Leaning Tower of Pisa: Behaviour after Stabilization Operations

John B. Burland, *Emeritus Professor of Geotechnical Engineering, Imperial College London; email: j.burland@imperial.ac.uk*
Michele B. Jamiolkowski, *Emeritus Professor of Geotechnical Engineering, Technical University of Torino; email: michele.jamiolkowski@polito.it*
Carlo Viggiani, *Professor of Geotechnical Engineering, University Federico II, Napoli; email: viggiani@unina.it*

ABSTRACT*: It is well known that the foundations of the Leaning Tower of Pisa were stabilised using the method of underexcavation to reduce the southward inclination of the Tower by about 10 percent in combination with controlling the seasonally fluctuating water table beneath the north side. Having been closed to the public since early in 1990, the Tower was re-opened in December 2001. The paper summarises the response of the Tower during the period of implementation of the stabilisation works. Monitoring of the movements of the Tower has been continuing and the observations obtained since 2001 are presented. It is shown that over the six years between 2003 and 2008 the induced rate of northward rotation of the Tower has been steadily reducing to less than 0.2 arc seconds per year. Similarly the rate of induced settlement of the centre of the foundation has been steadily reducing and is approaching the background rate of settlement of the Piazza. Piezometer measurements close to the north side of the foundation shows that the drainage system has been successful in stabilising the groundwater levels beneath the north side of the Tower's foundation. The paper concludes with a brief discussion on the possible future behaviour of the Tower.*

KEYWORDS: Leaning Tower of Pisa, leaning instability, stabilization works

SITE LOCATION: IJGCH-database.kmz (requires Google Earth)

INTRODUCTION

The purpose of this paper is to update the information on the behaviour of the Leaning Tower of Pisa after the work of stabilisation ended in 2001. The Tower of Pisa is the bell tower of the Cathedral and is one of the four monuments within the medieval Piazza dei Miracoli, three of which are shown in Fig. 1. Its construction began in 1173 and continued (with two long interruptions) for about two hundred years as illustrated in Fig. 2. The Tower is built as a hollow masonry cylinder surrounded by six colonnades with columns and vaults rising from the base cylinder. The outer and inner walls are faced with competent San Giuliano marble, while the annular cavity between is filled with miscellaneous rock fragments and mortar, forming a typical medieval infill masonry structure. The Tower commenced leaning southwards during the second construction stage as shown in Fig. 2, and thereafter its inclination continued to increase. Fig. 3 shows the cross section through the Tower in the plane of maximum tilt as it was in 1993 before the stabilisation work commenced. The average foundation pressure is 500kPa and a detailed computer analysis (Burland and Potts, 1994), indicates that the pressure at the south edge was about 1000kPa with the soil in a state of local yield, while the pressure at the north edge was close to zero.

The ground underlying the Pisa Tower consists of three formations as shown in Fig. 4. Horizon A, about 10m thick, is composed of soft estuarine deposits of sandy and clayey silts laid down under tidal conditions. Horizon B consists of soft sensitive normally consolidated marine clay extending to a depth of about 40m. Because it is very sensitive, this material loses much of its strength if disturbed. Horizon C is dense marine sand extending to a depth of about 60m. An upper perched water table in Horizon A is encountered between 1m and 2m below the level of Piazza dei Miracoli corresponding to elev. +3.0 above m.s.l. The contact between Horizon A and the marine clay of Horizon B is dished beneath the Tower, indicating that it experienced average settlements of between 3.0m and 3.5m.

Submitted: 6 March 2009; Published: 01 July 2009
Reference: Burland J.B., Jamiolkowski M.B., Viggiani C., (2009). *Leaning Tower of Pisa: Behaviour after Stabilization Operations.* International Journal of Geoengineering Case histories, http://casehistories.geoengineer.org, Vol.1, Issue 3, p.156-169.

In 1990 the Italian Government, concerned about the progressive increase in the rate of inclination and the risk of sudden structural collapse due to the fragility of the masonry, appointed a multidisciplinary International Committee for the safeguard and the stabilisation of the Leaning Tower of Pisa. An exhaustive description of the Committee activities, including those focused on the structural stability and the consequent needs for masonry strengthening, are reported in MIBAC (2006).

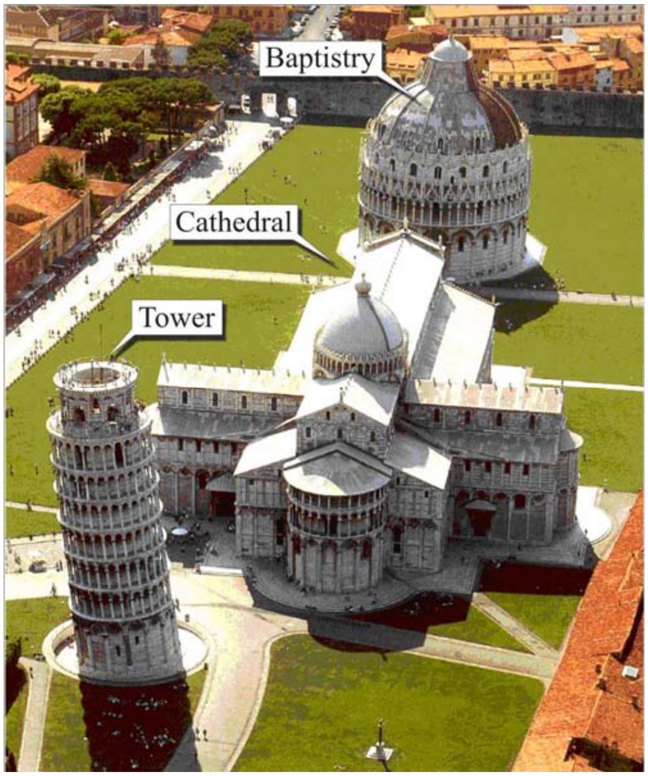


Figure 1. Piazza dei Miracoli, airview.

