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An update on the Tower of Pisa

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ABSTRACT: The Leaning Tower of Pisa has been stabilised in the years 1999–2000 by an International Committee appointed by the Italian Government. An analysis of the whole history of the monument, starting from its construction in the XII century and including the results of the modern monitoring of XIX and XX century led the Committee to the conclusion that the Tower is affected by a phenomenon of instability of the equilibrium, depending on the deformability and not on the strength of the foundation soils. The stabilisation intervention, totally respectful of the integrity of the monument, consisted in slightly decreasing the inclination of the Tower by underexcavating a small volume of soil beneath the north side of the foundation. The paper briefly reports the analysis and the intervention; the observation of the behaviour in the twenty years elapsed since then allows some preliminary evaluation of the future behaviour.

1 INTRODUCTION

The Tower of Pisa (Figure 1) is one of the most famous monuments in the world; it rests on a subsoil of poor mechanical properties (Figure 2), which is at the origin of its leaning. It has been stabilized some twenty years ago by an International Committee appointed by the Italian Government with an underexcavation intervention conceived to respect as far as possible the integrity of the monument. Since then, many papers, lectures, books, symposia have been devoted to this topic, but it appears that the knowledge of what has been done and why is not widespread. Therefore, we believe that a short informative paper, based essentially on the results of the monitoring currently under way and updated to the present date, may be of some interest. The potential future behaviour of the monument is also briefly discussed.

The history of the Tower is first recalled, subdividing it in four stages: (i) from the construction, which began in 1173, to 1911, the starting date of modern monitoring; (ii) from 1911 to 1999, the start of the stabilisation measures carried out by the International Committee; (iii) from 1999 to 2002, the period of implementation of the stabilization measures, and (iv) from 2002 to 2022. For each of these time intervals some of the available monitoring results are illustrated and briefly discussed.

In Figure 3 the whole history of the inclination of the Tower since its construction is reported. From the construction time to the beginning of XIX Century the only data available are the values of the inclination in the plane of maximum leaning, very nearly oriented in the North-South direction.

The monument was erected in three stages, over a period of around two centuries (1173–1368). It started leaning substantially during the second stage; however, the construction went on introducing geometrical corrections to counteract the effects of the inclination. The accuracy of the masonry works allows the use of these corrections to piece together very reliably the inclination developed during construction.

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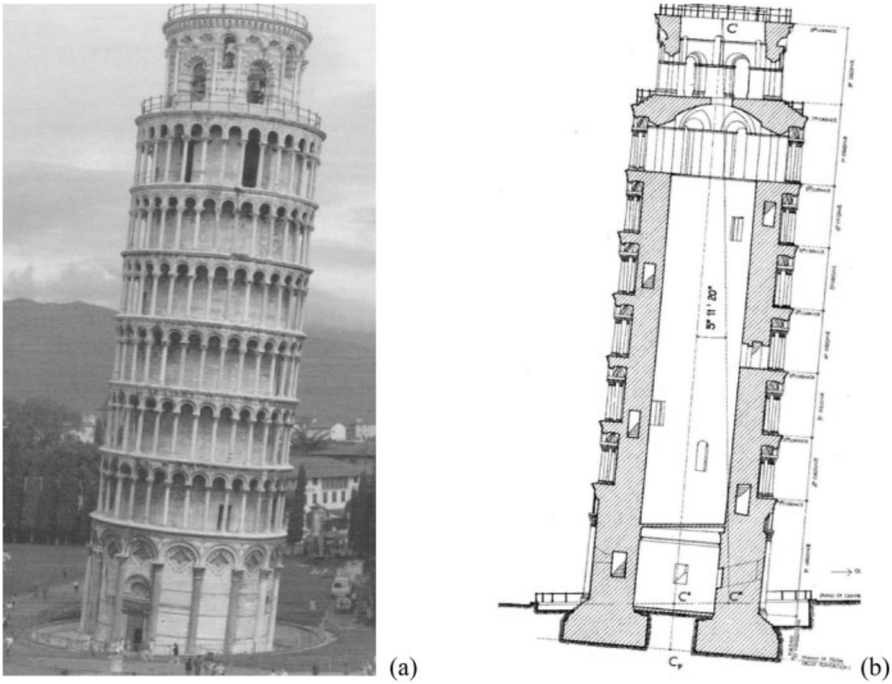

Figure 1. (a) View of the leaning tower from the West; (b) Section along vertical plane of maximum inclination (very nearly in the North – South direction).

