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The Behaviour of an Ancient Tower Through History and Monitoring

Carlo VIGGIANI [a,1]
[a] *University of Napoli Federico II, Italy*

Abstract. Geotechnical Engineering plays often a significant role in the conservation of historical buildings and monuments; this is particularly true for ancient towers, where soil structure interaction is a very important aspect.

From the viewpoint of an engineer, the peculiarity of any intervention on historical structures is the requirement of respecting their integrity, besides guaranteeing the safety. While the attainment of safety is a relatively straightforward matter for a well trained and experienced engineer, the respect of integrity is a much more difficult matter, since the concept itself of integrity has many facets and is somewhat elusive.

To conceive and implement any intervention intended to safeguard a monument, a clear understanding of its mechanisms of behaviour is essential. Such an understanding may be obtained by a careful reconstruction of its history and a complete observation of its actual behaviour by a proper monitoring program.

These concepts are exemplified referring to a famous medieval Italian tower: the leaning tower of Pisa.

Keywords. Integrity, monitoring, leaning instability.

1. Introduction

To defend, not to attack; to see further afield; to challenge the sky, or simply to observe it; to call to prayer or to sound the alarm; to look inside oneself and lift oneself above and away from the struggle of daily life. A tower can be used for all these things, a creation which sews together East and West and has its roots in the Bible and the Koran, and indeed in the origins of our common civilisation [1].

Consequently, there is an unbelievable number and variety of towers in the ancient and recent history of humankind: from the mythical tower of Babel, erected by Nebuchadnezzar in the 6th century BC, and the lighthouse of Alexandria, one of the seven wonders of the antiquity, to the Eiffel Tower, the Burj Khalifa and other skyscrapers, the modern towers for communication [2, 3]. In Christianity, since the 6th century, many churches and practically all monasteries have a tower, or a campanile. In Islam, the muezzin calls to prayer from a minaret. In the 10th century, Chinese pagodas had already reached a height of 150 m.

Many of these towers, especially the ancient ones, are affected by geotechnical (and structural) problems, due to their slenderness, the high stresses acting in their structure

[1]Carlo Viggiani; E-mail: viggiani@unina.it.

and foundations, the lateral actions such as wind and earthquakes. Here engineers, and among them geotechnical engineers, come into play.

2. Integrity

For the ancient towers, any engineering intervention must of course satisfy the requirements of safety (a task relatively easy to fulfil for a well trained and experienced engineer), but also respect the integrity of the monument. The integrity is an elusive concept, with many facets (formal integrity, material integrity, historical integrity) and varies in space and time, as does the prevailing culture of different regions and different ages. It is exactly this elusive value, however, that any intervention on a monument should preserve.

When dealing with this kind of problems, the safety and the integrity are often in conflict. The engineer, in charge of the safety, is influenced by his rational formation and tends to be suspicious about elusive concepts; on the other side the restorer, called to watch over the respect of integrity, is afraid about a possible oversimplifying and invasive approach of the engineer.

The first position may be exemplified by the following episode. Fernando Lizzi (1914-2003) was a very bright Neapolitan engineer, considered the father of micropiles technology. He is author of books on the restauration of ancient constructions [4]; the IMS (International Micropiles Society) has promoted a Lizzi lecture, that has reached the 9th edition. In a paper presented to an international symposium [5] Lizzi recalls that, in 1973, there was an international tender for the stabilisation of the Leaning Tower of Pisa. He participated with a project based on the use of micropiles, signed by himself and Jean Kerisel: names that are a guarantee of quality.

Lizzi writes: “The Competition was not awarded; no decision was taken and, at the date of the present paper (2000), the problem is still in the hands of a special Committee, appointed ten years ago. As for the above project, based on a network of Pali Radice, the present Committee admits its full validity from the engineering point of view; but its members solemnly declare that it cannot be accepted because the execution of piles, although concealed in the low masonry and in the subsoil … *spoils the integrity of the Monument* …. Therefore, the Committee is looking for a solution which can be carried out *without touching* the Monument”.

