In 1990 the Leaning Tower of Pisa was closed to the public because its foundations were on the point of becoming unstable. Eleven years later, in June 2001, the Tower was handed back to the civic authorities in Pisa after the delicate task of stabilising the foundations had been successfully completed. In the July 1999 issue of Ingenia Professor John Burland described the history of construction of the Tower, its behaviour during and after construction and the work leading up to the implementation of the permanent stabilisation measures. At the time of writing the previous article the stabilisation measures had just commenced. He now tells the rest of the story.

**Introduction**

The Leaning Tower of Pisa is not just some cranky Disneyland tourist attraction. It is an architectural gem and would be one of the most important monuments of medieval Europe even if it were not leaning. Standing in the Piazza dei Miracoli, it is part of the complex of four major gleaming white medieval buildings comprising: the Cathedral (Duomo), its bell tower (the Leaning Tower), its Baptistry and the Cemetery (Camposanto).

As with the other buildings in the Piazza, the bell tower was intended to represent the civic pride and glory of the wealthy city state of Pisa and as such it is beautiful, unique and enigmatic. In 1990 the Tower was closed to the public because of fears for its safety and in the same year a Commission was established by the Italian Prime Minister to implement stabilisation measures. There can be no doubt about the importance of such an operation to Pisa, to Italy and to World Heritage.

My article of July 1999 ended with the following statement: After ten years of work the first positive step has been taken, but there is a long tense journey still ahead for the Tower – and for the
This article describes that journey; first it is necessary to summarise briefly some of the important details of the Tower and its behaviour.

**Details of construction**

The eight-storey tower is 53.3 m high above ground level and weighs 14,500 metric tonnes. Its masonry foundations are 19.6 m in diameter and have a maximum depth of 5.5 m below ground level. The foundations sloped towards the south at 5.5 degrees to the horizontal and in 1990 the seventh floor overhung the ground by about 4.5 m.

Construction is in the form of a hollow cylinder surrounded by colonnades. The inner and outer surfaces of the cylinder are faced with tightly jointed marble but the material between these facings consists of mortar and stones in which extensive voids have been found. A spiral stairway winds up within the walls of the Tower. The stability of the masonry at second-storey level on the south side has been a matter of major concern.

The underlying ground consists of three distinct layers. Layer A is about 10 m thick and consists of variable soft silty deposits laid down in shallow water (lagoonal, fluvial and estuarine conditions) less than 10,000 years ago. Layer B consists of very soft sensitive marine clays laid down up to 30,000 years ago which extend to a depth of 40 m. This stratum is laterally very uniform. Layer C is a dense sand extending to considerable depth.

The water table in Layer A is between 1 m and 2 m deep. The many soil borings around, and even beneath, the Tower show that the surface of Layer B is dish-shaped due to the weight of the Tower above it. From this it can be deduced that the average settlement of the Tower is about 3 m, which shows how very compressible is the underlying soil.

**History of construction**

Construction of the Tower began in August 1173. By about 1178 it had progressed to one quarter the way up the fourth storey and then the work stopped. The reason for stopping is not known, but had the construction continued much further the soil in Layer B would not have been strong enough to carry the load and the Tower would have fallen over.

Work recommenced nearly 100 years later in about 1272, by which time the strength of the clay had increased due to consolidation under the weight of the Tower (although this would not have been known). By about 1278 construction had reached the seventh level when work again stopped. There can be no doubt that, had the Tower been completed at this stage, it would have fallen over. In about 1360, when further consolidation of the underlying clay had taken place, work on the bell chamber commenced and was completed in about 1370 – nearly two hundred years after commencement of construction.

Another important detail is that in 1838 the architect Alessandro della Gherardesca excavated a walk-way (catino) around the base of the Tower so as to reveal the column plinths and

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*Figure 1: Section through the Tower*
foundation steps, as was originally intended. The result of this was an inrush of water on the south side, since here the excavation is below the water table, and there is evidence to suggest that the inclination of the Tower increased by more than a quarter of a degree at this time. In 1995 it was found that Gherardesca had placed a 0.7 m thick ring of concrete in the floor of the catino.

**History of tilting**

The vertical axis of the Tower is not straight – it bends to the north. In an attempt to correct the lean, tapered blocks of masonry were placed at the level of each floor to bend the axis of the Tower away from the lean. Careful analysis of the relative inclinations of the masonry layers has revealed the history of the tilting of the Tower.

