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THE LEANING TOWER OF PISA REVISITED

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ABSTRACT

Stabilisation of the Leaning Tower of Pisa was achieved by means of an innovative method of soil extraction which induced a small reduction in inclination not visible to the casual onlooker. Its implementation has required advanced computer modelling, large-scale development trials, an exceptional level of continuous monitoring and daily communication to maintain control. Recently a number of historical examples have been found of the application of soil extraction to straightening leaning buildings – the earliest being 1832. Contemporary accounts of the work bring out interesting and important similarities and serve as reminders of the inventiveness and resourcefulness of engineers long before modern soil mechanics came into being.

INTRODUCTION

The story of the stabilisation of the Leaning Tower of Pisa using soil extraction (or underexcavation) is now well known. Detailed accounts of the work are given by Jamiolkowski (2001) and Burland, Jamiolkowski and Viggiani (2003). The purpose of this paper is to describe the theoretical and practical aspects of the soil extraction method as used at Pisa and to draw parallels between this and some early historical examples of the method which have recently come to light.

Details of Tower

Fig. 2 shows a cross-section through the tower. It is nearly 60m high and the foundations are 19.6m in diameter. The weight of the tower is 14,500t. In 1990 the foundations were inclining due south at about 5.5^{o} to the horizontal. The seventh cornice overhung ground level by about 4.5m.

Construction is in the form of a hollow cylinder. The inner and outer surfaces are faced with marble and the annulus between these facings is filled with rubble and mortar within which extensive voids have been found. A spiral staircase winds up within the annulus. Fig. 2 clearly shows that this staircase forms a large opening on the south side just above the level of the first cornice where the cross section of the masonry reduces. The high stresses within this region are a major cause of concern and could give rise to an instantaneous buckling failure of the masonry without warning. In the summer of 1992 this masonry was stabilised by applying lightly prestressed steel strands around the tower in the vicinity of the first cornice.

Fig. 1. The Leaning Tower of Pisa

Ground profile

Fig. 3 shows the ground profile underlying the tower. It consists of three distinct horizons. Horizon A is about 10m thick and primarily consists of estuarine deposits laid down under tidal conditions. As a consequence the soil types consist of rather variable sandy and clayey silts. At the bottom of Horizon A is a 2m thick medium dense fine sand layer (the upper sand). Based on sample descriptions and piezocone tests the material to the south of the tower appears to be more silty and clayey than to the north and the sand layer is locally thinner.

Horizon B consists of marine clay which extends to a depth of about 40m. It is subdivided into four distinct layers. The upper layer is a soft sensitive clay known as the Pancone. It is underlain by a layer of stiffer clay (the intermediate clay) which in turn overlies a sand layer (the intermediate sand). The bottom layer of Horizon B is a normally consolidated clay known as the lower clay. Horizon B is laterally very uniform in the vicinity of the tower. Horizon C is a dense sand which extends to considerable depth (the lower sand). The water table in Horizon A is between 1m and 2m below ground surface. Pumping from the lower sand has resulted in downward seepage from Horizon A with a vertical pore pressure distribution through Horizon B which is slightly below hydrostatic.

The many borings beneath and around the tower show that the surface of the Pancone clay is dished beneath the tower from which it can be deduced that the average settlement is approximately 3m.

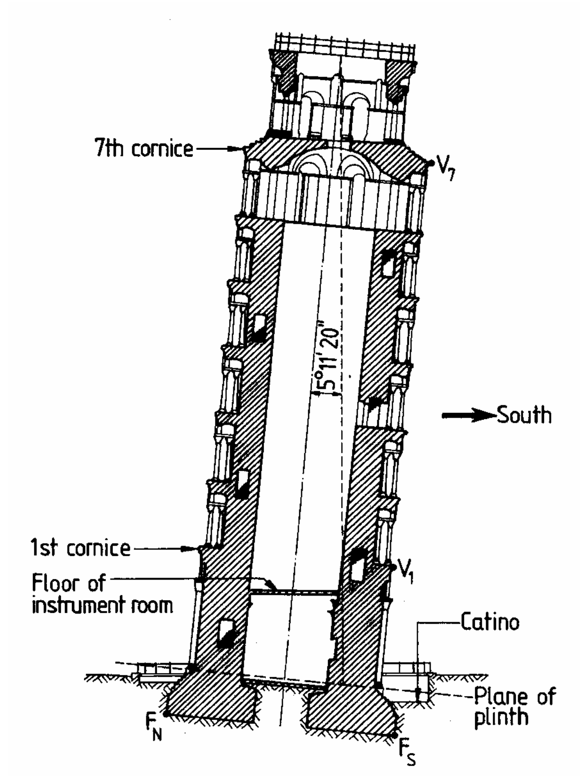

Fig. 2. Cross-section through the Leaning Tower of Pisa

HISTORY OF CONSTRUCTION

The tower is a campanile for the Cathedral, construction of which began in the latter half of the 11th Century. Work on the tower began on 9th August 1173 by the modern calendar. By about 1178 construction had progressed to about one quarter of the way up the fourth storey when work stopped. The reason for the stoppage is not known but had it continued much further the foundations would have experienced an undrained bearing capacity failure. The work recommenced in about 1272, after a pause of nearly 100 years, by which time the strength of the ground had increased due to consolidation under the weight of the tower. By about 1278 construction had reached the 7th cornice when work again stopped due to military action. Once again there can be no doubt that, had work continued, the tower would have fallen over. In about 1360 work on the bell chamber was commenced and was completed in about 1370 - nearly 200 years after commencement of the work.