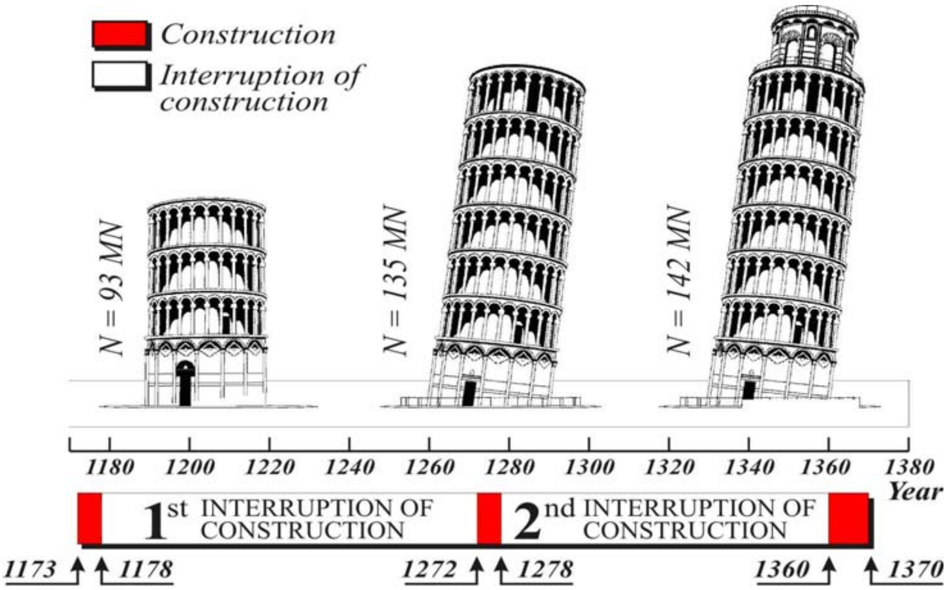
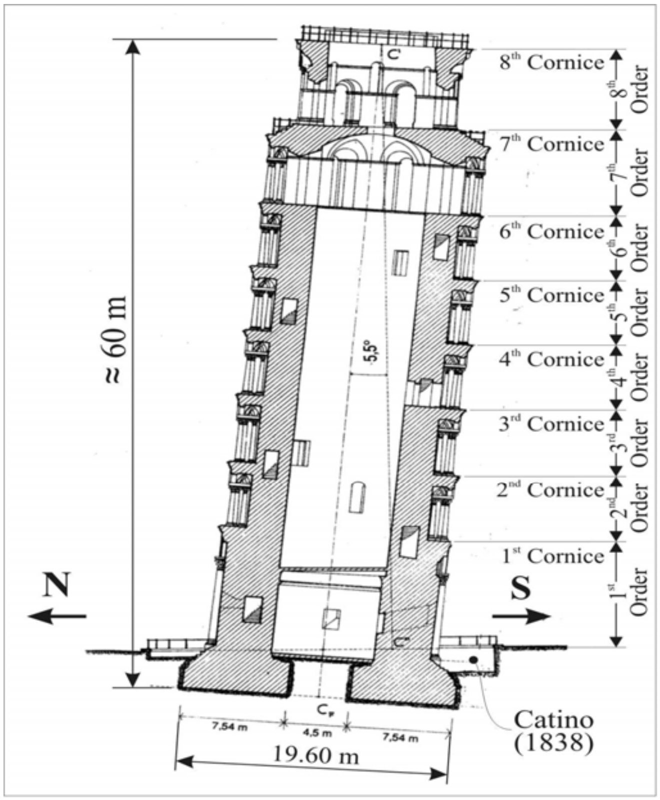


Figure 2. History of the Construction.



Weight	142 MN
Height of the centre of gravity	22.6 m
Overturning moment	327MNm
Average foundation pressure:	≈ 500 kPa

Figure 3. Cross-section in the plane of maximum inclination, situation in year 1993.

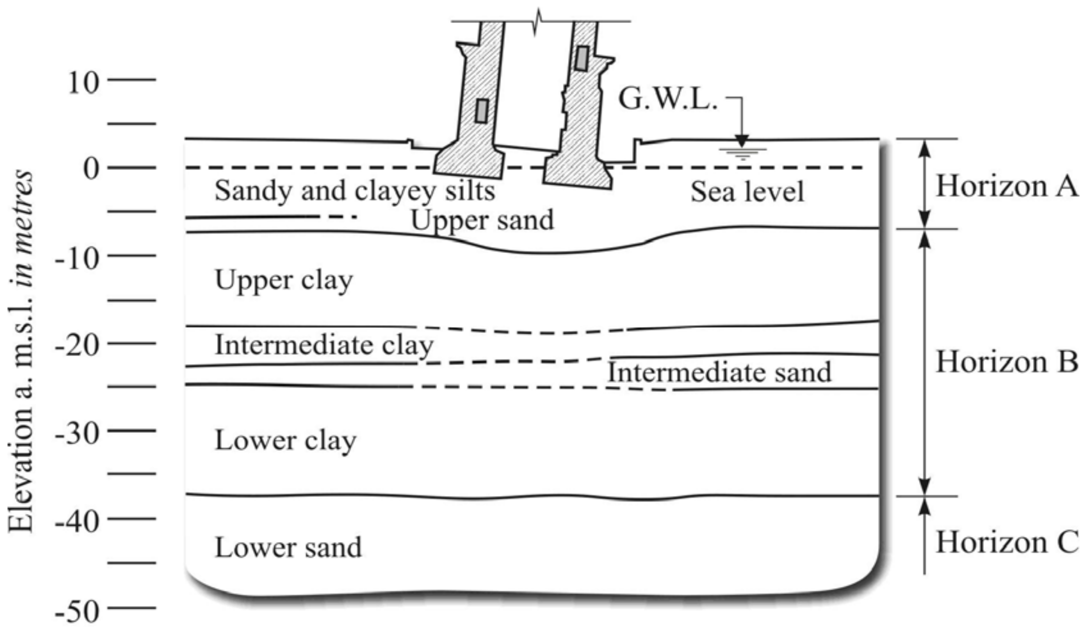


Figure 4. Soil profile.

STABILIZATION WORKS

The form of motion of the foundations of the Tower during the 20th Century

Precise measurements begun in 1911 and show that during the twentieth century the inclination of the Tower has been increasing inexorably each year and the rate of tilt has doubled since the 1930's. In 1990 the increase of tilt was about 6 arc seconds per year which is equivalent to a horizontal movement at the top of about 1.5mm per year (Jamiolkowski, 2001). There has been much debate about the cause of this progressive increase in inclination. It has usually been attributed to creep in the underlying soft marine clay, the assumption being made that the south side was settling more than the north side. A careful study of the geodetic survey measurements going back to 1911 revealed a most surprising form of motion of the foundations which was radically different to previously held ideas. The theodolite measurements showed that the first cornice had not moved horizontally – apart from two occasions in 1934 and the early 1970s when man had intervened. Also, precision level measurements which commenced in 1928 showed that the centre of the foundation plinth had not displaced vertically relative to the surrounding ground. Therefore, the rigid body motion of the Tower could only be as shown in Fig. 5, with an instantaneous centre of rotation at the level of the first cornice vertically above the centre of the foundation. The direction of motion of points FN and FS are shown by vectors and it is clear that the foundation has been moving northwards with FN rising and FS sinking (Burland and Viggiani, 1994).

The discovery that the motion of the Tower was as shown in Fig. 5 turned out to be crucial in four respects:

1. The form of motion is consistent with the phenomenon of 'leaning instability' rather than an iminent bearing capacity failure (Hambly, 1985). In simple terms, 'leaning instability' of a tall structure occurs at a critical height when the overturning moment generated by a small increase in inclination is equal to or larger than the resisting moment generated by the foundations. No matter how carefully the structure is built, once it reaches the critical height the smallest perturbation will induce leaning instability. As pointed out by Hambly: "…leaning instability is not due to lack of strength of the ground but is due to insufficient stiffness".

2. The observation that the north side had been steadily rising led directly to the suggestion that the application of a lead counterweight to the foundation masonry on the north side could be beneficial as a temporary stabilizing measure by reducing the overturning moment (Burland et al, 1993).

3. The pattern of ground movements depicted in Fig. 5 led to the important conclusion that the seat of the continuing long-term rotation of the Tower lies in Horizon A and not within the underlying marine clay as had been widely assumed in the past. It can therefore be concluded that the latter stratum must have undergone a considerable period of ageing since the end of construction. The ageing resulted in an increased resistance to yield – a conclusion that proved to be of great importance in the successful computer modeling of the application of the temporary counterweight (Burland and Potts, 1994).