At the end of the first phase the Tower was actually leaning northwards by about one quarter of a degree. Then as construction advanced above the fourth storey it began to move towards the south and accelerate so that by 1278, when the seventh level had been reached, it was inclining southwards by about 0.6 of a degree. This had increased to about 1.6 degrees by 1360 when work on the bell chamber commenced.

In 1817 two British architects used a plumb line to measure the inclination, which by then was 5 degrees. Thus the construction of the bell chamber caused a very significant increase in inclination. Advanced computer analysis has revealed that the rapid increase in inclination as the seventh level was reached and the bell chamber was added is directly analogous to constructing a tower from model bricks on a soft carpet. It is possible to build to a certain critical height, but no higher, however careful one is – a phenomenon known as leaning instability. The Tower was just at its critical height and was very close to falling over! The excavation of the catino again brought the Tower very close to collapse.

Precise measurements (begun in 1911) show that during the twentieth century the inclination of the Tower was increasing inexorably each year and the rate of tilt had doubled since the mid 1930s. In 1990 the rate of tilt was equivalent to a horizontal movement at the top of about 1.5 mm per year. Moreover, any interference with the Tower had resulted in significant increases in tilt. For example, in 1934 consolidation of the foundation masonry by means of grout injection resulted in a sudden movement south of about 10 mm, and groundwater abstraction

![Figure 2: Location of soil extraction tubes adjacent to and beneath the Tower](image-url)
from the lower sands in the 1970s resulted in an increase in movement of about 12 mm. These responses confirm how very sensitively poised the Tower was and how delicate any method of stabilisation would have to be.

**Stabilisation**

The internationally accepted conventions for the conservation of valuable historic monuments require that their essential character should be preserved, together with their history, craftsmanship and enigmas. Thus any invasive interventions on the Tower had to be kept to an absolute minimum and permanent stabilisation schemes involving propping or visible support were unacceptable – and in any case could have triggered the collapse of the fragile masonry. Any temporary stabilisation measure had to be non-invasive and reversible.

Temporary stabilisation of the foundations was achieved during the second half of 1993 by the application of 600 tonnes of lead weights to the north side of the foundations via a post-tensioned removable concrete ring, cast around the base of the Tower at plinth level. This caused a reduction in inclination of about one minute of arc and, more importantly, reduced the overturning moment by about 10%. In September 1995 the load was increased to 900 tonnes in order to control the movements of the Tower during an unsuccessful attempt to replace the unsightly lead weights with temporary ground anchors. The masonry problem was tackled in 1992 by binding a few lightly post-tensioned steel tendons around the tower at the first cornice and at intervals up the second storey.

A permanent solution was sought that would result in a small reduction in inclination by half a degree, which is not enough to be visible but which would reduce the stresses in the masonry and stabilise the foundations. Given that the foundation of the Tower was on the point of instability and that any slight disturbance to the ground on the south side would almost certainly trigger collapse, finding a method of reducing the inclination was far from straightforward and gave rise to many heated debates within the Commission.

Many possible methods of inducing controlled subsidence of the north side were investigated. These included drainage by means of wells, consolidation beneath the north side by electro-osmosis and loading the ground around the north side of the Tower by means of a pressing slab pulled down by ground anchors. None of these methods proved satisfactory.

**Studies of soil extraction**

A method known as soil extraction gradually evolved. This involves installing a number of soil extraction tubes adjacent to and just beneath the north side of the foundation. The method had been successfully used previously, notably to reduce the damaging differential settlements within the Metropolitan Cathedral of Mexico City. But using it on a tower that was on the point of falling over was altogether another matter. How could we be sure that removal of soil from beneath the high side would not create instability of the Tower?

Over a number of years the method was studied first by means of physical

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![Sequence of operations of the soil extraction drill](image)
models, then by numerical modelling and finally by means of a large-scale trial. A key finding from the model studies and numerical analysis was the existence of a critical line located about half a radius in from the northern edge of the foundation. Provided soil extraction from beneath the foundation took place north of this line, the response of the Tower appeared always to be positive.