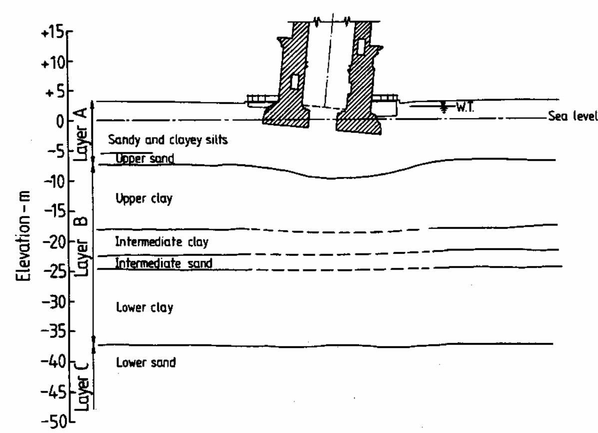

Fig. 3. Ground profile beneath the Tower

MOVEMENTS OF THE TOWER

Historical Movements

It is known that the tower must have been tilting to the south when work on the bell chamber was commenced as it is noticeably more vertical than the remainder of the tower. Indeed on the north side there are four steps from the seventh cornice up to the floor of the bell chamber while on the south side there are six steps. Another important detail of the history of the tower is that in 1838 the architect Gherardesca excavated a walk-way around the foundations. This is known as the catino and its purpose was to expose the column plinths and foundation steps for all to see as was originally intended. This activity resulted in 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 significantly at this time.

The axis of the tower is not straight – at each floor tapered layers of masonry have been inserted to correct for the lean of the tower at that time. Thus the history of the tilting of the tower is tantalisingly frozen into the masonry layers. Burland (1991) developed the hypothesis that, at the start of each storey, the masons aimed to bring the centre line of the tower back, vertically over the centre of the foundations by completion of that storey.

Fig. 4 shows the deduced history of inclination of the foundations of the tower. In this figure the weight of the tower is plotted against the deduced inclination. During the first phase of construction to just above the third cornice (1173 to 1178) the tower inclined slightly to the north. The northward inclination increased slightly during the rest period of nearly 100 years to about 0.2^o. When construction recommenced in about 1272 the tower began to move towards the south and accelerated shortly before construction reached the seventh cornice in about 1278 when work again ceased, at which stage the inclination was about 0.6^o towards the south. During the next 90 years the inclination increased to about 1.6^o. After the completion of the bell chamber in about 1370 the inclination of the tower increased significantly. In 1817, when Cressy and Taylor made the first recorded measurement with a plumb line, the inclination of the tower was about 4.9^o. The excavation of the catino in 1834 appears to have caused an increase in inclination of approximately 0.5^o and the inclination of the foundations in 1990 was about 5.5^o. It can be seen from Fig. 4 that significant inclination of the tower only began once the height exceeded the sixth cornice. The history of inclination depicted in Fig. 4 was used to calibrate the numerical model described later in the paper.

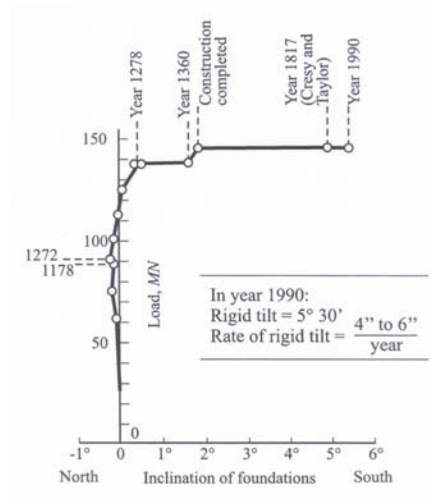

Fig. 4. Deduced history of inclination of the Tower

Changes is Inclination During 20th Century

For most of the 20th Century the inclination of the tower was increasing. These changes of inclination were extremely small compared with those that occurred during and immediately following construction. Nevertheless the study of these movements has been important in developing an understanding of the mechanisms of behaviour and in developing the stabilisation measures. Since 1911 the inclination of the tower has been measured regularly by means of a theodolite and in 1928 four levelling stations were placed around the plinth level of the tower and were referred to a bench mark on the Baptistry. The measurements showed that the tower is very sensitive to local interventions such as drilling and pumping. In 1990 the rate of inclination was approximately 6 arc seconds per year (about 1.5mm at the top) which was twice what it was in 1930 – a very worrying trend.

Motion of the Tower Foundations

In the past, attention had concentrated on the changes of inclination of the tower. Little thought had been given to the complete motion of the foundations relative to the surrounding ground. A careful study of the theodolite and precision levelling measurements revealed that for most of the 20th Century, point V_1 (see Fig. 2) on the first cornice did not move horizontally. Moreover, negligible average settlement of the foundations took place relative to the surrounding ground.

It follows from these observations that the principal motion of the foundations during the 20th Century has been one of rotation about a point level with the 1st cornice and vertically above the centre of the foundations as shown in Fig. 5. The direction of motion of points F_N and F_S are shown by vectors and it is clear that the foundations were moving northwards with F_N rising and F_S sinking. The identification of the mode of movement of the foundations played a key role in understanding the behaviour of the tower and in developing stabilisation measures. The following important conclusions were drawn:

(a) Since the north side was rising it might be possible to place a temporary counterweight on the north side to increase stability in the short term. This led to the solution of placing lead weights on the north side of the foundations.

(b) The cause of the continuing movement must be shallow-seated and not due to creep in the underlying clay as had previously been thought. This ultimately led to the realisation that the continuing movement was caused by a seasonally fluctuating water table in the upper sandy and clayey silts.