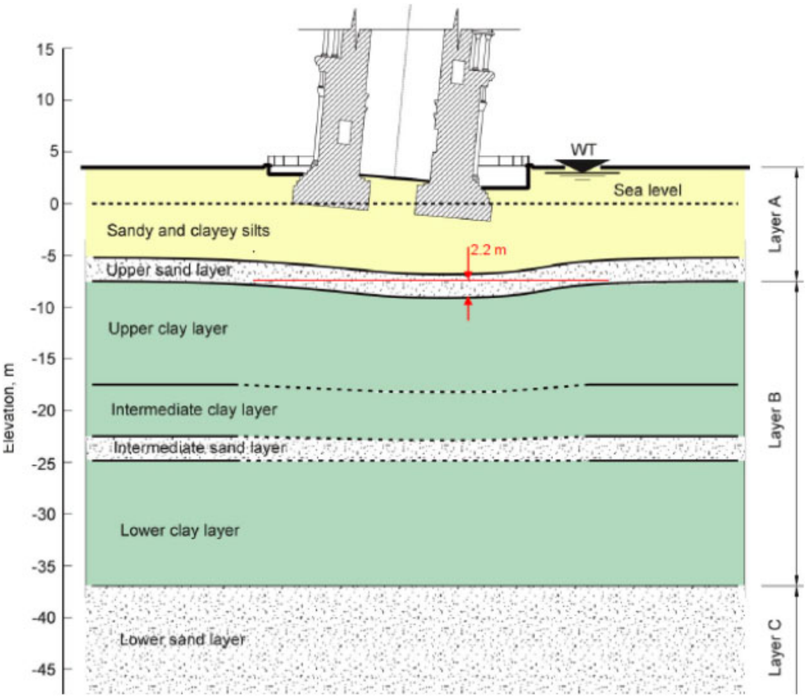

Figure 2. The subsoil of the Tower.

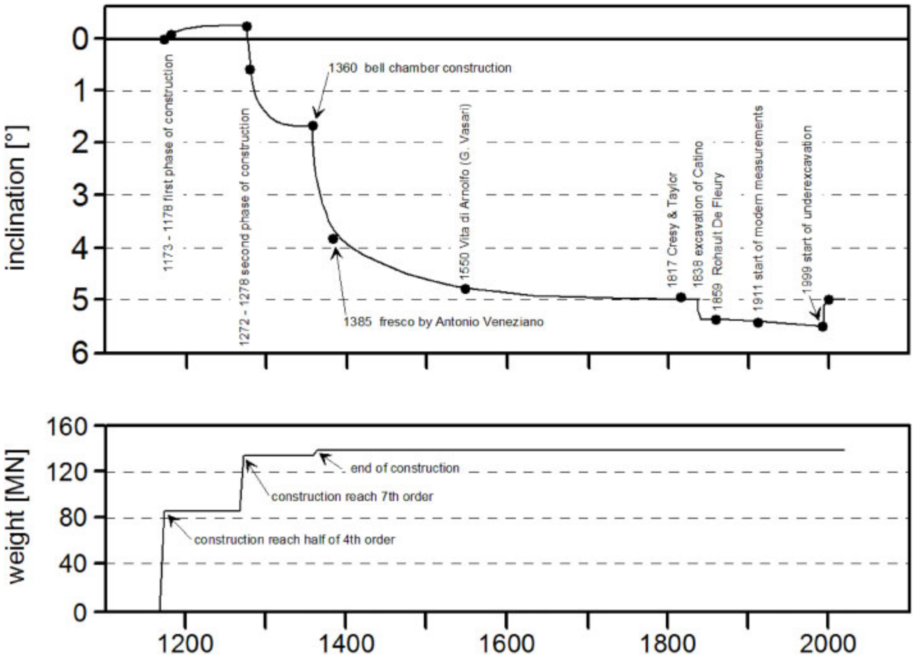

Figure 3. History of the inclination of the tower from the construction to 2022.