However, if extraction took place south of this line the Tower would become unstable. Onset of impending instability is first manifest as an accelerating settlement of the south edge of the foundation and this precedes the onset of southward rotation. This lesson was learned during the large-scale soil extraction trials which were carried out on a 7 m diameter eccentrically loaded trial foundation on the Piazza north of the Baptistry. Initially emphasis was placed on measuring change of inclination rather than absolute settlement. Over-enthusiastic drilling resulted in extraction from south of the critical line which gave rise to rapid settlement of the south side followed by southward rotation of the trial foundation. It took six weeks to regain stability of the trial foundation and a salutary lesson was learned.

The main purpose of the large-scale trials was to develop the drilling technology for soil extraction. A drill was developed which consisted of a hollow-stemmed continuous flight auger (otherwise known as an Archimedes screw) housed inside a contra-rotating 180 mm diameter casing. This arrangement ensured that the drill could be advanced without any disturbance to the surrounding ground.

When the drill was withdrawn to form a cavity, an instrumented probe located in the hollow stem could be left in place to measure the closure of the cavity. The trials showed that the cavities formed in the silty soil of Layer A closed gently and that repeated extractions could be made from the same location. The trial foundation was successfully rotated by about 0.25° and directional control was maintained even though the ground conditions were somewhat non-uniform. Very importantly, an effective system of communication, decision taking and implementation was developed.

**Preliminary soil extraction**

In April 1996 the Commission agreed to carry out limited soil extraction from beneath the Tower with a view to observing its response. Due to bureaucratic and administrative delays it was not until the end of 1998 that preparatory work actually began.

In December 1998 some temporary safeguard cables were attached to the third storey of the Tower. These stretched horizontally some 100 m north of the Tower, passed over pulleys on the top of two massive A-frames and were lightly tensioned by means of lead weights. In the event of adverse movements of the Tower these safeguard cables could be further tensioned by lead weights to hold the Tower steady. It was never intended that they should be used to move the Tower northward.

Preliminary soil extraction was carried out over a limited width of 6 m using twelve bore holes lined with 220 mm diameter casings. The group of bore holes was offset by one metre to the west in order to induce a small westward component of movement. The auger and rotating casing had to be moved from hole to hole so that the operation was slow and cumbersome:
at most two extractions could be performed each day. Originally a target of a minimum of 20 arc seconds reduction in inclination was set; this was considered large enough to demonstrate unequivocally the effectiveness of the system. Initially only 20 litres of soil were to be extracted each day.

A carefully developed system of communication and control was established between the site and the engineers responsible for the soil extraction. This involved a system of twice-daily faxes from the site containing real-time information on the inclination and settlement of the Tower. A daily fax was issued by the responsible engineer summarising the observed response, commenting on it and then giving a signed instruction for the next extraction operation with clearly stated objectives.

Green, amber and red trigger levels were set for taking action in the event of adverse responses of the Tower. These included both rates and magnitudes of changes of inclination and settlement. The trigger levels were set after a careful study of about six years of records of movements of the Tower so as to avoid over-stringent requirements and false alarms.

On 9 February 1999, in an atmosphere of great tension, the first soil extraction took place. For the first few days, as the drills were advanced towards the edge of the foundation, the Tower showed no discernable response. Then slowly it began to rotate northwards. On 23 February the Tower, having rotated about 7 arc seconds north, suddenly began to rotate southwards by 2 arc seconds in one day.

Careful examination of the results showed that this was not associated with settlement at the south, which was reassuring. It turned out that a northerly gale coupled with snow in the Alps caused a sudden drop in temperature which past records show usually results in small southward movements. When the gale subsided and the temperatures rose the Tower began, to our huge relief, to move northwards again. This small episode illustrates the state of constant alertness that was required at all times during soil extraction.

Figure 5 shows the results of preliminary soil extraction. When the northward rotation had reached about 80 arc seconds by early June 1999, soil extraction was stopped. Northward rotation continued at a decreasing rate until July 1999. Then three of the lead
Figure 6: Drilling rig and 41 extraction tubes

Figure 7: Results of full soil extraction
weights were removed and all movement ceased.

Two features can be seen from Figure 5. First, a small westward component of rotation took place as planned. Secondly, the southern edge of the foundation rose during soil extraction. This was most gratifying as it demonstrated that the soil extraction was remote from the critical line and that unloading was taking place on the south side.