4. In the light of the measured motion of the Tower foundation, and consistent with the seat of the movement lying within Horizon A, it was concluded that, in addition to creep, the most likely cause of the progressive seasonal rotation was a fluctuating ground-water level due to seasonal heavy rainstorms that occur between September and December every year. Accordingly a number of stand-pipes were installed in Horizon A around the Tower. Measurements made over a number of years have confirmed this hypothesis. Commencement of rotation each year coincides with very sharp rises in the ground water level in the Horizon A following each heavy rainstorm (Burland et al, 2003). Fig.6 shows the ground water level fluctuations for a selected period of time in the piezometers located to the North and to the South in the vicinity of the Tower. The insert figures to the right show the changes in inclination of the Tower in arc seconds as a result of two heavy rainstorms that occurred in September and October of 1995. Each of these events caused a larger rise in piezometric head on the North side than the South side of the Tower. This resulted in a southward rotation of about one arc second in each case which was only partly reversible.

Understanding the motion of the foundations of the Leaning Tower of Pisa is perhaps the single most important finding in the development of the strategies for both the temporary and long-term stabilisation.

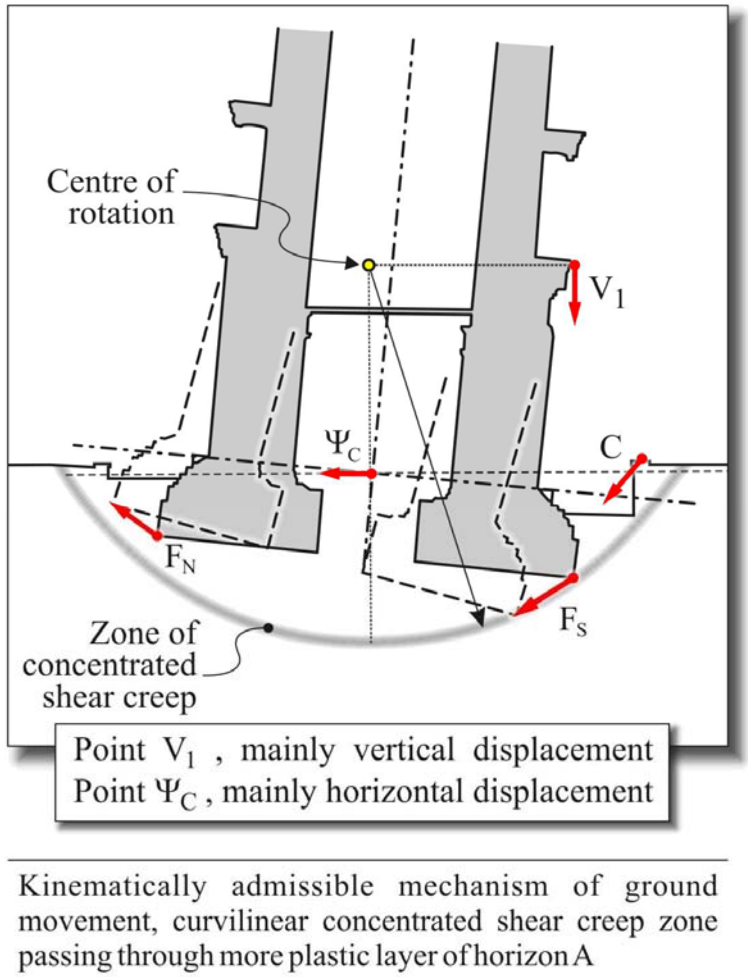


Figure 5. Motion of Tower foundation during steady creep (gradually accelerates) - Burland, Viggiani (1994).

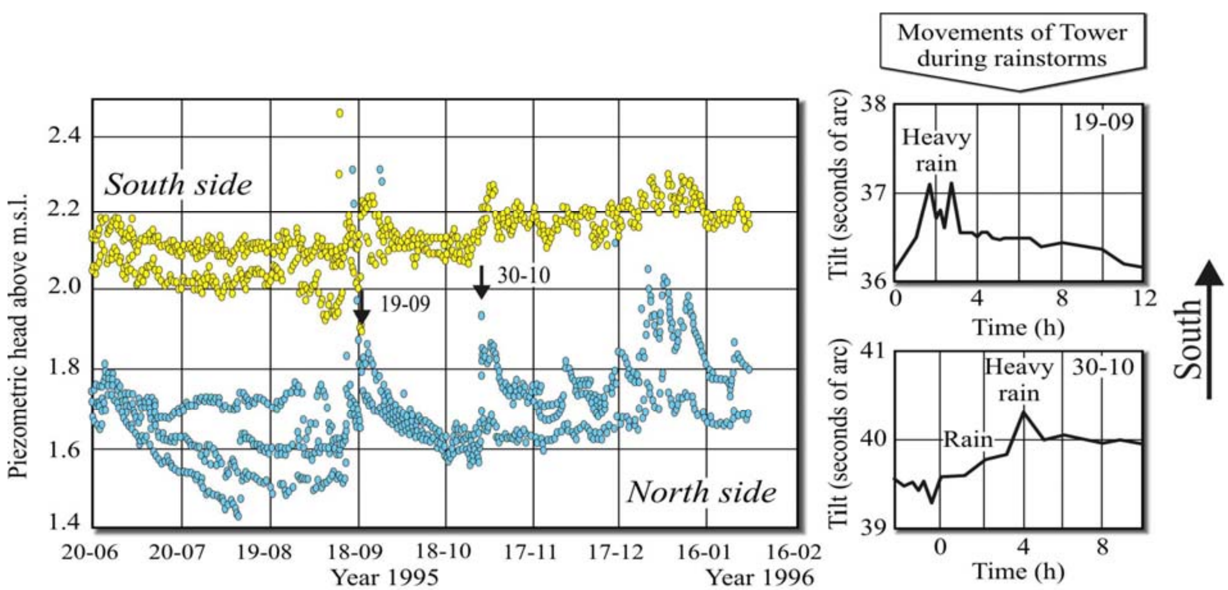


Figure 6. Ground water level fluctuation in horizon A.

Temporary foundation stabilization measures

Temporary stabilisation of the foundation was achieved during the second half of 1993 by the application of 600t of lead weights on the north side of the foundations via a post-tensioned removable concrete ring cast around the base of the Tower at plinth level, see Fig. 7. This caused a reduction in inclination of about one minute of arc and, more importantly, reduced the overturning moment by about ten percent. In September 1995 the load was increased to 900t in order to control the accelerating southward movements of the Tower during an unsuccessful attempt to replace the unsightly lead weights with temporary ground anchors. This difficult period during the Committee's activity has been called "Black September" and is referred to in Fig.16.

Figure 7. Lead counterweight on the North Side.

Permanent foundation stabilization measures

A permanent solution was sought that would result in a small reduction in inclination of the Tower by half a degree which is not enough to be visible but which would reduce the stresses in the masonry on the south side and stabilise the foundation. Given that the foundation of the Tower was very close to failure 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 straight forward. Many possible methods of inducing controlled subsidence of the north side were investigated. These included drainage beneath the north side using 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 loaded by ground anchors. None of these methods proved satisfactory.

At this stage, the idea of slightly reducing the inclination of the Tower by means of controlled ground extraction under the north side of foundation began to attract the interest of the Committee. The advantages include its non-invasive nature to the fabric of the Tower and the high degree of day to day control that can be exerted.

This method, known as underexcavation, gradually evolved. It involves installing a number of soil extraction tubes adjacent to and just beneath the north side of the foundation. The method was originally proposed by Terracina (1962) for Pisa and had been successfully used previously (Johnston and Burland, 2004), notably to reduce the damaging differential settlements within the Metropolitan Cathedral of Mexico City (Tamez, Ovando and Santoyo, 1997). But using it on a Tower that was on the point of falling over was altogether another matter. Over a number of years the method was studied first by means of physical models, then by numerical modelling and finally by means of a large-scale trial (Burland et al, 2000).