From 1360 to 1817 the only available data are obtained by old pictures or documents and are undoubtedly less reliable; but this does not influence the reconstruction of the overall trend. The picture that emerges from Figure 3 is clear: the Tower had already reached an inclination of almost 2° when the construction had reached the 7th cornice.

The inclination continued to increase gradually with time to reach a value of about 5° in 1817 when Cresy and Taylor, two English architects, published a detailed geometrical survey of the monument. At that time, the tower was probably motionless or its rotation was increasing with a very small and continuously decreasing gradient; the motion, anyway, was probably tending towards a final equilibrium configuration.

In 1859, the French architect Rohault de Fleury carried out a new survey of the Tower finding a value of the inclination significantly larger than that measured in 1817 and clearly out of the trend just described. As a matter of fact, since its construction the Tower had undergone a settlement of at least 3 m, so that its basement had sunk into the soil. To correct this effect, a walkway (the so called catino) was excavated around the base of the Tower in 1838. This imprudent excavation produced a sudden increment of the inclination and the motion re-started with a higher and increasing gradient, tending to a final overturning.

In conclusion, in 1911 the Tower had experienced a vertical displacement (average settlement) of at least 3 m and a southward rotation of more than 5°.

2 MONITORING

The inclination of the Tower from 1911 to 1999, as obtained by different procedures, is reported in Figure 4. This shows a continuous increase of the inclination, affected by some perturbations.

Because the bottom of the catino was well below the water table, there was a continuous inflow of water into the excavation, which required continuous pumping to keep it dry. The resulting flow of water in the soil around and below the foundation was believed to be dangerous for the stability

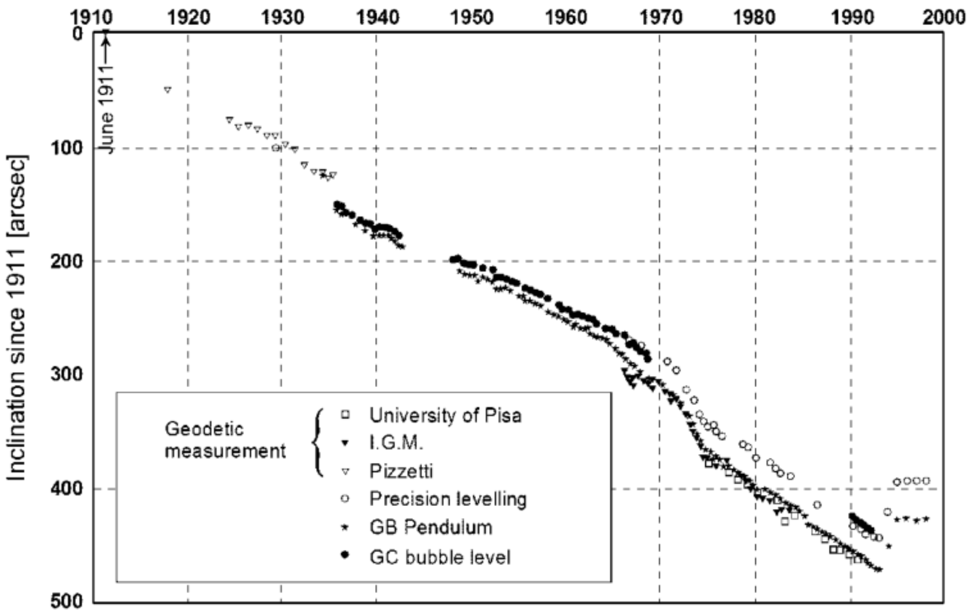

Figure 4. Inclination of the Tower from 1911 (start of modern monitoring) to 1999 (start of the underexcavation). GB inclinometer and geodetic measurements include the deformations of the Tower body, and hence their results are slightly larger than those of GC level and optical levelling, representative of the rotation of the foundation.

of the Tower and therefore in 1935/36 an intervention to prevent the water inflow was carried out, by injecting cement grout into the foundation masonry and chemicals into the soil below and around the catino. The intervention was successful in stopping the water inflow but produced a sudden increment of inclination and had no effect on the progress of the inclination with time.