Lizzi makes ironic references to the Committee (italic and dots are in the original paper), and a large majority of the civil engineers would probably agree with his position. The common sense of a familiar, good, reliable underpinning to be obviously preferred to the apparently meaningless pretension of stabilising the Tower without even touching it!

The opposite position, the sacerdotal position of the strict respect of the integrity, may be exemplified by a book by Pierotti [6], a professor at the University of Pisa. In his enjoyable book Pierotti lays out a very documented and complete history of the Tower; in the final part, however, he seriously suggests that the monument could tend to a spontaneous self-equilibrating state, behaving as a biologic organism, and hence it does not need any stabilisation measure.

Trying to find the right way between these irreducible opposites, we will show that the rational, merely mechanicistic approach of the engineer may suggest respectful solutions to some difficult restoration problems. As a matter of facts, in the case of Pisa, a solution which can be carried out *without touching* the Monument.

3. Mechanics

As noted above, towers are often affected by geotechnical problems, due to the high stresses acting on their foundations and the lateral actions of wind and earthquakes. Cadignani et al. [7] claim that the historic towers we observe today survived to an initial stage of their life in which they were probably close to a bearing capacity failure, due to insufficient strength of the foundation soils. A long duration of the construction period, and possibly delays or interruptions of the construction, allowed the foundation soil to improve its strength by consolidation and the tower to be successfully finished; this has been actually the case for the Tower of Pisa, whose case history will be dealt with in this paper, and other famous towers as the Ghirlandina in Modena [8]. Due to uneven settlement, many of these towers appear today inclined; this recall the danger of a different form of failure, due to insufficient stiffness of the soil, the so called leaning instability.

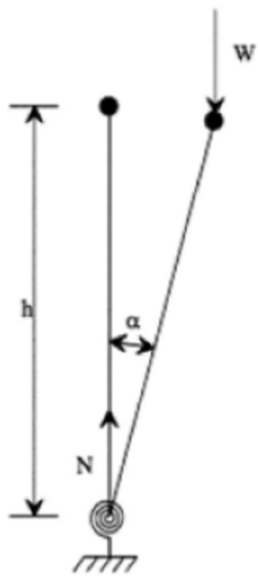

Figure. 1. The inverted pendulum.

To introduce leaning instability, the simple conceptual model of an inverted pendulum may be used. It is a rigid weightless vertical pole (Figure 1) with a concentrated mass W at the top and hinged at the base to a constraint that reacts to a vertical displacement w with a vertical force $F = wk_w$ and to a rotation α with a stabilizing moment $M_S = \alpha k_\alpha$. On the other hand, the rotation induces an offset of the mass and hence an overturning moment $M_O = W\ h\ sin\alpha$. If the stabilising moment is larger than the overturning one, the equilibrium is stable; the system returns to its initial configuration. If the contrary occurs, the equilibrium is unstable; the system collapses. If the two moments are equal, the equilibrium is neutral: the system stays in the displaced configuration. The stability of the equilibrium may be characterized by the ratio $FS = M_S/M_O$ between the stabilizing moment and the overturning one.

Modelling the tower as an inverted pendulum, the restraint exerted by the foundation may be evaluated, as a first approximation, by assimilating the foundation to a rigid circular plate of diameter *D* resting on an elastic half space of constants *E, ν*. The plate is subjected to a vertical force *W* applied at the height *h* of the centre of gravity and hence with an eccentricity $e = h \sin\alpha$. Calling $M = We$ the overturning moment and w, α the settlement and the rotation of the foundation, it may be shown that k_α and k_w are given by:

$$k_w = \frac{ED}{i - \nu^2}; \qquad k_\alpha = \frac{ED^3}{6(1-\nu^2)} \tag{1}$$

In this simple linear model, there is no coupling between settlement and rotation, and the terms k_α, k_w are intrinsic properties of the ground – monument system. The stability may be characterized by a factor of safety *FS* given by the ratio between the stabilising moment and the overturning one:

$$FS = \frac{M_S}{M_O} = \frac{k_\alpha \alpha}{Wh \sin\alpha} = \frac{ED^3}{6(1-\nu^2)} \frac{1}{Wh} \tag{2}$$

having posed $\sin\alpha \approx \alpha$ for small rotations. In the linear model, hence, the safety factor is also an intrinsic property of the ground – monument system, not depending on the value of the rotation.