A key finding from the above studies was that, provided soil extraction from beneath the foundation takes place north of a critical line, the response of the Tower is always positive. This critical line is located about half a radius in from the northern edge of the foundation (i.e. away from the leaning side).

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 housed inside a contra-rotating 168mm diameter casing (Fig. 8). The arrangement permits the drill to be advanced with minimum disturbance to the surrounding ground. When a chosen location is reached the drill is stopped and withdrawn by about a meter leaving a cylindrical cavity. The trials showed that the cavities formed in the silty soil of Horizon A closed gently and that repeated extractions could be made from the same location. The trial foundation was successfully rotated by about 0.25^{o} and directional control was maintained even though the ground conditions were somewhat non-uniform. Very importantly, an effective system of communication, decision making and implementation was developed. This system consisted of a daily report from the site to the responsible engineer of the response of the foundation to the previous day's soil extractions. The responsible engineer then issued a signed document in which the previous day's response was summarized and analysed, the objectives of the coming day's soil extraction were set out and instructions given for the locations and volumes of the next soil extractions.

In August 1998 the Committee agreed to carry out limited soil extraction from beneath the Tower with a view to observing its response. This preliminary underexcavation was to be carried out over a limited width of 6m north of the Tower using twelve bore holes lined with 219mm diameter casings (Fig. 9). On 9th February 1999, in an atmosphere of great tension, the first soil extraction took place. The Tower slowly began to rotate northwards. When the northward rotation had reached about 80 arc seconds by early June 1999 the preliminary soil extraction was stopped. Northward rotation continued at a decreasing rate until October 1999.

The success of the preliminary underexcavation persuaded the Committee that it was safe to undertake soil extraction over the full width of the foundation. Accordingly, between December 1999 and January 2000, 41 extraction holes were installed north of the Tower at 0.5m spacing with a dedicated auger and casing in each hole (Fig.10). Full underexcavation commenced on 21st February 2000 and the Tower was steered northwards in a remarkably straight path. Towards the end of May 2000 progressive removal of the lead ingots was commenced. Although this resulted in an increase of overturning moment the soil extraction continued to be effective.

On 16th 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 2001 the concrete ring itself was removed and at the beginning of March progressive removal of the augers and casings commenced with the holes being filled by a bentonitic grout. The final extraction and auger removal took place on 6th June 2001 at which time the Tower had been rotated northwards by about 1800 arc seconds, see Fig. 11. Full details of the soil extraction operation and the associated response of the Tower are given by Burland et al, (2003).

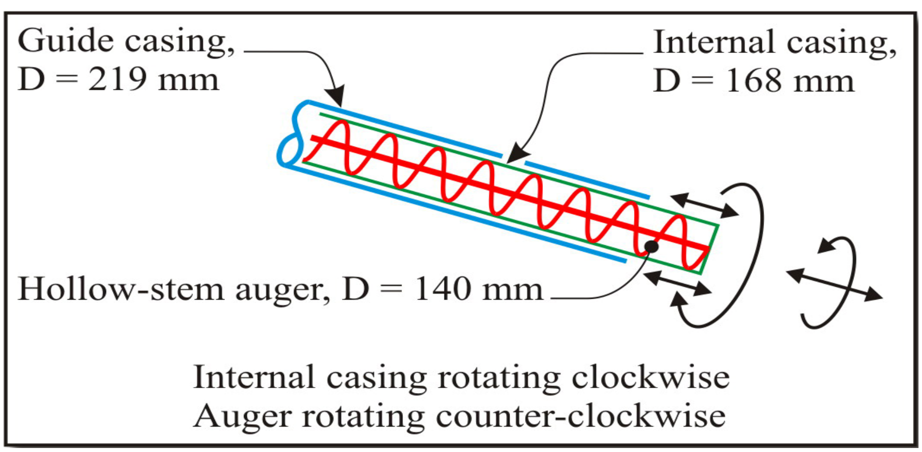


Figure 8. Tool for ground extraction.

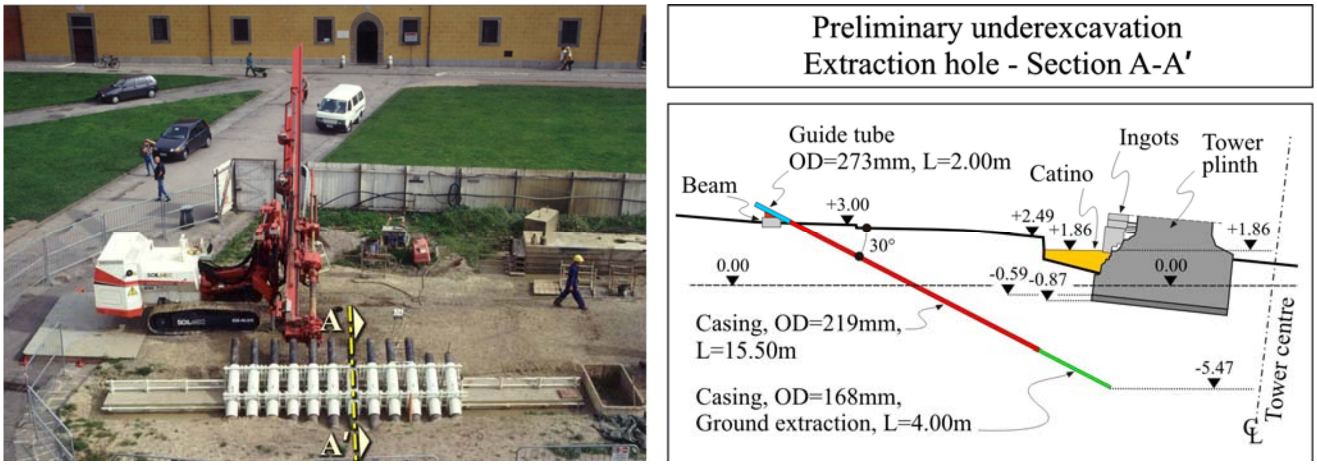


Figure 9. Holes for preliminary underexcavation.

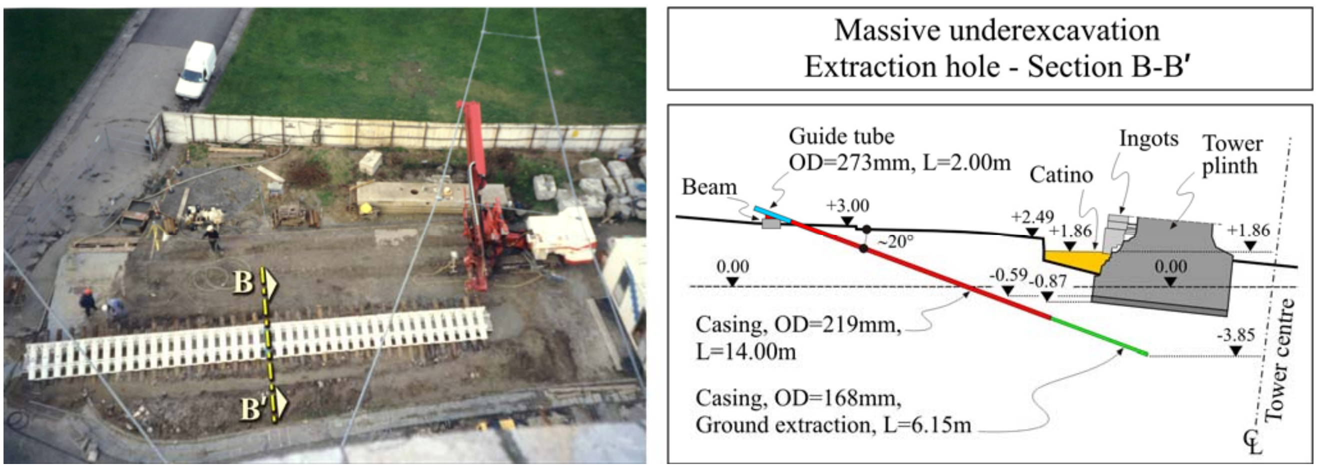


Figure 10. Holes for massive underexcavation.