From the early 1970s, an increase of the rate of tilt of the Tower is evident in Figure 4. This has been related to the increasing pumping of water from the deep sands (Figure 5) inducing subsidence all over the Pisa plain (Croce et al. 1981) and was eventually brought to an end by closing a number

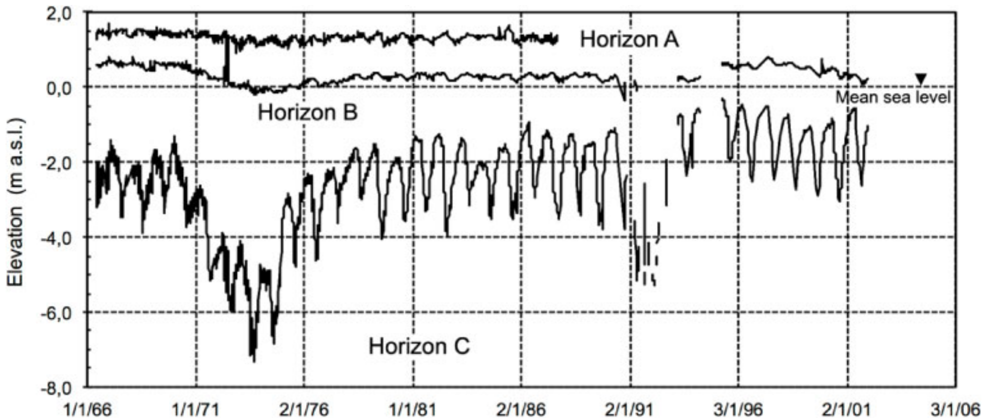

Figure 5. Groundwater regime in the subsoil of the Tower. The piezometric elevation in the lower sand is affected by pumping in the whole Pisa plain; in the 70's pumping increased because of a sequence of dry years.

of wells in the surroundings of the Tower. Since then, the water regime in the lower sand is carefully kept under control.

Through a careful analysis of all the available data, Burland and Viggiani (1994) discovered that in the stages of unperturbed motion the kinematics of the movements of the Tower was a rotation, without any settlement (Figure 6).