Full soil extraction

The success of preliminary soil extraction persuaded the Commission that it was safe to undertake full soil extraction over the full width of the foundations. Accordingly, between December 1999 and January 2000, 41 extraction holes were installed at 0.5 m spacing, with a dedicated auger and casing in each hole. Full soil extraction commenced on 21 February 2000 and the results of both preliminary and full soil extraction are shown in Figure 7.

It can be seen that a much higher rate of northward rotation was achieved than for preliminary soil extraction, averaging about 6 arc seconds per day and resulting from the removal of about 120 litres of soil. There was a tendency for the Tower to move towards the east and to control this it proved necessary to extract about 20% more soil from the western side than from the eastern side. In spite of this tendency it can be seen that the Tower was steered northwards in a remarkably straight path. It was also gratifying to note that significant uplift of the southern edge of the foundation took place.

Towards the end of May 2000 progressive removal of the lead ingots was commenced, initially with two ingots per week (about 18 tonnes). In September 2000 this was increased to three per week and then to four per week in November 2000. Removal of the lead ingots resulted in a significant increase in overturning moment but the soil extraction continued to be effective. On 16 January 2001 the last lead ingot was removed from the post-tensioned concrete ring and thereafter only limited soil extraction was undertaken.

In the middle of February the concrete ring itself was removed and at the beginning of March progressive removal of the augers and casings commenced. The holes were filled by a bentonitic grout. Finally in the middle of May the safeguard cables were removed from the Tower, which resulted in a southward rotation of a few arc seconds. To counter this a small amount of additional soil extraction was carried out. The final extraction and auger removal took place on 6 June 2001 – the date when the Tower was released from intensive care.

In addition to reducing the inclination of the Tower by half a degree, a limited amount of strengthening work has been carried out on the most highly stressed areas of masonry. This has consisted in grouting of voids in the rubble core and the use of radial stainless steel reinforcing where there is a risk of masonry cladding buckling outwards. The circumferential steel tendons around the first cornice and second storey have been replaced with much less intrusive prestressed wires embedded in resin. The old concrete ring that was placed in the floor of the catino by Gherardesca in 1838 has been securely attached to the foundation of the Tower bymeans of stainless steel reinforcement and has been strengthened by circumferential post tensioning. Thus the effective area of the foundations has been substantially increased.

Back to the future

The target reduction of inclination had been half a degree; this amount is not visible to the casual observer but is sufficient to stabilise the foundations of the Tower and reduce the stresses in the masonry by a significant amount. At the time of writing in September 2001 a total reduction (including the effects of the lead counterweight) of 1830 arc seconds has taken place and is continuing at about one arc second per week. This reduction in inclination is equivalent to a northward movement of the seventh floor of 440 mm. The Tower is now back at its inclination in 1838 at the time Gherardesca dug the catino and before its dramatic lurch south.

An obvious question is: how will the Tower behave in the future? Two scenarios have been developed. A pessimistic one is that the Tower will remain stable for a while, and then resume its rotation southwards at a much reduced rate. With this scenario it may take 300 years before another intervention on the foundation is required. An optimistic scenario is that continuing rotation will cease apart from small cyclic movements caused by seasonal changes in the groundwater table, and also movement influenced by the differential subsidence which is affecting the whole Piazza and which is reflected in the Tower.
Conclusion

The stabilisation of the Tower of Pisa has proved to be an immensely difficult challenge to civil engineers. The Tower is founded on weak, highly compressible soils and its inclination has been increasing inexorably over the years to the point at which it was in a state of leaning instability. Any disturbance to the ground on the south side was very dangerous, ruling out conventional geotechnical processes such as underpinning and grouting. Moreover the masonry was highly stressed and at risk of collapse. The internationally accepted conventions for the conservation of valuable historic monuments, of which the Tower is one of the best known and most treasured, require that their essential character should be preserved, with their history, craftsmanship and enigmas. Thus any invasive or visible intervention in the Tower had to be kept to an absolute minimum.

The technique of soil extraction has provided an ultra-soft method of increasing the stability of the Tower which at the same time is completely consistent with the requirements of architectural conservation. Its implementation has required advanced computer modelling, large-scale development trials, an exceptional level of continuous monitoring and day-by-day communication and control. On 16 June 2001 a formal ceremony was held in which the Tower was handed back to the civic authorities. It is hoped to open the Tower to the public in the Autumn of 2001.

Photo: James Hunkin

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