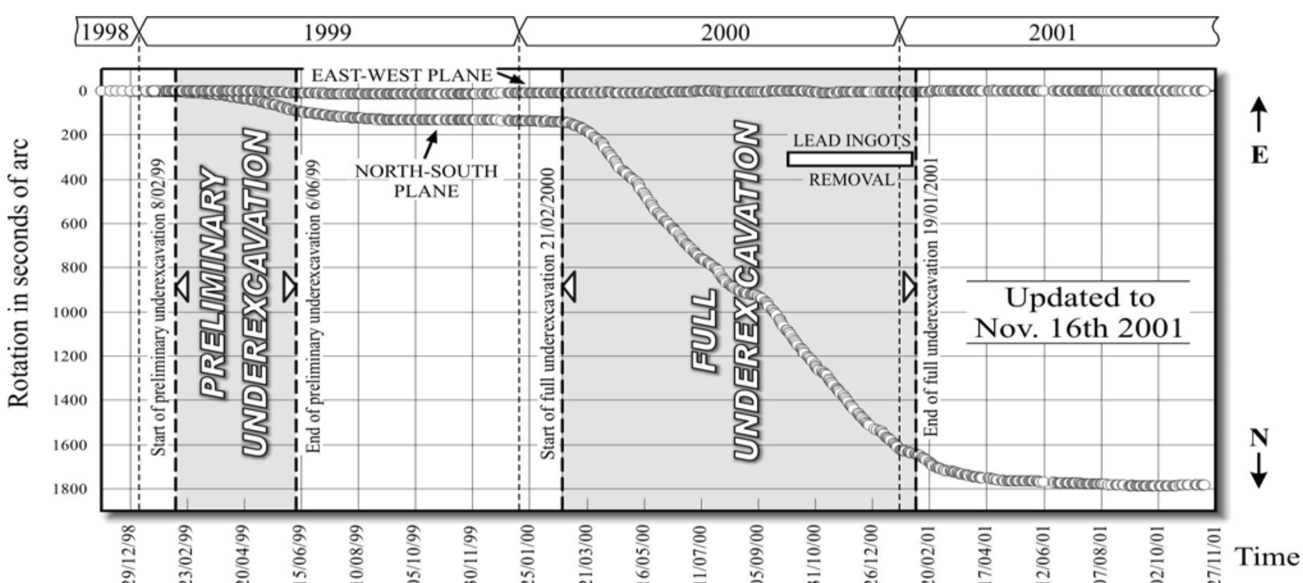


Figure 11. Rotation of Tower plinth during underexcavation.

Additional foundation stabilization works

In addition to reducing the inclination of the Tower by half a degree, two other permanent foundation stabilisation measures have been carried out. During the work of the Committee, a 0.8m thick cement-conglomerate ring was detected in the bottom of the catino around the base of the Tower. This ancient concrete ring is of high quality and it has now been connected to the masonry foundation of the Tower by means of stainless steel reinforcement and has been strengthened by circumferential post-tensioning (Fig. 12). As a result, the effective area of the foundations has been substantially increased thereby increasing the factor of safety against leaning instability.

As mentioned previously, the deduced motion of the Tower foundation shown in Fig. 5 led to the conclusion that the seasonal fluctuating water table in Horizon A during intense periods of rain was the main factor responsible for this continuing movement, see Fig. 6. It is also of significance that, apart from these intense periods of rain, the average ground water levels close to the South side of the Tower in Horizon A are 200mm to 300mm higher than those to the North, as shown in Fig. 6. This difference generates a small, but not negligible stabilising moment for the Monument which is so close to falling over. In the autumn and winter, when rainfall events are more intense, the water table rises sharply, reduces the difference in piezometric level and thereby produces southward rotations of the Tower which are not fully recoverable. To minimise this effect it was necessary to eliminate the fluctuations of the water table and, with this objective, a drainage system was installed consisting of three wells sunk on the north side with radial sub-horizontal drains running into them from beneath the north side of the catino, (Fig. 13). The water levels in the wells are controlled by the level of the outlet pipes. The drainage system was implemented in April and May 2002 and lead to a decrease in the pore water pressure as well as a significant reduction in its seasonal fluctuations, as shown in Fig. 14. The installation of this drainage system induced a further northward rotation of the Tower as can be seen in Fig. 15.

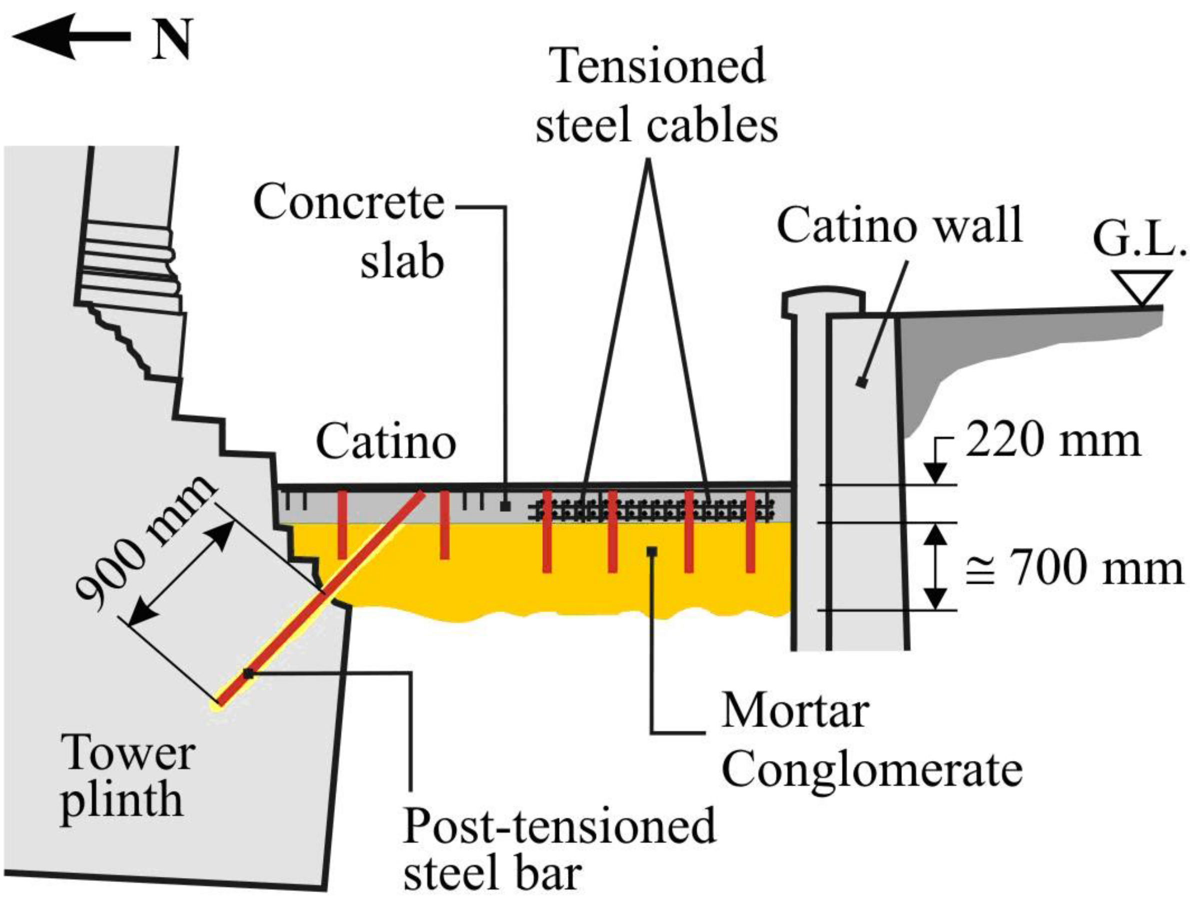


Figure 12. Structural connection of concrete ring to the Tower foundation.