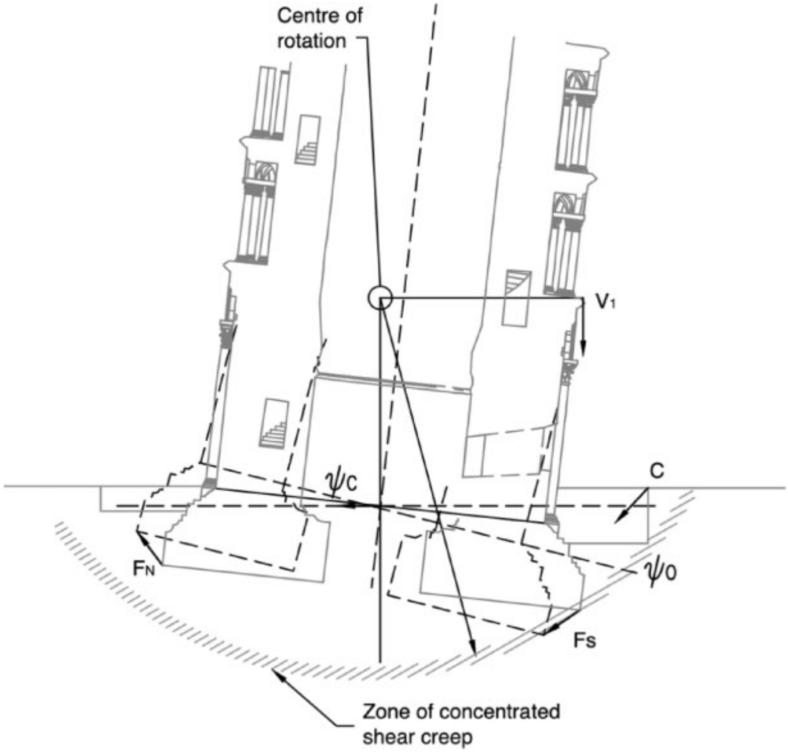

Figure 6. Kinematics of the displacements of the Tower during unperturbed motion.

This in turn revealed that the Tower was affected by a problem of stability of equilibrium, and a preliminary evaluation led to the conclusion that it was on the verge of collapse by leaning instability. Therefore, in 1993, the International Committee decided to implement temporary interventions to improve the safety of the Tower, pending conception and implementation of the final stabilisation measures.

From a structural point of view, a hoop of pre-tensioned steel wires was installed around the first cornice of the Tower. From a geotechnical point of view, a counterweight of 5.9 MN consisting of 64 lead ingots was installed on the North edge of the base of the Tower, producing a counter rotation of 53″. This may be seen in Figure 4 and in more detail in Figure 7.

In 1995, for different reasons, a medium term temporary intervention was developed to replace the lead weights with ten tensioned steel cables anchored in the lower sands at a depth of over 40 m (Figure 8).

The anchors had to be connected to the foundation of the Tower through a ring beam to be constructed under the floor of the catino, which required to carry out an excavation around the Tower below ground water level. It was decided to protect the excavation by ground freezing.

Without going into the details, it can be reported that the northern sections of the ring beams were successfully installed (Figure 9). However, when freezing was commenced on the South-West and the South-East sides, the Tower began to rotate southwards; after some attempts of controlling the

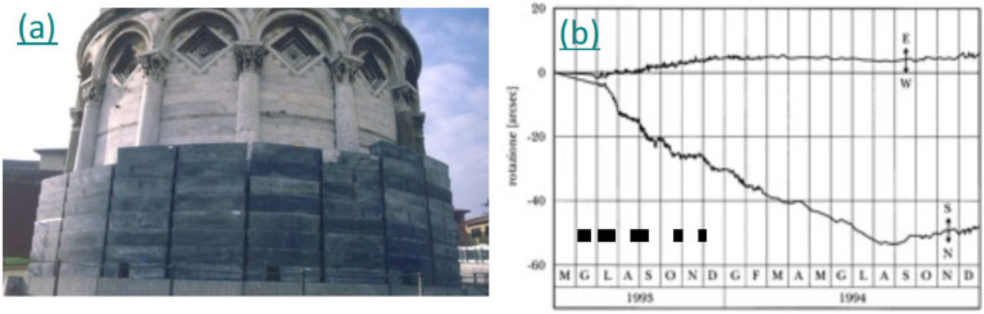

Figure 7. (a) Lead ingots counterweight and, (b) induced counter rotation.