(c) Because of the shallow seated nature of the movements the underlying Pancone clay had not been subjected to continuing deformations and had therefore aged, thereby increasing its yield stress. This conclusion had profound implications for the numerical modelling of the lead weights and soil extraction.

(d) As will be described later, the mode of movement depicted in Fig. 5 is consistent with the phenomenon of leaning instability rather than bearing capacity failure.

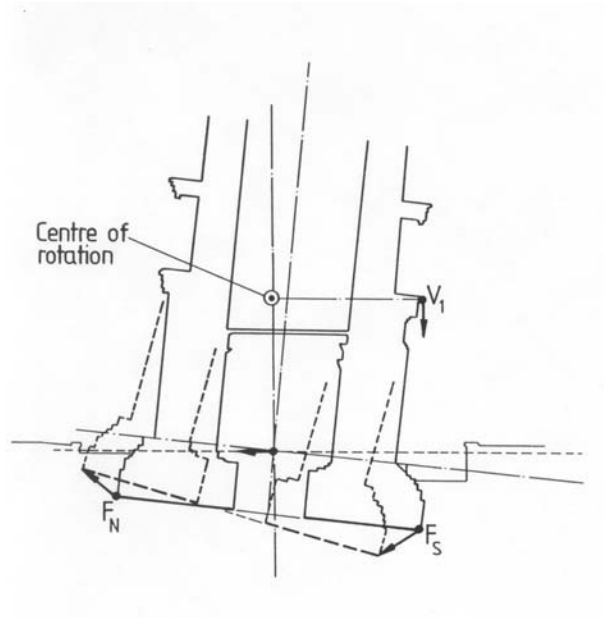

Fig. 5. Motion of the foundations

NUMERICAL ANALYSIS

Burland and Potts (1994) give a full description of the numerical analysis that was carried out on the historical movements of the tower. The underlying clay soils were modelled using a form of the Modified Cam Clay model with fully coupled consolidation for all of the soil layers. Particular care was taken over the choice of compression index C_c and yield stress for each of the silty and clayey layers in the soil profile. Initially a plane strain formulation was used but later the analysis was repeated using a three-dimensional approach.

The finite element mesh is shown in Fig. 6 and there are two important features to note in Fig 6(b). Firstly, if any change of inclination 2 of the tower takes place, the centre of gravity moves horizontally and generates an overturning moment M due to the current weight of the Tower W acting at a height h_a such that

$$M = W.h_a.\sin 2.I_c \qquad (1)$$

where I_c is a correction factor which takes account of the ratio between the second moments of area of a rectangular and a circular foundation. Unless this geometric feature is incorporated into the analysis, instability due to changes of geometry cannot be captured by the model. Secondly, a tapered layer of slightly more compressible material was incorporated into the mesh for horizon A as shown by the shaded elements in Fig. 6(b). The presence of such a layer was noted from the site investigations and its incorporation in the analysis serves as an 'imperfection' in applied mechanics terms. Thus, the model was capable of generating its own changes in overturning moment during and subsequent to construction.

The only factor that was adjusted to calibrate the model was the factor I_c in equation (1). For the first run, the value of I_c was set equal to unity. At the end of the run the final inclination of the tower was found to be less than the present value of 5.5°. A number of runs were carried out with successive adjustments being made to the value of I_c until good agreement was obtained between the actual and predicted value of the final inclination. It was found that, with a value of I_c = 1.27, the final calculated inclination of the tower was 5.44°. Any further increase in I_c resulted in instability of the tower. It is therefore clear from this analysis that the tower must have been very close to falling over. The final value of I_c is very close to the theoretical value for rotation about the centroid but this is probably coincidental.

In Fig. 7 the results of the analysis are plotted on a graph of load against inclination and compared with the deduced

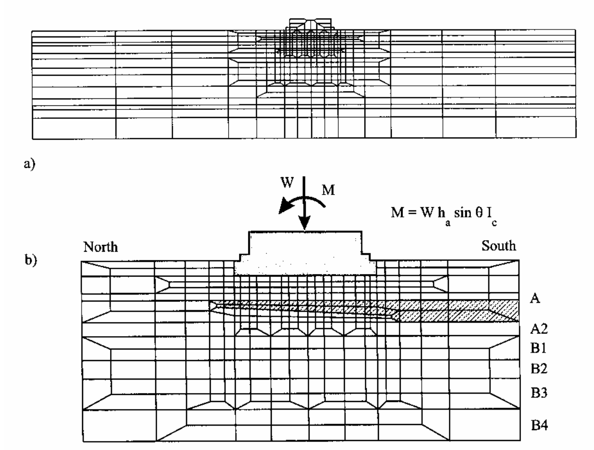

Fig. 6. Finite Element mesh. (a) General; (b) In the vicinity of the Tower

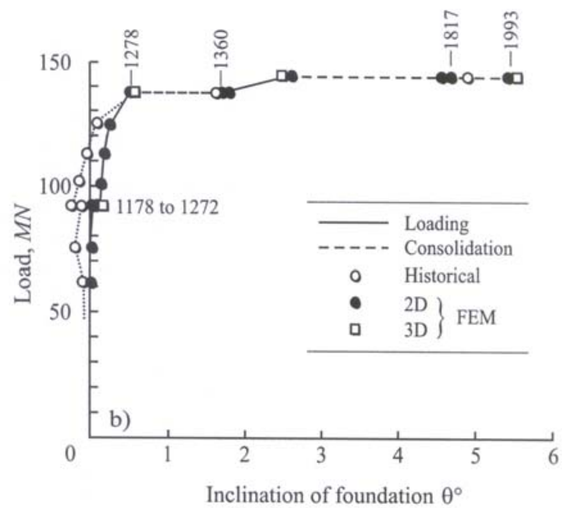

Fig. 7. Comparison between deduced and computed history of inclination of the Tower