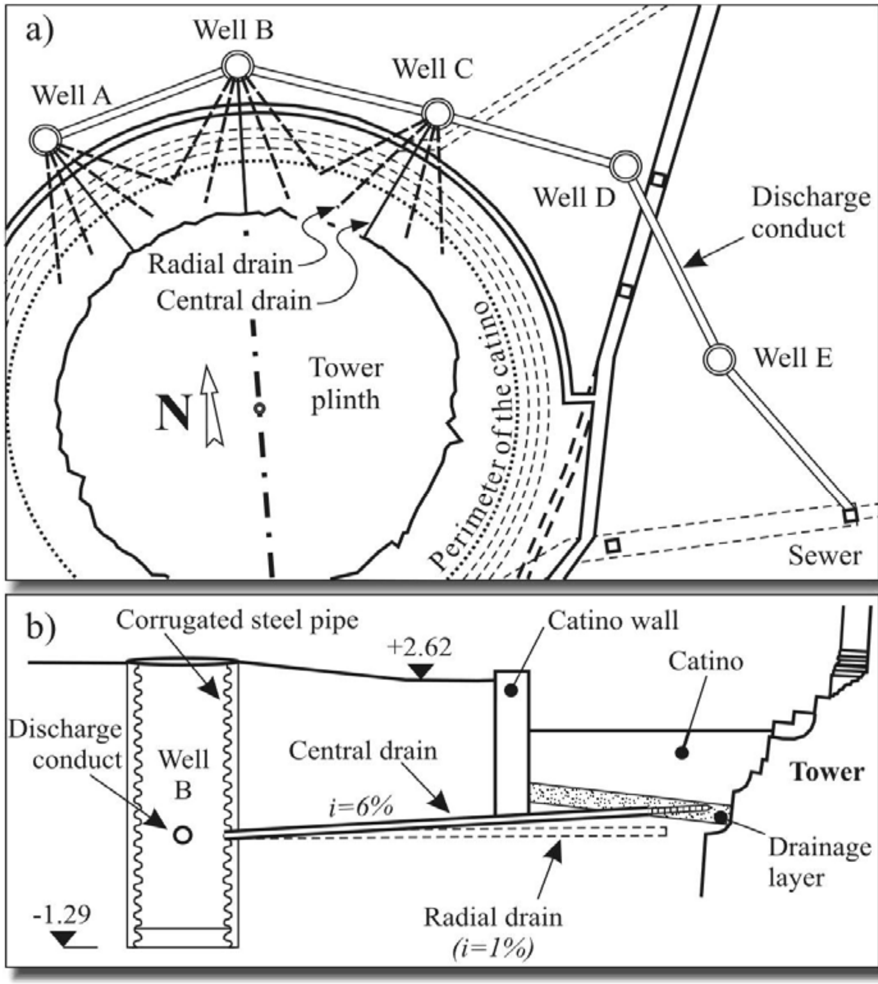


Figure 13. Control of GWL on North Side a) Plan view, b) Cross-section.

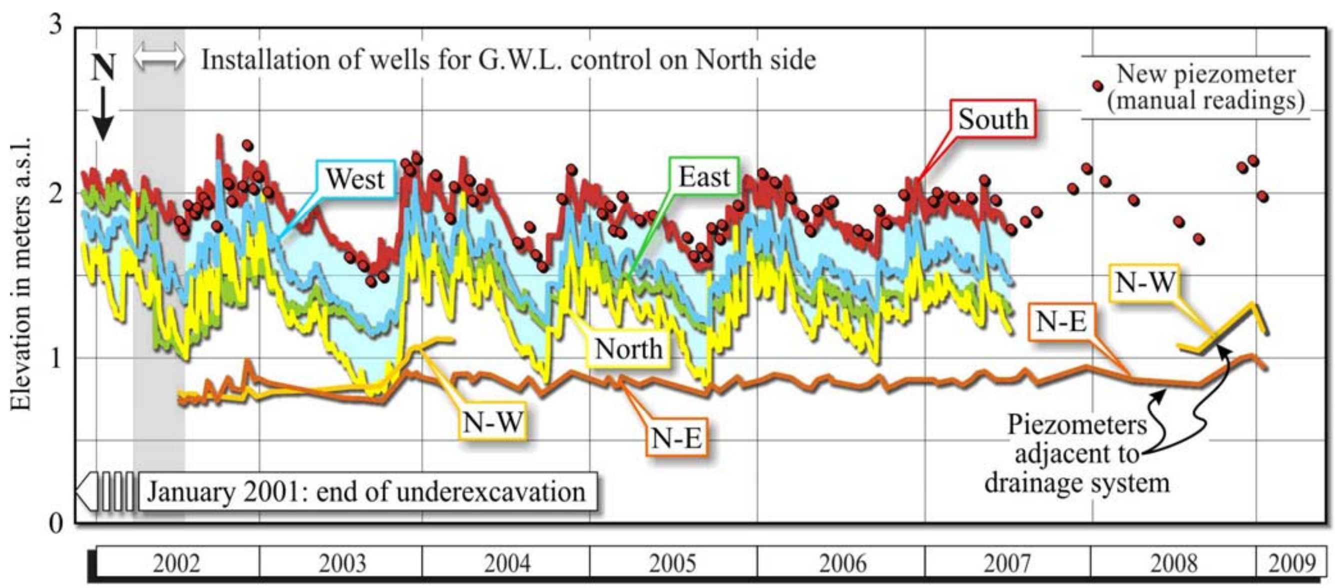


Figure 14. Perched ground water table in horizon "A".