In undrained conditions and in terms of total stress, the elastic constants of a linearly elastic, saturated porous medium are given by $E_u = 3E/2(1+\upsilon)$ and $\upsilon_u = 0.5$ (incompressible medium), where E and υ are the constant of the solid skeleton in terms of effective stress. It follows that:

$$2 \geq \frac{FS_u}{FS} = 2(1-\upsilon) \geq 1$$

showing that the safety against leaning instability *decreases* passing from undrained to drained conditions. This underlines the difference between the mechanisms of bearing capacity failure (lack of strength) and of leaning instability (lack of stiffness).

4. A case history: Pisa

4.1. The Monument

The Leaning Tower of Pisa, bell tower of the Pisa Cathedral (Figure 2), is undoubtedly one of the world's most beautiful and famous monuments. Its weight is 14.500 t, its height nearly 60 m, the foundation is 19.6 m in diameter, the centre of gravity is 22.6 m above the foundation plane. It is inclined to south at 5.5° and the seventh cornice overhang the ground by about 4.5 m.

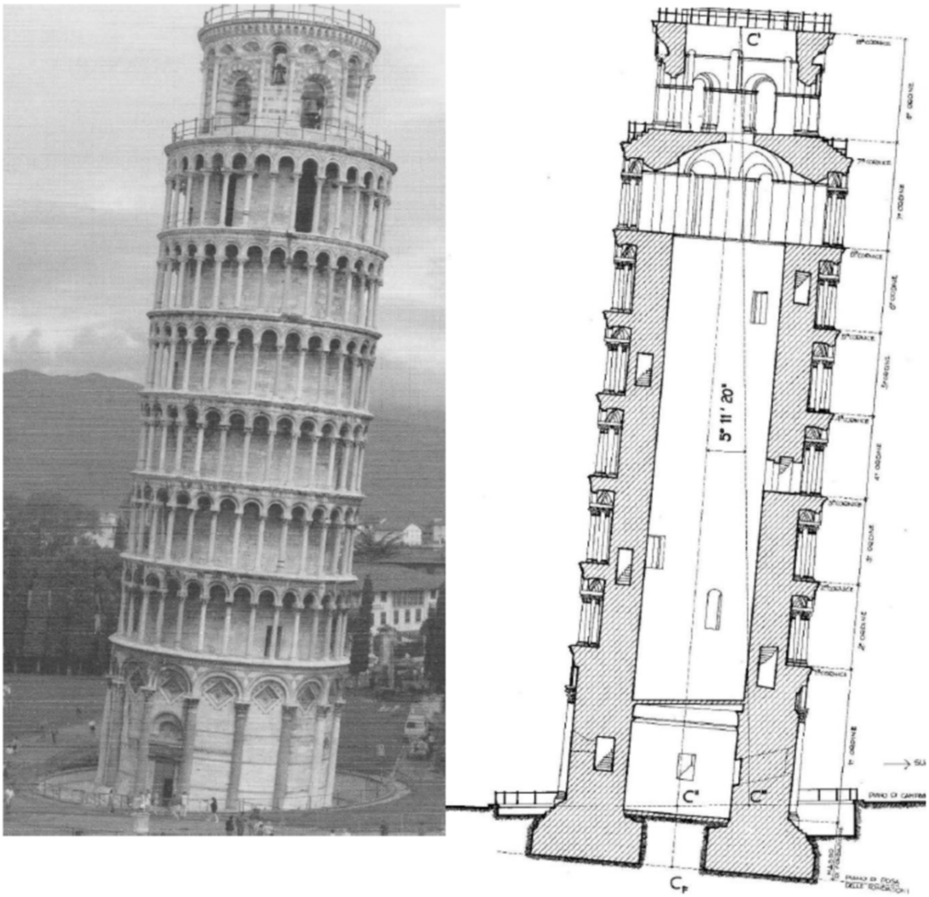

Figure 2. The Leaning Tower of Pisa.

The Tower is founded on weak, highly compressible soils and its inclination had been inexorably increasing over the years to a point at which it was very close to collapse.