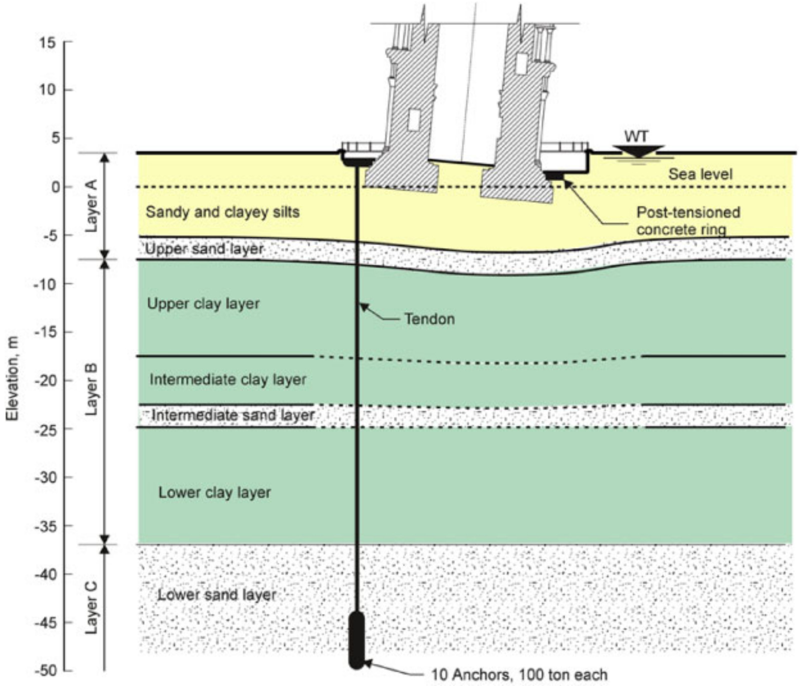

Figure 8. The ten anchors solution.

rotation by the application of further lead weights on the North, the intervention was abandoned. The negative effect of this attempt may be seen in Figure 4.

The results of small scale model tests of underexcavation, carried out both at 1 g and at increased gravity in a geotechnical centrifuge, and of numerical analyses encouraged the Committee to undertake a large scale field experiment. To this end, a 7 m diameter eccentrically loaded instrumented footing was constructed in the Piazza dei Miracoli and subjected to underexcavation.

The field trial was very successful and allowed the development of field equipment and operational procedures. A safeguard structure (Figure 10) consisting of two sub-horizontal steel stays and capable of applying a stabilizing moment if needed was connected to the Tower.

Figure 9. Construction of the northern sections of the ring beam for the ten anchors.

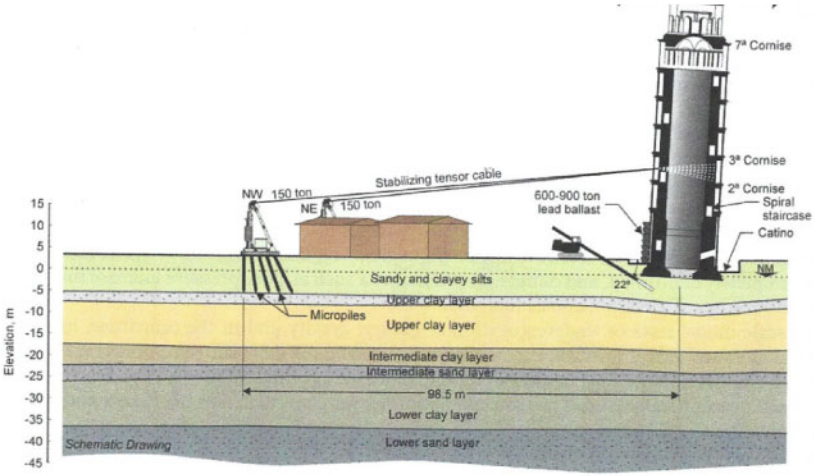

Figure 10. Scheme of the underexcavation and of the safeguard structure with steel stays.

3 STABILIZATION MEASURES

Between February and June 1999, a preliminary underexcavation intervention was carried out with 12 inclined drill holes, from which a total of 7 m^3 of soil, were removed.

Between February and June 2001 the full underexcavation was carried out with 41 holes, removing a total of 38 m^3 of soil, 70% of which below the catino, i.e., outside the perimeter of the foundation. In the same period all the lead ingots were progressively removed and the cable stays were dismantled, without having been ever operated.

As a final intervention, in 2002, a drainage system was installed in the upper soils North of the Tower, essentially aimed at stabilizing the groundwater level in the vicinity of the foundation.

The results of these operations, in terms of rotation of the Tower, are reported in Figure 11; they succeded in moving the Tower back northwards by about 2000 arcsec. Since then, the tower is still slowly moving northwards, at a very slow and decreasing rate.

