# THE ENIGMA OF THE LEANING TOWER OF PISA

*The Sixth Spencer J. Buchanan Lecture*

*by*

## John B. Burland

*Wednesday December 9, 1998*

*Auditorium B*
*George Bush Presidential Conference Center*
*George Bush Drive*
*Texas A&M University*
*College Station, Texas*

# THE ENIGMA OF THE LEANING TOWER OF PISA

by. John B Burland
Professor of Soil Mechanics
University of London - Imperial College
London, United Kingdom

# THE ENIGMA OF THE LEANING TOWER OF PISA

by

**JOHN BURLAND**
Professor of Soil Mechanics
Imperial College of Science, Technology and Medicine

## INTRODUCTION

In 1989 the civic tower of Pavia collapsed without warning, killing four people. The Italian Minister of Public Buildings and Works appointed a commission to advise on the stability of the Pisa Tower. The commission recommended closure of the Tower to the general public and this was instituted at the beginning of 1990. There was an immediate outcry by the Mayor and citizens of Pisa who foresaw the damage that the closure would inflict on the economy of Pisa, heavily dependent on tourism as it is. In March 1990 the Prime Minister of Italy set up a new Commission, under the chairmanship of Professor Michele Jamiolkowski, to develop and implement measures for stabilising the Tower. It was the sixteenth commission this century and its membership covered a number of disciplines including structural and geotechnical engineering, architecture, architectural history, archaeology and restoration.

It is instructive to imagine a tower, founded on jelly and slowly inclining to the point at which it is about to fall over. Any support would also have to rest on the jelly. Worse still, the masonry composing the tower is so fragile that it could explode at any time. This is a reasonable description of the state of the Leaning Tower of Pisa, and helps to explain why stabilising it represents the ultimate civil engineering challenge.

## DETAILS OF THE TOWER AND GROUND PROFILE
Fig. 1 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. At present the foundations are inclined due south at about 5.5 degrees to the horizontal. The average inclination of the axis of the Tower is somewhat less due to its slight curvature as will be discussed later. The seventh cornice overhangs the first cornice 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. The spiral staircase winds up within the annulus.