As shown in Figure 3, the ground profile below the monument may be schematized in three layers. Layer A is about 10 m thick and consists of soft estuarine deposits of sandy and clayey silts laid down under tidal conditions. Layer B consists of soft, sensitive, normally consolidated or slightly overconsolidated marine clay, which extends to a depth of 40 m. Layer C is a dense sand, which extends to considerable depth. The surface of layer B is dished beneath the Tower, showing that the average settlement is about 3 m.

The construction of the Tower began in 1173, under Bonanno Pisano, architect and sculptor. Work progressed to the fourth order, reached in 1178, and was then suspended for a century; had the construction proceeded without interruption, the Tower would have collapsed due to an undrained bearing capacity failure. Work resumed in 1271 under Giovanni di Simone and reached the seventh cornice in 1278; then a second 80 years interruption followed. Once again, the interruption saved the monument from collapsing. Between 1360 and 1370 Tommaso di Andrea built the belfry, completing the construction two centuries after it had first begun.

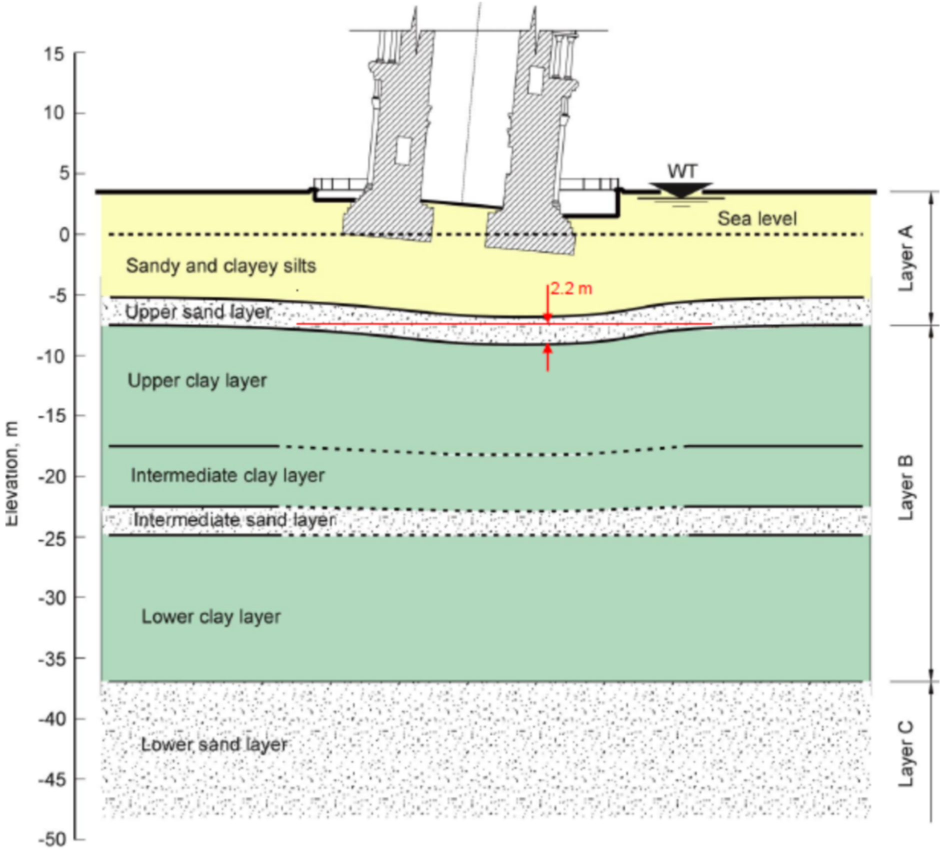

Figure 3. The subsoil of the Tower.

The tower began leaning during construction, as it is apparent from the corrections made by the ancient masons to compensate for the inclination that was progressively occurring. The most evident correction can be seen in the belfry: between the seventh cornice and the floor of the belfry there are six steps on the South side, and only four on the North.

The corrections carried out during the construction may be used to work out the inclination at that time [9]. As we see in Figure 4, at the beginning the Tower leaned to North to an inclination of 0.2° in 1272. In 1278, at the seventh cornice, the inclination was 0.6° to South. During the 80 years of the second interruption, it increased to 1.6°; at this point the belfry was added.