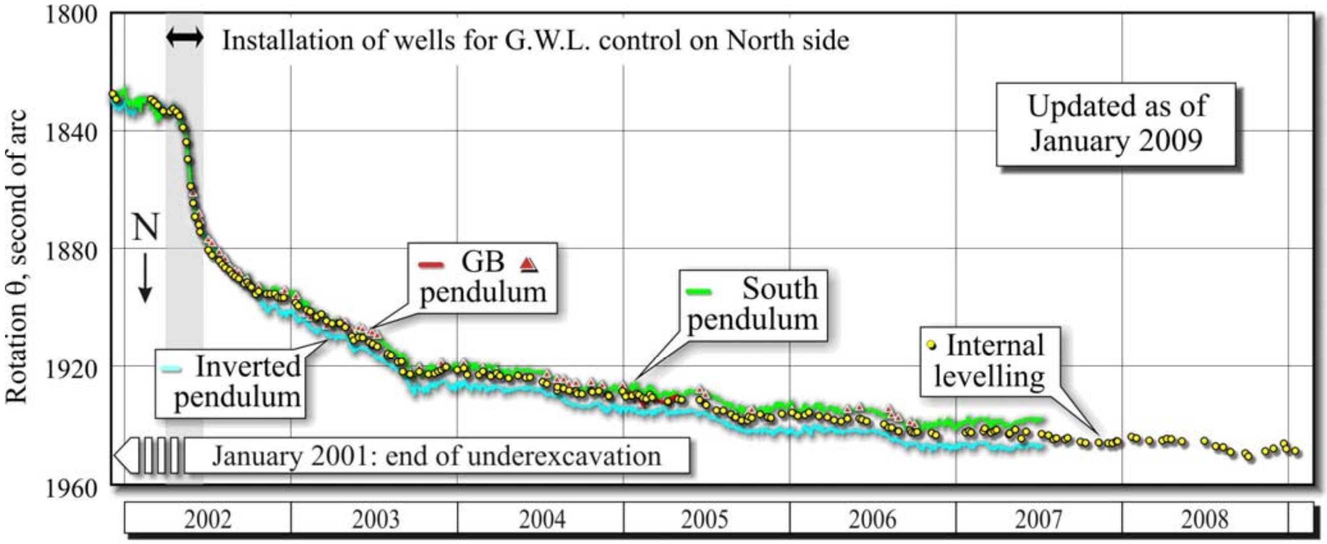


Figure 15. Rotation of Tower plinth after end of underexcavation.

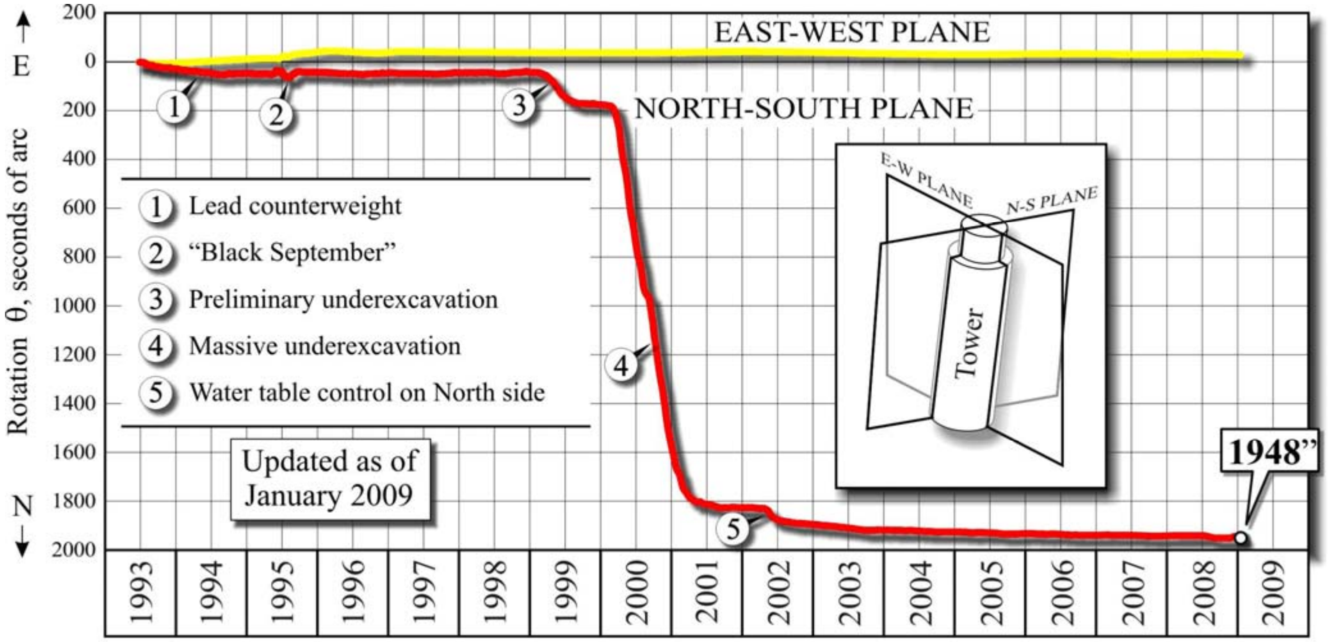


Figure 16. Rotation of Tower foundation as result of stabilization works.

OBSERVED POST STABILIZATION MOVEMENTS

The previous section of the paper gives a short description of the interventions carried out on the Tower subsoil, aimed at reducing the leaning instability phenomenon, hence preventing for ever, or at least for a long period of time, further increase of inclination. The behaviour of the Tower foundation after the conclusion of the stabilization works in terms of rotations and settlements is summarised in Figs. 16 and 17 respectively.

As a result of the full underexcavation and of the implementation of the ground water control in Horizon A, the Tower foundation in mid 2002 had reduced its tilt by 1880 arc seconds - about 10% of the maximum value reached in 1993. In the succeeding six years the Tower has continued rotating northwards at a reducing rate, so that by September 2008 the accumulated reduction of the foundation tilt reached 1948 arc seconds, see Fig.16. In the two years from September 2006 to September 2008 the residual rate of rotation northwards has reduced to less than 0.2 arc second per year.

The settlements of the south edge, centre and north edge of the foundation generated by the stabilisation operations, mainly by full underexcavation, are shown in Fig.17. In September 2008 the centre of the foundation had settled around 90mm and is continuing to settle at a rate that, over the last two years, is less than 1.0 mm/year. This is approaching the background rate of settlement of the Piazza due to the general subsidence of the Pisa plain. As regards the South edge of the foundation, it rose by about 15 mm during the underexcavation and has since settled around 12mm. This behaviour indicates that during underexcation, the axis of rotation was located under the imprint of the plinth and that the pressures due to the Tower weight at the south edge had reduced.