7th cornice

$V_7$

5°11′20″

South

1st cornice

Floor of instrument room

$V_1$

Catino

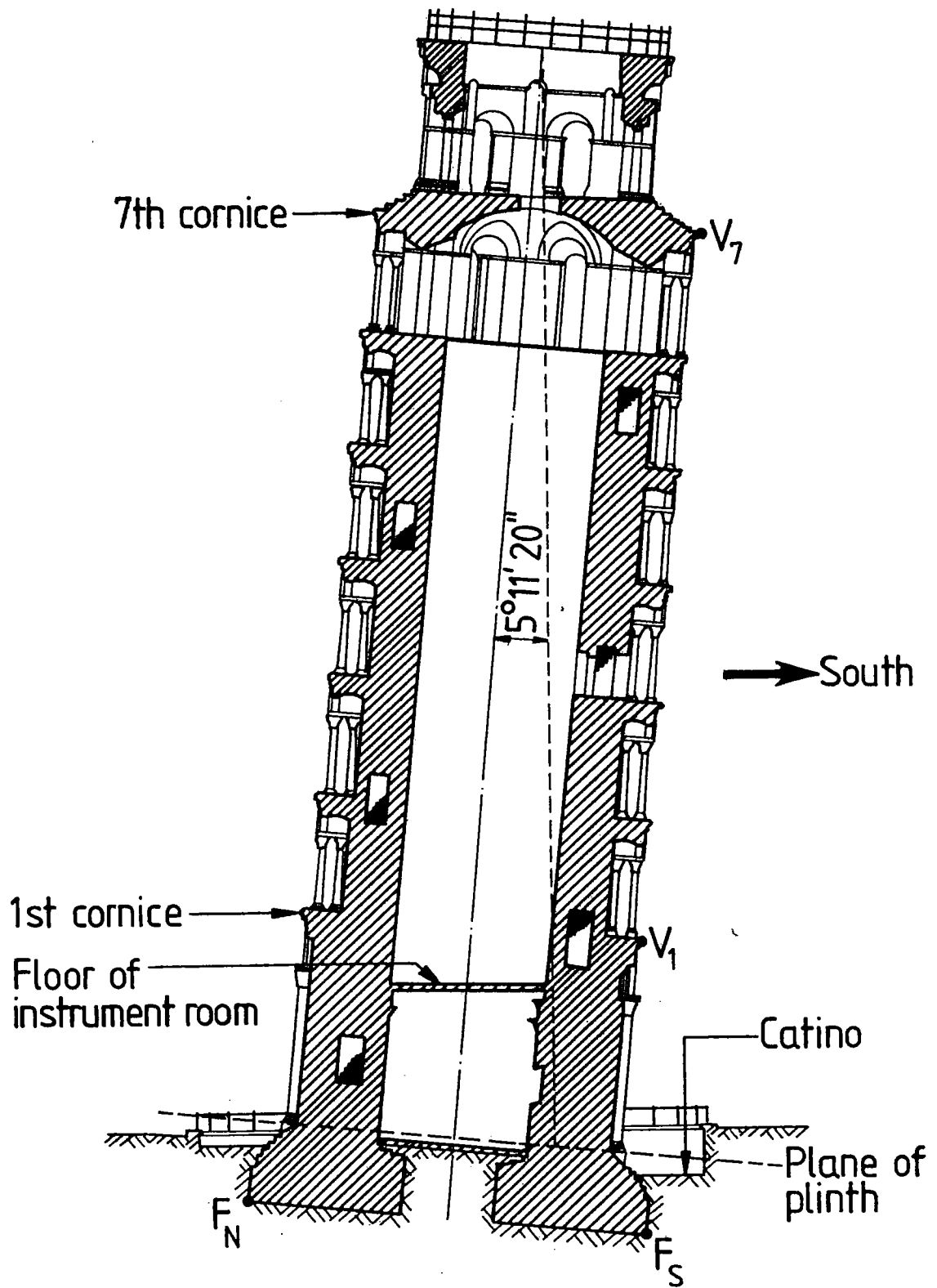Plane of plinth

$F_N$

$F_S$

Fig. 1    Cross-section through Tower

Fig. 2 shows the ground profile underlying the Tower. It consists of three distinct layers. Layer 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 Layer A is a 2m thick medium dense fine sand layer (the upper sand). Based on sample descriptions and cone tests, the material to the south of the Tower appears to be more clayey than to the north and the sand layer is locally much thinner. Therefore, to the south Layer A could be expected to be slightly more compressible than to the north.

Layer B consists of soft sensitive normally consolidated marine clay which extends to a depth of about 40m. The upper clay, known as the Pancone Clay, is very sensitive to disturbance which causes it to lose strength. The lower clay is separated from the Pancone Clay by a sand layer (the intermediate sand) overlain by a layer if stiffer clay (the intermediate clay). The Pancone Clay is laterally very uniform in the vicinity of the Tower. Layer 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 Layer A with a vertical pore pressure distribution through Layer 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 between 2.5m and 3.0m.