After the end of construction, indications on the lean may be obtained by pictures (*e.g.*, a fresco by Antonio Veneziano dating back to 1385) or by documents (*e.g.*, a passage of the Arnolfo's life by Giorgio Vasari, 1566). In 1817 two English architects, Cresy and Taylor [10], carried out a detailed survey; another one was performed 40 years later by Rohault de Fleury [11].

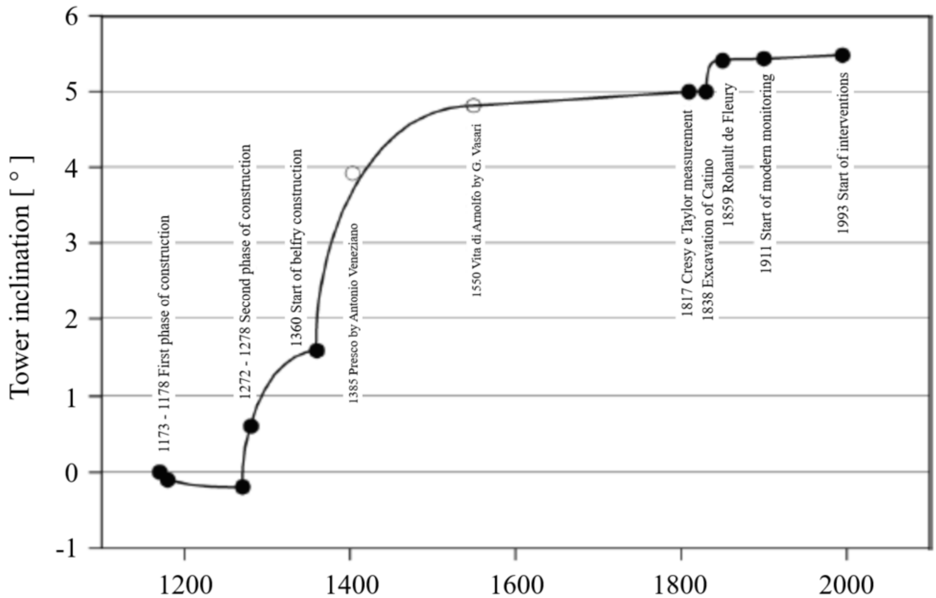

Figure 4. History of the inclination of the Tower.

Between the two measurements, an important event in the history of the Tower had occurred: the excavation of the walkway around the base of the Tower, known as the "catino" (the basin), with the purpose of exposing the column plinths and foundation steps, for all to see as originally intended (as mentioned above, the base of the tower had sunk into the soil due to the 3 m settlement). The excavation of the catino produced a sudden increase of the inclination of the Tower, but also a variation of the characteristics of its motion. Before the excavation, the Tower had come to rest or, in any case, its motion was going on at a very small and progressively decreasing rate. After the excavation, the Tower moves at a progressively increasing rate, ineluctably destined to end in a collapse.

Since 1911 the inclination of the Tower has been observed by a monitoring system, progressively improved and completed [9], [12]; between 1911 and 1990 it has been increasing each year by about six seconds, equivalent to about 1.5 mm horizontal displacement at the top. There has been much debate about the cause of this progressive increase in inclination. It has usually been attributed to a differential settlement due to creep in the underlying soft clay. It has also been suggested that the Tower is affected by impending bearing capacity failure in the underlying soft clay.

4.2. Monitoring

An International Committee, installed in 1990 with the task of conceiving, designing and implementing the stabilisation of the Tower, examined in detail the historical documentation and the available monitoring results. The history of the inclination, as depicted in Figure 4, was one of the outputs of this work.

If one plots the inclination of the Tower against its weight, progressively increasing during construction, the diagram in Figure 5 is obtained. It shows that the Tower kept essentially vertical till the end of construction, and afterward it inclined significantly. This behaviour suggests the occurrence of a stability problem.