history from Fig. 4. It is important to appreciate that the only point that has been pre-determined on this plot is the final inclination of about 5.5°. The agreement between the simulated and historical behaviour is remarkable and gives considerable confidence in the reliability of the computer model. A striking difference is that the model does not predict the initial northerly inclination of the tower. This is not felt to be of importance for the intended application of the model. It was found that, during the early stages of loading, the model did show a small inclination to the north. This was due to the fact that consolidation of the thin northern end of the tapered layer of compressible soil took place more rapidly than the thicker southern end. It should be possible to devise a soil profile in Horizon A that more accurately simulates the early history of inclination of the tower but this was outside the scope of the project.

The numerical analysis revealed that the mechanism of instability was due, not to a general shearing failure of the underlying ground (bearing capacity failure), but due to the phenomenon of leaning instability. The latter phenomenon results from the high compressibility of the underlying ground such that, at a critical height of the tower, the overturning moment generated by a small increase in inclination is greater than the resisting moment generated by the foundations.

Potts and Burland (2000) illustrated the difference between leaning instability and bearing capacity failure by means of a large displacement finite element analysis of an initially leaning tower resting on a uniform deposit of undrained clay modelled as a linear elastic perfectly plastic Tresca material. The undrained strength s_u was fixed at 80kPa and three different values of shear modulus G were studied. In each case the self weight of the tower was increased until failure occurred. Fig. 8 shows the failure mechanism for $G/s_u = 10$ when leaning instability was controlling. This may be compared with the mechanism shown in Fig 9 for $G/s_u = 1000$ and for which the shear strength was controlling. It is evident that for leaning instability only a small, localised plastic zone develops whereas for a bearing capacity failure the plastic zone is very extensive.

SOIL EXTRACTION

Once the mechanism of behaviour of the foundations had become apparent both from measurements on the tower and from the numerical analysis, various stabilisation measures were considered. After careful study on the numerical model, temporary stabilisation was achieved by applying nine hundred tonnes of lead weights to the north side of the foundations by means of a removable post-tensioned concrete ring. The response of the tower to the application of the lead weights was accurately predicted by the numerical model.

It was decided early on that an appropriate way to permanently stabilise the tower would be to decrease its inclination by about 10 percent. This would significantly reduce the stresses in the masonry on the south side and, at the very least, would add some hundreds of years to the life of the tower before the inclination again became a problem. It could be achieved without carrying out any invasive actions on the tower itself such as propping, anchoring or underpinning.

Consistent with the imperative of working on the north side of the tower, a method was sought for inducing controlled

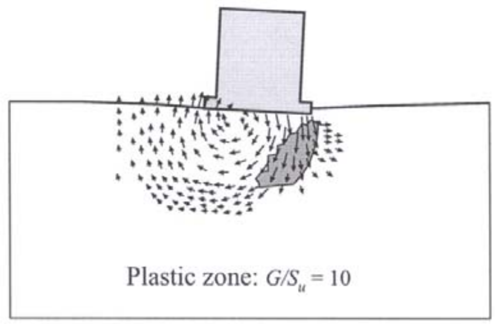

Fig. 8. Vectors of incremental displacement and extent of plastic zone for leaning instability

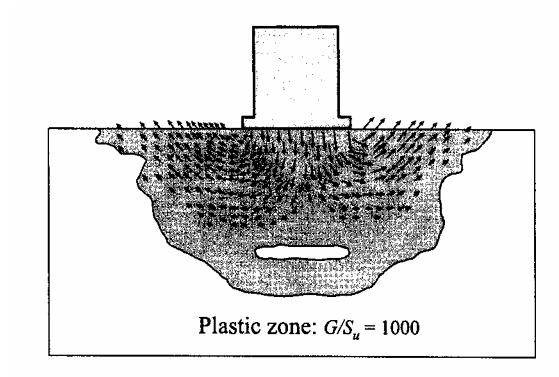

Fig. 9. Vectors of incremental displacement and extent of plastic zone for bearing capacity failure

subsidence at the north. Many approaches were considered and eventually the system known as soil extraction, or underexcavation, emerged as a very promising method. It consists in drilling a series of inclined holes towards and beneath the north side of the foundations and extracting small volumes of soil in a highly controlled way – see Fig. 10. The method was originally suggested for the Pisa Tower by Terracina in 1962. It was then adapted by the Mexicans, who coined the term "underexcavation", for correcting buildings that had suffered from earthquake effects and differential subsidence (Tamez, Ovando and Santoyo, 1997).

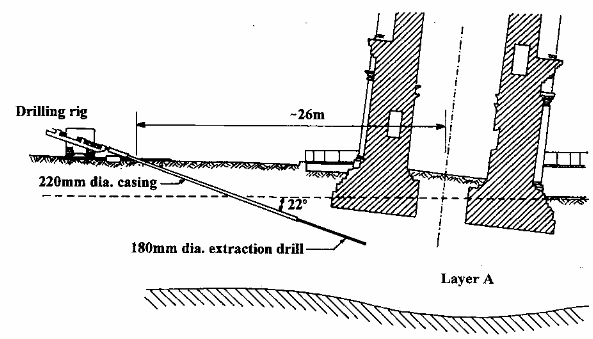

Fig. 10. Concept of soil extraction alongside and beneath the Tower

At the time that underexcavation trials were being carried out at Pisa, the late Professor Sir Alec Skempton drew the author's attention to a thesis by Ann Bayliss on '*The life and works of James Trubshaw*' an engineer of the early 19th Century. The book mentions what is possibly the earliest documented example of the use of soil extraction and describes how Trubshaw stabilised the 15th Century tower of St Chad's church in Wybunbury, South Cheshire in 1832. Since then several other early examples of soil extraction have come to light and these are described in the next section.