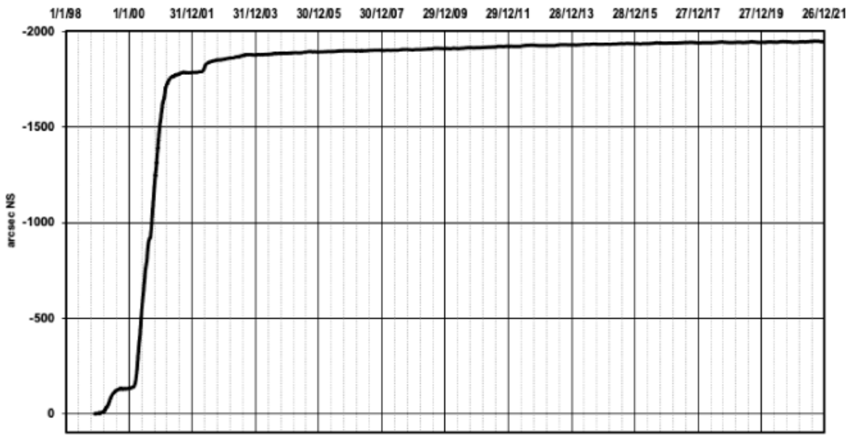

Figure 11. Results of preliminary and full underexcavation and of intervention on the water table.

Going back to Figure 3, showing these results in the wider context of the entire history of rotation of the Tower, it is evident that the intervention of the International Committee have compensated the effects of the excavation of the catino in 1836. We may say that there is a kind of justice in the fact that the detrimental effects of an incautious excavation have been repaired by another excavation, but this time carefully conceived and implemented.

4 FUTURE SCENARIOS

To evaluate the final success of the implemented stabilisation measures, a prediction of the future behaviour of the Tower is needed. The International Committee, on conclusion of their work, has not attempted to give a single solution to this question (Jamiolkowski 2005). Considering the complexity of the phenomena involved and the number and variety of factors that influences the behaviour of the Tower, the International Committee presented two possible scenarios, bounding the range of the future movements.

In the first one, rather conservative, it is predicted that the Tower will continue its very slow northwards rotation for a while, then remain motionless (a so-called honeymoon) and then gradually resume a southward rotation, initially at a very small rate and then progressively accelerating. In this scenario, the Tower would reach the value of the 1999 inclination in no less than three or four centuries.

In the more optimistic scenario, the rotation will cease, apart from small cyclic movements caused by seasonal factors, and the honeymoon will last for the foreseeable future.

At present, the results of twenty years of monitoring after the underexcavation was carried out are available (Figure 12). An attempt to extrapolate these results does not yet allow a choice between the two scenarios; the observation period is still too short. In any case, the importance of continued observation of the behaviour by careful monitoring coupled with a thorough evaluation of the results is evident.

Some people have criticised the adopted solution, claiming that actually it is not a true stabilisation, but only a small reduction of the inclination without substantial effects on the stability of the Tower and that a definitive stabilisation (whatever that means) was only handed down to posterity (Lizzi 2000, 2001).

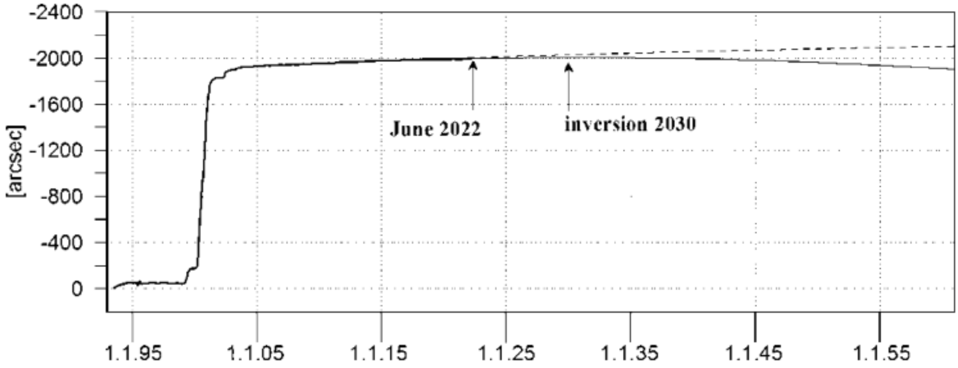

Figure 12. Rotation of the Tower after stabilisation intervention and possible extrapolation.