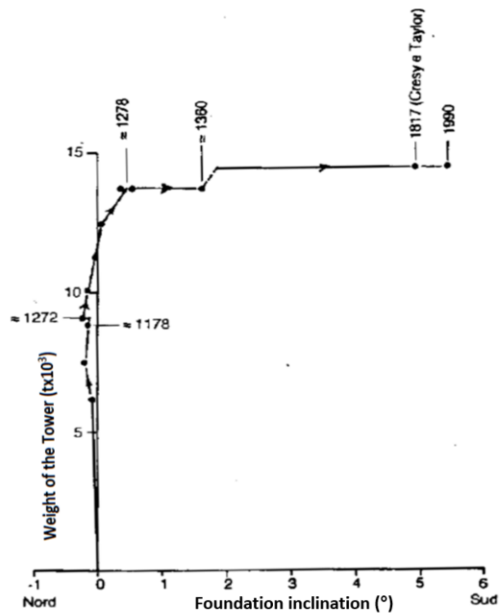

Figure 5. Inclination vs. weight.

A study of the geodetic survey measurements revealed a surprising form of motion, different to previously held ideas. They showed that the first cornice (point V1 in Figure 6) had not moved horizontally, apart from periods when there were external disturbances. Precision levelling, furthermore, showed that the centre of the foundation had not displaced vertically relative to the surrounding ground. Therefore, the rigid body motion of the Tower could only be as shown in Figure 6, with a centre of rotation at the level of the first cornice and vertically above the centre of the foundation. Again, the motion of the Tower shown in Figure 6 is typical of a leaning instability.

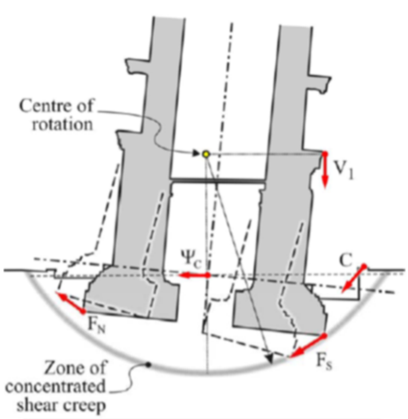

Figure 6. Observed kinematic of the Tower motion.

We can try to describe the phenomenon with the simple linear model outlined in § 4. From the first Eq. (1) one gets:

$$w = \frac{W}{k_w} = \frac{W(1 - \upsilon^2)}{ED}$$

With W = 14,500 t, w = 3 m, D = 19,6 m, one obtains:

$$\frac{ED}{1 - \upsilon^2} = 4{,}833\ t/m$$

With h = 22.6 m, Eq. (2) gives:

$$FS = \frac{ED}{1 - \upsilon^2}\frac{D^2}{6Wh} = 0.95\ \approx 1$$

Even the very rough linearly elastic half space model confirms that the Tower is very nearly in a situation of neutral equilibrium, and that its impending instability is not due to a bearing capacity problem, but to leaning instability due to the very compressible foundation soil.

4.3. The intervention

The discovery of the motion shown in Figure 6 was crucial in many respects; it suggested the application of a lead counterweight to the north side of the foundation as a temporary stabilising measure and the underexcavation beneath the north side as a long term stabilisation measure. A complete description of these interventions and their effect on the Tower may be found in the Proceedings of the International Committee for the Safeguard of the Tower of Pisa [13].

The study of the movements of the Tower, depicted in Figure 6, led to the conclusion that the seat of the continuing long-term rotation of the Tower lies in Horizon A. It was then concluded that, probably in addition to creep, the most likely cause of the progressive rotation was the fluctuating ground water level due to rainstorms.

Piezometric measurements made over years have shown that the average ground water level close to the south side of the Tower in Horizon A is 200 to 300 mm higher than that to the north. This difference generates a small, but not negligible stabilising moment for the monument that is so close to falling over. In the autumn and winter, when the rainfall events are more intense, the water table raises sharply, reducing the difference in piezometric level and thereby producing southward rotations of the Tower, which are not fully recovered. It is believed that the cumulative effects by ratchetting of these repeated impulses has been one of the factors producing the steady increase of inclination in the long term.

To minimise this effect a drainage system controlling the water table was installed; it led to a significant reduction in its seasonal fluctuation and to another northward rotation of the Tower.