SOME HISTORIC EXAMPLES OF SOIL EXTRACTION

St Chad's tower, Wybunbury, UK

St Chad's tower (Fig.11) is situated on a ridge overlooking the village of Wybunbury, five miles south of Crewe and three and a half miles east of Nantwich in South Cheshire. There have been many churches on this site, but due to the unstable ground in the area each has had to be demolished. Church wardens' accounts reveal that over the years five churches have become unsafe and have had to be demolished in 1595, 1793, 1833, 1892 and 1977. The fifteenth century tower is all that now remains.

The tower, 29.3m tall, 9.8m square and estimated to weigh 1,500 tons, was part of a late fifteenth century church, built in the Perpendicular style. The tower's tendency to lean has earned it the title of the "Leaning Tower of South Cheshire", or in earlier days, the "Hanging Steeple of Wimberie". Over the past five centuries it has tilted steadily towards the north-east at the rate of between 5 and 10 mm per year.

The tower is founded on stiff clay between 1.5m and 4.9m thick, overlying fine sand which, in turn, overlies stiff boulder clay. A nearby deep borehole confirms the presence of thick saliferous beds at considerable depth containing in the order of 80% salt. The top of the first saliferous beds is estimated to be at a depth of about 107m. It was concluded from investigations that the whole area on which the tower is founded has been experiencing deep-seated subsidence, resulting from salt extraction.

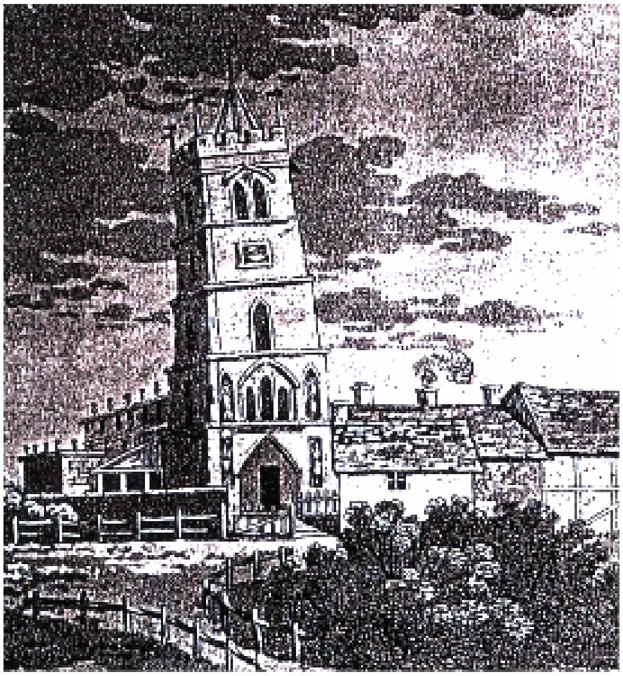

Fig. 11. The Hanging Steeple of Wybunbury (engraving 1751)

Fig. 12. View of the church at Nijland (Drawing in Indian ink, circa 1750)

In 1758, the Wybunbury tower was recorded as leaning north-east by 0.9m and in 1790 this had increased to 1.05m. Just over 40 years later, when Trubshaw started his restoration, the tower was leaning over 1.56m from the perpendicular. Trubshaw undertook the task of stabilising the tower after others had declined it - in fact the fulfilment of a boyhood wish. His daughter recorded that even as a boy her father had conceived the method by which the tower should be stabilised.

The following extract in the Architectural Magazine of 1836 describes the method he used :
"Mr Trubshaw, after examining well the outside of the foundations, commenced digging down the inside. After having got below the level of the footings (lowest stones of the foundation), he proceeded to bore a row of auger-holes clear through under the foundations of the high side, the holes nearly touching each other. These holes he filled with water; and, corking them up with a piece of marl, let them rest for the night. In the morning, the water had softened the marl to a puddle; and the building gradually began to sink, another row of holes were bored, but, not exactly so far as the first row. They were filled with water as before; and the high side not only kept sinking, but the fracture in the centre kept gradually closing up. This process was continued till the steeple became perfectly straight, and the fracture imperceptible."

Trubshaw drilled the extraction auger holes just below the foundation of the tower which is known to extend to a depth of 1.73m. A borehole alongside the tower reveals that the soil at this depth is stiff red-brown boulder clay with occasional sand lenses. Trubshaw stabilised the tower without any "wonderful machinery or secret inventions" (Bayliss, 1978). Using this procedure the building suffered the minimum intervention which by today's standards would be considered to be a good restoration.

Church tower of Nijland, Freisland, Holland

Barends (2002) gives a full contemporary account of the stabilisation of a leaning church tower at Nijland by means of soil extraction. Fig. 12 shows a drawing of the 52m high church spire which in 1866 was out-of-plumb by nearly 1.6m and increasing at a rate of about 20mm per year. The foundations rest on stiff clay. After detaching the tower from the adjacent church, the lean was corrected by digging down inside and outside the foundations and then drilling horizontal holes in the underlying clay from the inside outwards. The drill holes were about 25mm in diameter and were subsequently repeatedly reamed out to about 36mm in diameter. The holes were concentrated in the regions where the most settlement was required. The following is a quotation by the superintendent architect:
"*After the tower started to settle, it was sufficient to repeatedly and gradually outbore* (ream out) *again the same holes which had become more closed by compression of the*

soil. The soil was removed in small portions and constantly wetted with water, so, making it possible to penetrate the solid clay layer."