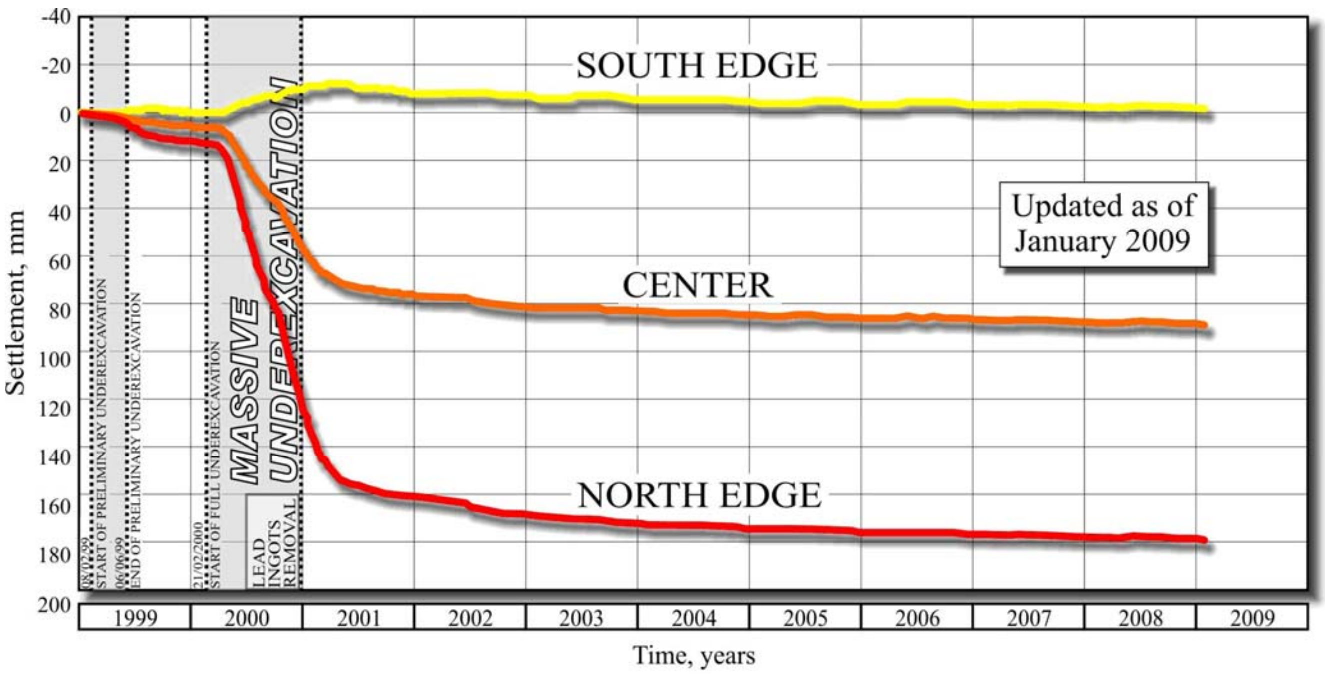


Figure 17. Settlement of Tower foundation as result of stabilization works.

A GLIMPSE INTO THE FUTURE

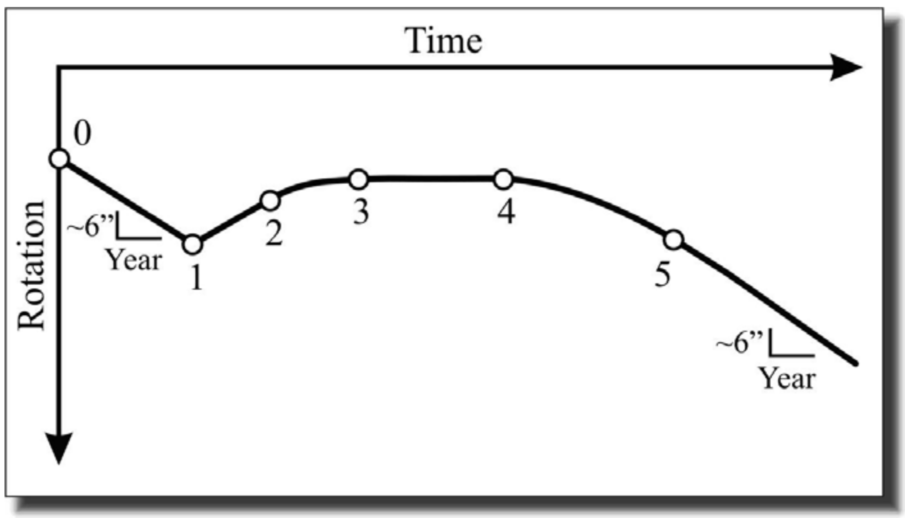
While monitoring of the Tower continues, the question from the scientific community and from the media is how the Tower will behave in future. Because of the complexity of the phenomena controlling this, almost unique, soil-structure interaction problem, an unequivocal answer is not possible. The issue has been debated by the authors who envisage the two following possible scenarios:

- Optimistic Scenario. The phenomenon of the leaning instability has been stopped, continuing rotation ceases, except for some minor movements caused by the seasonal oscillations of the ground water and of the effects of the solar radiation on the masonry. This scenario implies that the dominant mechanism driving the leaning instability was fluctuations of the ground water level in Horizon A, see Fig. 6.

- Pessimistic Scenario. As illustrated in Fig. 18, after the completion of time effects of the underexcavation (period 2-3), the Tower will remain motionless for a period estimated as a few decades (period 3-4), followed by a possible resumption of the southward rotation. Initially this southward rate of rotation will be very much less than the 6 arc second per year that existed before the stabilisation works. However the rotation rate will gradually increase (period 4-5) and may approach again, after a very long time, a value close to 6 arc seconds. In what period of time this will occur is difficult to estimate. However, considering that the stabilisation works brought the Tower inclination back to the situation that existed at the beginning of the XIX century, the authors believe that the period of time for the Tower to return to its 1993 inclination will be at least 200 years.

The above scenarios assume that the continuing increase of foundation inclination with time was originated by the combined effects of the foundation soil creep and of the ground water oscillation within Horizon A. It seems clear that the future behaviour of the Tower will depend to a large extent on the continued effectiveness of the drainage system on the north side.

Finally it should be emphasised that, thanks to the non invasive nature of the underexcavation, in all events and at any time in future, this kind of intervention can be repeated to reduce once again the tilt of the foundation by the required amount.



0 1	"Steady" motion towards South of Tower before intervention
1 2	Reduction of inclination during intervention
2 3	"Delayed" effect of intervention
3 4	Tower motionless
4 5	Southward rotation resumed
5	Rotation rate as before intervention

Figure 18. Expected future behaviour of the Leaning Tower of Pisa.

REFERENCES

Burland, J.B., Jamiolkowski, M.B. and Viggiani, C. (2003). The stabilisation of the Leaning Tower of Pisa. Soils and Foundations Vol. 43, 5, pp. 63-80.

Burland, J.B., Jamiolkowski, M.B. and Viggiani, C. (2000). Underexcavating the Tower of Pisa: Back to the future. GEOTECH-YEAR 2000, Developments in Geotechnical Engineering, Bangkok,Thailand, Balasubramaniam,A.S. et al. Eds, pp. 273-282.

Burland, J.B. and Potts, D.M. (1994). Development and application of a numerical model for the Leaning Tower of Pisa. Int. Symp. on Pre-Failure deformation characteristics of geomaterials, Sapporo, Japan, Vol. 2; pp. 715-738.

Burland, J.B. and Viggiani, C. (1994). Osservazioni del comportamento della Torre di Pisa. Rivista Italiana di Geotecnica Vol. 28, 3, pp. 179-200.

Burland, J.B., Jamiolkowski, M.B., Lancellotta, R. Leonards, G. and Viggiani, C. (1993). The Leaning Tower of Pisa, what is going on? ISSMFE News, Vol. 20, No. 3.
Hambly, E.C. (1985). Soil buckling and the leaning instability of tall structures. The Structural Engineer, Vol. 63, 3, pp. 78-85.
Jamiolkowski, M.B. (2001). The Leaning Tower of Pisa: End of an Odyssey. 15th Int. Conf. on SMGE, Third Millenium, Terzaghi Oration, Istanbul, Turkey, Vol 4, pp. 2979-2996.
Johnston, G. and Burland, J.B. (2004). Some historic examples of underexcavation. Int. Conf. on Advances in Geotechnical Engineering, The Skempton Conference, London, UK, Jardine, R.J. Potts, D. M. and Higgins, K. G. Eds, Vol. 2, pp. 1068-1079.
Ministero per i Beni e Le Attività Culturali (MIBAC) (2006), Torre Restituita, Bollettino d'Arte, Vol. 1,2 and 3.
Tamez, E., Ovando, E. and Santoyo, E. (1997). Underexcavation of Mexico City's Metropolitan Cathedral and Sagrario Church, 14th Int. Conf. on SMFE, Hamburg, Germany Vol. 4, pp. 2105-2126.
Terracina, F. (1962). Foundations of the Leaning Tower of Pisa. Géotechnique Vol. 12, 4, pp. 336-339.

The International Journal of Geoengineering Case Histories (IJGCH) is funded by:

GEI Consultants