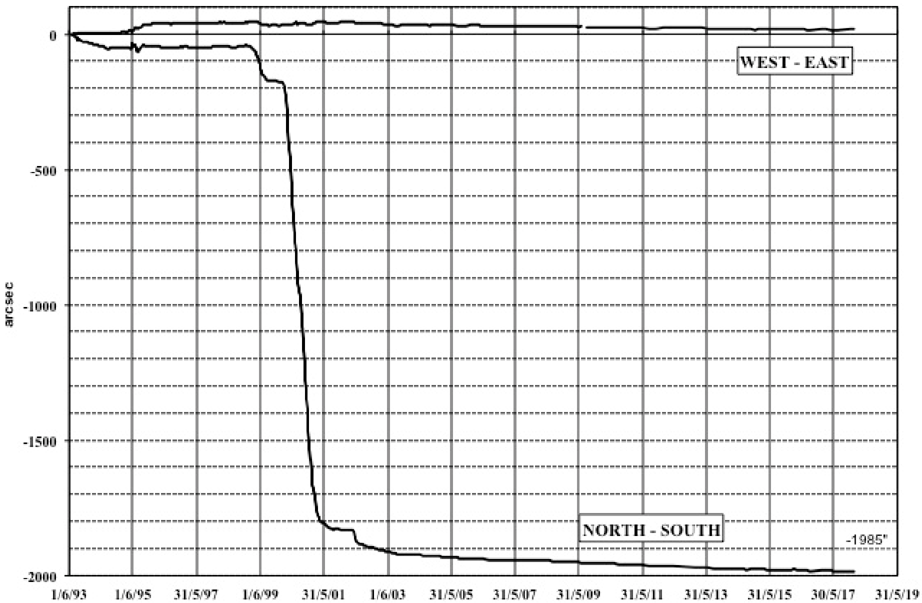

Figure 7. Rotation of the foundation of the Tower since 1993.

The results of these interventions may be seen in Figure 7. Figure 8 shows the effect of underexcavation on the history of the inclination from the beginning of the construction.

The stabilisation work may be seen as a mere reparation to the detrimental effect of the excavation of the catino; there is a kind of poetic justice in the fact that the detrimental effects of an incautious excavation have been repaired by another excavation, this time well conceived and carefully executed.

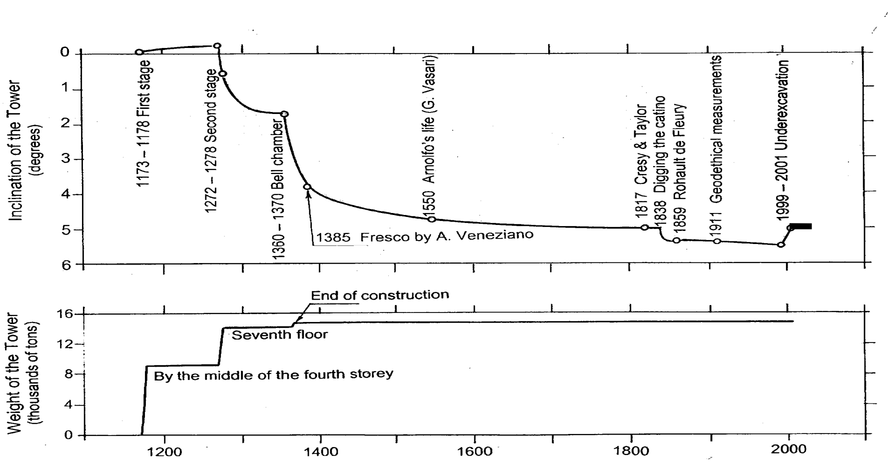

Figure 8. The complete history.

4.4. Has the stabilisation been achieved?

After the intervention of the International Committee and the publication of its results, Fernando Lizzi, already quoted in § 2, believes that the Tower has not been stabilised and expresses his doubts in a letter to a newspaper [14]. The model outlined in § 3 above seems to enhance his opinion: the safety factor is an intrinsic property of the ground-monument system and does not depend on the inclination. So, why a reduction of the inclination should increase the safety?