With reference to the first remark, it must be recalled that the Tower is affected by a leaning instability phenomenon. It has been shown repeatedly (e.g., Viggiani 2019) that the increase of rotational rigidity of the complex subsoil-foundation following the decrease in inclination resulted in a substantial increase of the stability.

As for the future behaviour, even in the pessimistic scenario of a resumption of the southward inclination, there will be time enough to repeat an underexcavation intervention, if needed. In some way, underexcavation may be considered a sort of extraordinary maintenance!

5 INTENTIONS AND ACHIEVEMENTS

There are numerous lessons learnt by this extraordinary case history, with a Tower 850 years old surviving a settlement of 3 m and an inclination of more than 5°. One of the most significant may be expressed by an old saying: the way to hell is paved with good intentions.

Good intentions are obvious when studying and implementing any intervention on the heritage but unfortunately, though being necessary, they are far from sufficient.

In the case of the Pisa Tower, we have already encountered at least two significant examples of good intentions leading to very unfavourable results.

The excavation of the catino in 1838, aimed at uncovering the lower part of the Tower which had sunk into the soil, was actually the factor bringing a monument that was finally attaining a stable configuration (Figure 3) on the verge of collapse.

The provisional intervention with ten steel cables, attempted by the International Committee in 1995, had also a detrimental effect on the Tower and had to be abandoned.

But an older sensational example of dangerous good intentions has been recently discovered (Leoni & Squeglia 2016; Leoni et al. 2018). A sophisticated numerical model of the Tower and its subsoil, including 230000 tetrahedral elements and adopting the Soft Soil Creep model (Vermeer & Neher 1999) for the clay layers, has been used to back analyse rather successfully the entire history of the monument.

In the framework of this analysis, the model has been used to predict the rotation of the Tower in the assumption of no correction of its shape during construction, and hence with a straight axis. Surprisingly, the comparison of these results with those obtained with the actual curved axis (Figure 13), reveals that without corrections – the rotation of the Tower in 1993 would have been 4.3°, i.e., significantly smaller than the actual 5.5°.

The ancient magistri lapidum, with their corrections to the axis of the Tower leading to the famous banana shape, have actually made the stability of the monument worse. Perhaps they were engaged in giving the Tower its present extraordinary inclination!

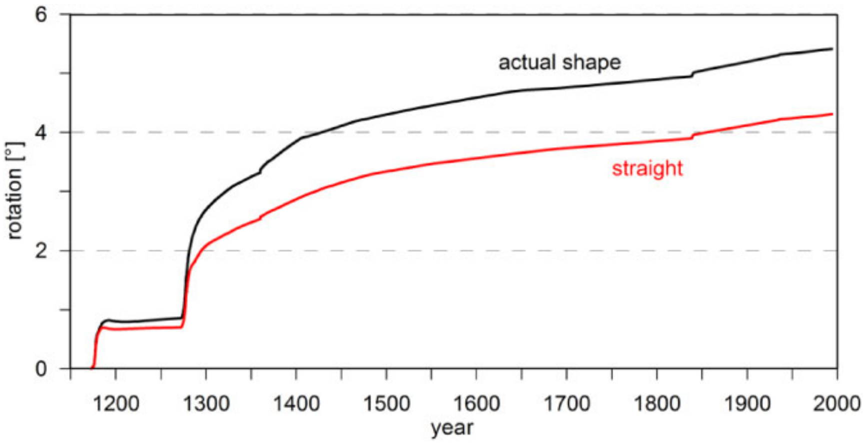

Figure 13. Rotation of the Tower with and without correction of its shape.

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