The boring operation commenced on 15th July 1866 and was successfully completed on 1st August 1866.

Chimney at Bochum, Germany

In 1866, the same year that the Church at Nijland was stabilised, it has come to light that the method of soil extraction was also used to straighten a 100m high chimney at the Bochum Cast Steel Works in Germany. The report on the work was discovered in the journal the '*Zeitschif Bauwesen'* published in 1867 and written by Haarman – the engineer who executed the work.

The circular chimney stood 100m above the base of the factory and 106m above foundation level. The foundations were in the form of an annulus having an outside diameter of 10m and inside diameter of 3.7m. The structure stood on a solid layer of clay under which there was firm marl. The two lower sections of the foundations consisted of hardcore, the rest of the chimney was constructed from engineering bricks.

On completion in early November 1865 the chimney stood vertical but soon began to lean such that by the middle of May 1866 it was 1.4m out-of-plumb. Although the lean gave no serious cause for alarm it was decided that it would be desirable to return it to its original vertical position. Haarman reasoned that:

"*As a result of having in this connection gathered various experiences with smaller chimneys, I believed I could justify, without danger, the use of an already tried method in the case in hand. This method consists in the gradual removal of the ground beneath the foundations on the opposite side to the one in which the structure is leaning, in the case here this meant in the south eastern half, which is what was done with complete success in the following way:*

After access to the foundations had been gained from the outside by means of a four foot wide excavation on the south eastern side, drilling took place from the inside of the chimney beneath this half of the building (see Fig. 13). This was done with a 2 inch diameter screw auger and started in the centre of the half that was to be lowered and drilling to both sides was continued equally for 90^o either side in a radial fashion. In the vicinity of the highest point the holes were placed very close, approximately 2 inches apart, and to both sides this distance increased gradually to about 5 inches.

After the drilling beneath the semicircle had been completed, water was poured into the holes from the inside as well as from the outside for the purpose of softening the clay. This

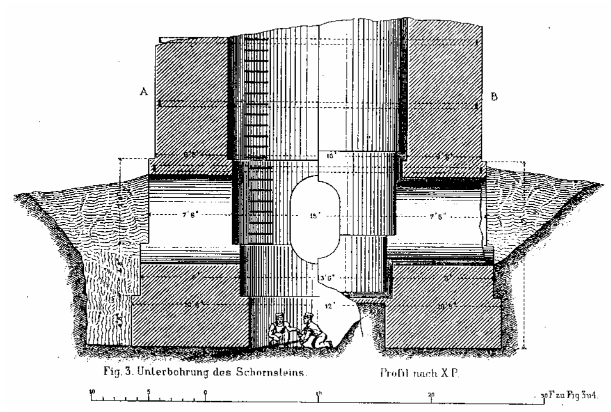

Fig. 13. Cross-section through foundation of chimney at Bochum showing two workers extracting soil with a hand auger (published 1866)

was conveniently poured in through the cup-shaped hollows which had formed in front of the drill holes. After about a week the drill holes had almost completely disappeared due to the pressure of the masonry and the chimney gradually returned to its true plumb position. The same experiment of drilling and softening up by means of water was repeated as often as was necessary for the chimney to reach its former vertical position."

Two workers were employed to carry out these tasks and they drilled, on average, 8 holes per day. This was mostly done continuously since, as a rule, on completion of the last hole in the semi-circle to be drilled under, the earlier holes had largely disappeared under the pressure and the work could begin anew.

The drilling, which had begun on May 19, ceased on August 15 and on August 28 the chimney had regained its vertical position. It was commissioned at the beginning of October and a survey of its trueness taken immediately before that showed it still to be in its correct true position, so that it can be assumed that any movement in the structure has now ceased."

These are three remarkable contemporary and highly practical accounts of the process of soil extraction in clay using augers, as was done at Pisa. The big difference between these three cases and Pisa was that, for Pisa, we were dealing with a tower that was on the point of falling over and the key question to be answered was whether the process of soil extraction would de-stabilise it. This could only be answered by careful numerical modelling.

NUMERICAL MODELLING OF SOIL EXTRACTION

The finite element model described in Section 4 was used to simulate the extraction of soil from beneath the north side of the foundation. It should be emphasised that the finite element mesh had not been developed with a view to modelling soil extraction and to have repeated the complete history of construction of the tower on a new mesh would have been both expensive and time consuming. Thus, the purpose of the modelling was to throw light on the mechanisms of behaviour rather than attempt a somewhat illusory "precise" analysis.

The soil extraction was simulated by reducing the volume of any chosen element of ground incrementally, so as to achieve a pre-determined reduction in volume of that element. The insert in Fig. 14 shows the finite element mesh in the vicinity of the foundation on the north side. The elements numbered 6 to 12 were used for carrying out the intervention and are intended to model the inclined drill. The procedure for simulating the soil extraction was as follows:

(a) the stiffness of element 6 was reduced to zero;

(b) equal and opposite vertical nodal forces were applied progressively to the upper and lower faces of the element until its volume reduced by about 5%. The stiffness of the element was then restored;

(c) the same procedure was then applied successively to the elements 7. 8, 9, 10 and 11 thereby modelling the progressive insertion of the soil extraction drill. For each step the inclination of the tower reduced;

(d) when element 12 was excavated the inclination of the tower increased, confirming that excavation south of a critical line gave a negative response. The analysis was therefore restarted after excavating element 11;

(e) the retraction of the drill probe was then modelled by excavating elements 10, 9, 8, 7, and 6 successively. For each step the response of the tower was positive;

(f) the whole process of insertion and retraction of the drill probe was then repeated. Once again, excavation of element 12 gave a negative response.