Albert Einstein used to say that things should be made as simple as possible, but not simpler! And the linear model of subsoil that we have used above is surely oversimplified. Figure 9 reports the results of a series of model tests in the centrifuge, on the rotation of a circular rigid plate resting on a clay bed. It appears evident that the process is non linear and that there is coupling between normal force and rotation. At unloading, only a minor part of the rotation is reversed, and at reloading the behaviour is quasi elastic until the previous load is reached. All these are characters of an elasto-plastic hardening behaviour.

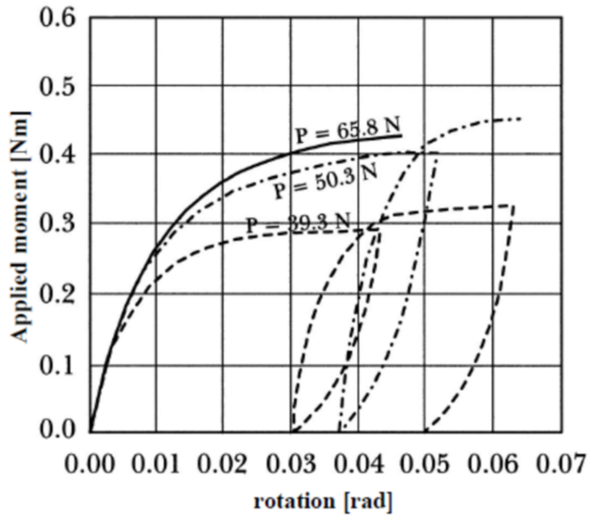

Figure 9. The tests by Cheney et al. [15].

With a non linear, elasto-plastic behaviour the relation between the external actions (*W, M*) and the displacements (*w, α*) becomes:

$$\begin{Bmatrix} \partial w \\ \partial \propto \end{Bmatrix} = \begin{bmatrix} \dfrac{1}{k_w} & \dfrac{1}{k_{w\propto}} \\ \dfrac{1}{k_{\propto w}} & \dfrac{1}{k_\propto} \end{bmatrix} \begin{Bmatrix} \partial W \\ \partial M \end{Bmatrix}$$

in which the terms of the stiffness matrix are not constant of the soil-monument system but vary as a function of the current stress state and of the previous stress history. Consequently, the safety against overturning is also a function of the current state and of the previous history.

In simple terms, the rotational stiffness of the soil-monument system is but the tangent $\partial M/\partial \alpha$ to the curves depicted in Figure 9. On a first loading curve, such a stiffness decreases with increasing α, and this explain why with increasing inclination the Tower was approaching the collapse: the situation was evolving from neutral equilibrium to instability. On the unloading branch, however, the stiffness is much larger than that at first loading, and this explains why even a small decrease of the inclination produces a substantial increase in the safety.

A question, however, remain to be answered: how will the Tower behave in the future? Attempting an answer is not easy, due to the complexity of the phenomena involved and the number and variety of factors influencing them.

4.5. Future scenarios

The International Committee, upon concluding its work, outlined two possible future scenarios [16].

In the first one, rather conservative, the Tower will remain motionless for some decades (a time span that the Committee called the honeymoon) and then gradually resume a southward rotation, first at a rather slow rate and then progressively accelerating. In this scenario, the Tower would reach the value of the inclination it had in 1999 in a time span of the order of three centuries. Should better options not be available, before reaching this point one could repeat the underexcavation intervention.

In a more optimistic scenario, the rotation will cease, apart the cyclic movements caused by daily sun irradiation, seasonal changes in the water table and the influence of the generalized subsidence of the whole Pisa plain, which affects the Piazza and the Tower [17].

Going back to Figure 7, let us have a look to the observed inclination of the Tower, almost twenty years after the stabilisation works. At present, the situation appears satisfactory; the Tower is still slowly moving northwards and approaching a motionless state with a decreasing rate. There are, however, several more detailed questions that can be asked. Is the honeymoon finishing? Have the stabilisation works modified the daily and seasonal cyclic movements? What about the east-west movements? Is the Tower stable in the east-west direction? The answers to these questions are to be searched in the careful observation of the behaviour of the monument, by going on monitoring it in the next decades.

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