because all those involved in this extraordinary project were so clever and had such knowledge and such a belief in the work that the entire team was certain it would succeed and go down in history.

Load test of the stay supports at the in the Soilmec workshop in Cesena (Italy) before they were shipped to the Tower of Pisa

The first time Ditillo had gone up the Tower was many years previously, during a school trip, and on the way up, he too, had focused on that strange sensation that only the Tower of Pisa gives visitors as they climb it when the lean, which is first in your favour, then goes against you. Climbing the spiral steps and at a certain point having the impression of descending because of the lean, is a spell the Tower manages to cast on everyone.

But things were very different when the cable-stayed supports were installed; now, when he climbed the Tower he did not only count the 276 steps, contemplate the eight floors to climb and gaze at the bell tower that had been built askew, to counter the lean the Tower had already begun to acquire during its construction. Now, he also had to consider the work going on all around the site: the cables girding the Tower connected to the cable-stayed support, the wood cladding protecting the stones, those very stones that might collapse or implode because of the extreme strain caused by the Tower's lean, the sensors constantly monitoring all the Tower's vital parameters (lean, temperature, humidity, etc.).

Stabilising the Tower

Work undertaken by the Pisa Tower consortium included the installation of 15.2mm steel strands sheathed in plastic sheaths and slightly post-tensioned. Eight cables were below the first cornice, four cables at the base of the first balcony and two plus two plus two on the body of the first balcony.

6000kN of lead blocks were placed on the north edge of the plinth.

A cable stay structure was then designed and put in place to prevent potential unexpected movements. Two cables were lowered between the tower body at the third order and two block anchors on 33m-deep micropiles behind the Opera del Duomo building.

The distances between the centre of the Tower and the blocks were 105.3m (east) and 106.3m (west). The 4.5-degree angle was adopted in order to pass over the roof of the Opera building. The angles to the plane of maximum tilt were selected as a function of the possible location of the two anchor blocks.

The system was not conceived to support the Tower, but only to apply a stabilising force to it. For this reason, each cable passed over a saddle that took it to a vertical position and was connected to a tensioning mechanism equipped with both lead kentledges and hydraulic jacks. Each of the two systems could apply a maximum force of 1,500kN to each backstay; if both were used at the same time, the overall tensioning could not exceed 2,000kN. The actions of the kentledges and the jacks could be applied independently: the jacks allowed for faster intervention and the best tensioning regulation, while the kentledges permitted the tensioning force to be applied constantly for a long time.

Alessandro Ditillo is Director of the Large Diameter Pile Engineering Division at Soilmec, where he has over 20 years' experience of working in the ground engineering field. In his current position, he leads the Large Diameter Pile Division, which deals with developing pertinent equipment and all related technology