The computed displacements of the tower are plotted in Fig. 14. The sequence of excavation of the elements is given on the horizontal axis; the upper diagram shows the change of inclination of the tower due to soil extraction; the lower diagram shows the settlement of the north and south sides of the foundation. As soil extraction progresses from elements 6 through 11, the rate of change of northward inclination increases as do the settlements. As the drill is retracted the rate decreases. After the third insertion of the drill the resultant northward rotation is 0.36°. The corresponding settlements of the north and south sides of the foundation are 260mm and 140mm respectively. As regards the contact stress distribution, the process results in a slight reduction of

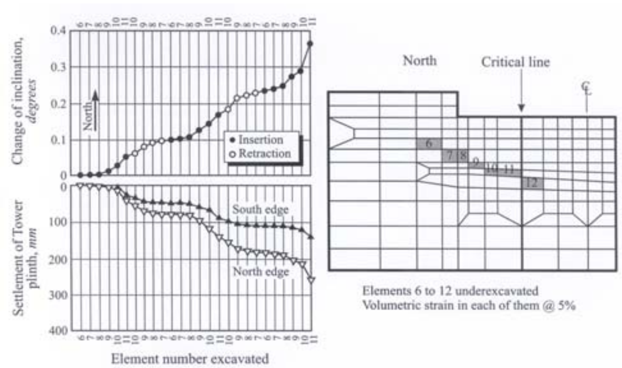

Fig. 14. Finite Element simulation of soil extraction, carried out after simulating the history of inclination during and subsequent to construction

stress beneath the south side. Beneath the north side, some fluctuations in contact stress take place, as is to be expected, but the stress changes are small. The analysis also showed that the process of soil extraction gave rise to only very small stress changes in the underlying Pancone clay – a most important result. The identification of a critical line mentioned in (d) above is consistent with the results of simple 1g model tests carried out by Edmunds (1993) and later confirmed by cenrifuge tests.

RESULTS OF SOIL EXTRACTION AT PISA

Large-scale trial

The positive results obtained from the numerical modelling led to the decision to carry out large-scale fiels trials of the soil extraction process alongside a 7m diameter eccentrically loaded trial foundation. This trial was aimed at developing the drilling technology and exploring the many practical aspects of controlling the soil extraction process. The trial is described in detail by Burland, Jamiolkowski and Viggiani (2003). Drilling was carried out using a hollow stemmed continuous flight auger inside a 180mm diameter counter-rotating casing. Cavities formed in the Horizon A material were found to close smoothly and rapidly. The trial foundation was successfully rotated by about 0.25° and directional control was maintained even though the ground conditions were somewhat non-uniform. Rotational response to soil extraction was rapid, taking a few hours. The stress changes beneath the trial foundation were found to be very small. Very importantly, an effective system of communication for decision taking and implementation of the works on site was developed.

Preliminary soil extraction

The successful large-scale trials together with the positive results of the numerical and physical studies led to the decision to proceed with soil extraction alongside the Pisa Tower itself. The Commission was well aware that these studies might not be completely representative of the possible response of a tower on the point of leaning instability. Therefore it was decided to implement preliminary ground extraction beneath the tower itself, with the objective of observing its response to a limited and localised intervention.

Preliminary soil extraction was carried out over a limited width of 6m using twelve bore holes lined with 220mm diameter casings. The auger and rotating casing had to be moved from hole to hole so that the operation was slow and cumbersome with a maximum of two extractions each day. Originally a target of a minimum of 20 arc seconds reduction in inclination was set as being large enough to demonstrate unequivocally the effectiveness of the system. Initially only twenty 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 engineer (the author) 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 9th 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 discernible response. Then slowly it began to rotate northwards. Figure 15 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 when three of the lead weights were removed whereupon all movement ceased. It should be noted that 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 soil extraction over the full width of the foundations. Accordingly, between December 1999 and January 2000, 41 extraction holes were installed at 0.5m spacing with a dedicated auger and casing in each hole. Full soil extraction commenced on 21st February 2000 and the results of both preliminary and full soil extraction are shown in Fig. 16. The induced rotation of the tower is plotted in arc seconds on the left hand vertical axis and in centimeters at the seventh level on the right hand vertical axis. 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 resulting from the removal of about 120 litres of soil per day. 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, once again, significant uplift of the southern edge of the foundation took place. This is in contrast with the numerical analysis of soil extraction that predicted that settlement of the south side of the foundations would take place - see Fig. 14. The difference may be due to the fact that a plane strain formulation was used for the numerical analysis. Three dimensional modelling of the process would be formidable.

Towards the end of May 2000 progressive removal the lead ingots was commenced, initially with two ingots per week (about 18t). 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 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 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. Final soil extraction was carried out on 6th June 2001 - the date when the tower was released from intensive care. By this time a total volume of about 50 cubic metres of soil had been extracted and the target of reducing the inclination by half a degree was achieved. The maximum penetration of the extraction holes southwards beneath the foundations was 2m – well inside the critical line.

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. An ancient concrete

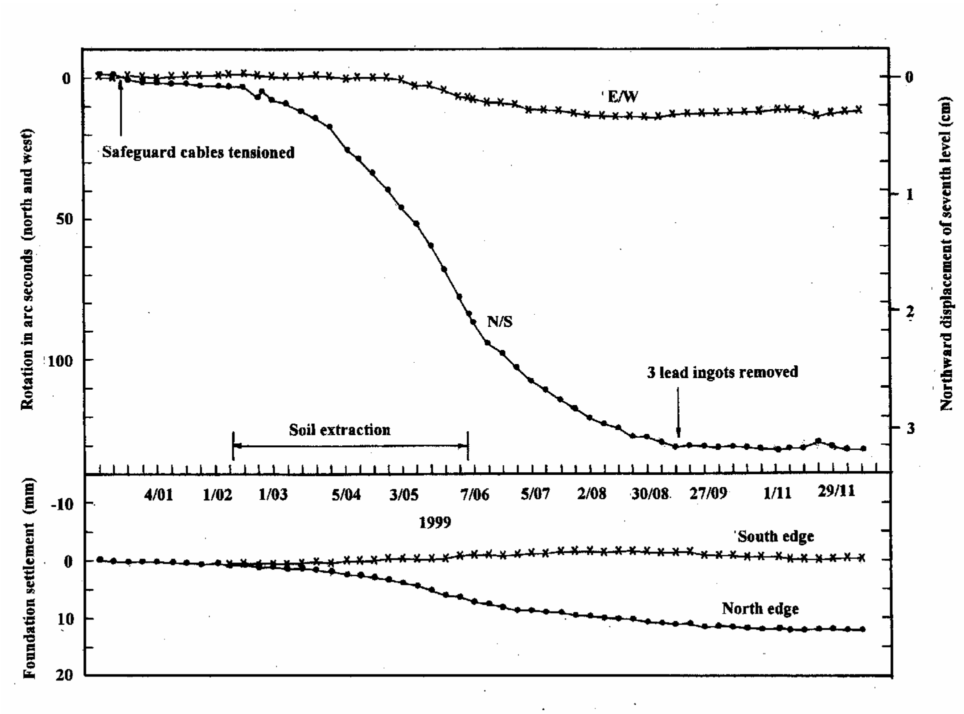

Fig. 15. Results of preliminary soil extraction

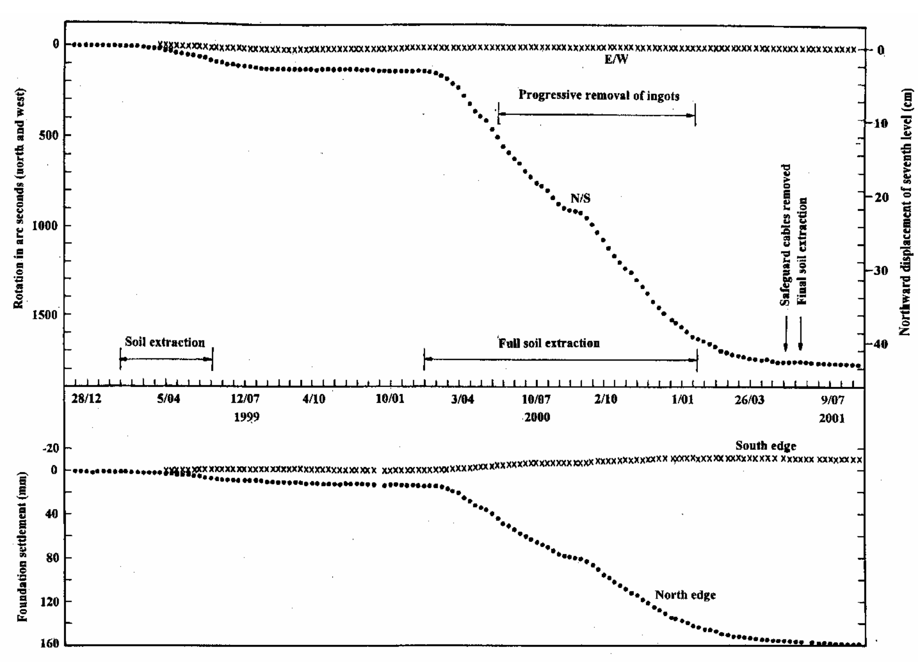

Fig. 16. Results of full soil extraction

ring that was placed in the floor of the catino by Gherardesca in 1838 has been securely attached to the foundation of the Tower by means of stainless steel reinforcement and has been strengthened by circumferential post tensioning. Thus the effective area of the foundation has been substantially increased as has its factor of safety against leaning instability. In April 2002 a drainage system was installed below the catino on the north side the effect of which is to substantially reduce the seasonal fluctuations in water level at this critical location which were the prime cause of the continuing movements of the Tower.

Fig. 17. Pageantry during the ceremony on 16th June 2001

CONCLUSIONS

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 16th June 2001 a formal ceremony was held in which the tower was handed back to the civic authorities (see Fig. 17) and it was again opened to the public on 15th December 2001.

It is of considerable interest to note that the technique of soil extraction is not new. The earliest recorded example to date is that of James Trubshaw who used it to straighten the St Chad's Tower in 1832. Further examples have recently been found of the use of the technique in 1866 on a Church in Nijland, Holland and a chimney in Bochum, Germany. These historical examples of soil extraction were developed independently of each other. Nevertheless there are some interesting and important similarities. Each mentions using an auger drill to bore a row of holes on the high side, these holes were then filled with water and the process was repeated until the building was perpendicular. These cases are demonstrations of the inventiveness and resourcefulness of engineers long before modern soil mechanics came into being. To quote the superintendent architect for the Nijland church, A. Breunissen Troost: "*By them a new proof is provided that only then the work attains its full value, when the hand that works is steered by a head that thinks.*"

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