**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 a bearing capacity failure within the Pancone Clay. The work recommenced in about 1272, after a pause of nearly 100 years, by which time the strength of the clay had increased due to consolidation under the weight of the Tower. By about 1278 construction had reached the 7th cornice when work again stopped - possibly 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.
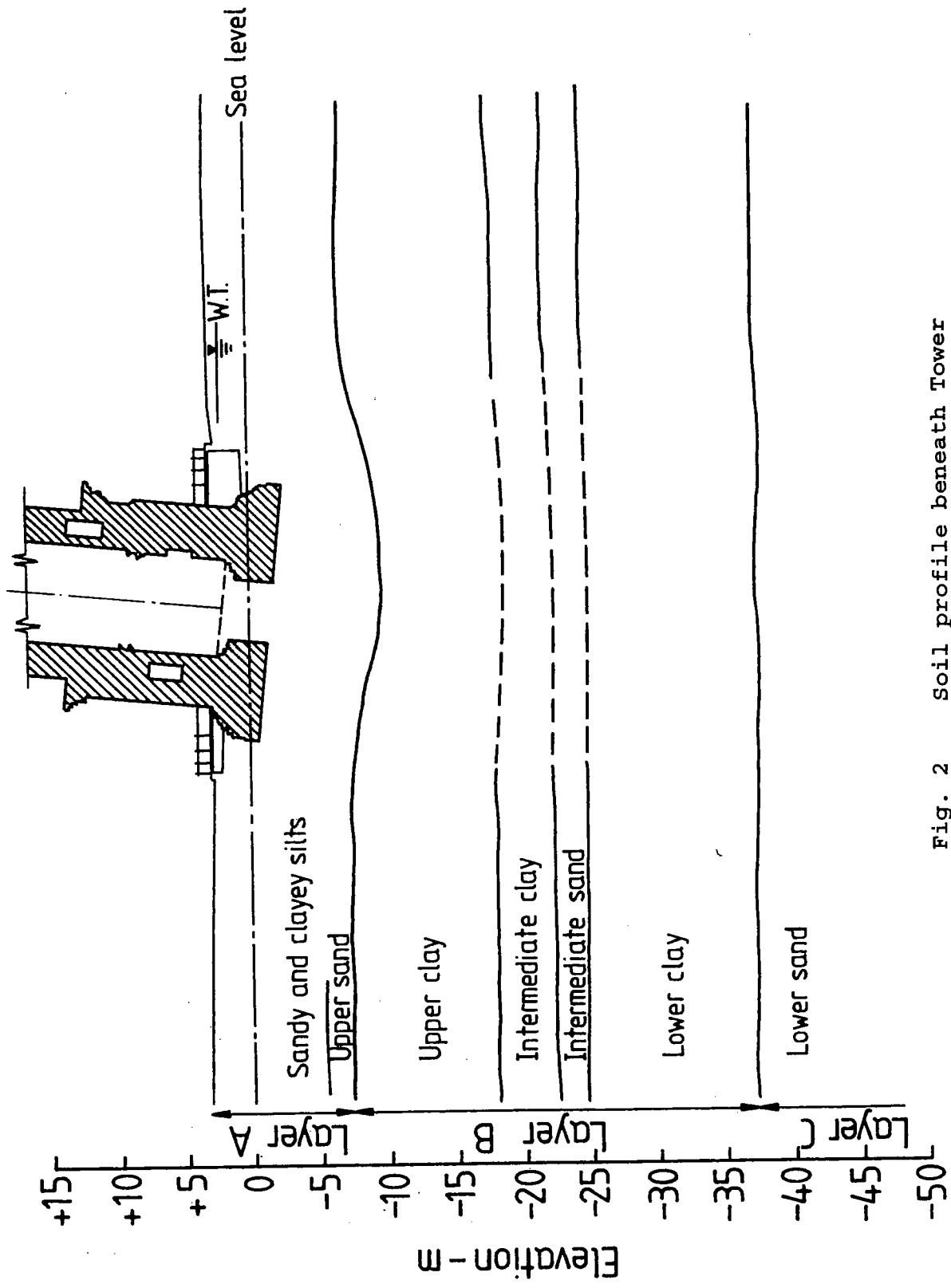
Fig. 2   Soil profile beneath Tower

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 historical detail is that in 1838 the architect Alessandro Della 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 by as much as half a degree. As is described later, Gherardesca left us an unpleasant surprise.

## HISTORY OF TILTING

One of the first actions of the Commission was to undertake the development of a computer model of the Tower and the underlying ground that could be used to assess the effectiveness of various possible remedial measures. Calibration of such a model is essential and the only means of doing this is to attempt to simulate the history if tilting of the Tower during and subsequent to its construction. Hence it became apparent very early on that we needed to learn as much as possible about the history of the tilt of the Tower. In the absence of any documentary evidence all the clues to the history of tilt lie in the adjustments made to the masonry layers during construction and in the shape of the axis of the Tower.

Over the years a number of measurements of the dimensions of the Tower have been made and many of them are conflicting. The Polvani Commission measured the thickness of each of the masonry layers and its variation around the Tower [1]. This information has proved extremely valuable in unravelling the history of tilt.

Fig. 3 shows the shape of the axis of the Tower deduced from the measured relative inclinations of the masonry layers assuming that construction proceeded perpendicular to each masonry layer. This shape compares favourably with other independent measurements at a few locations up the Tower. It can be seen that the axis is curved. For years the Tower has been unkindly referred to as having a banana shape. I prefer to call it a question mark (?) so as to reflect the enigma of the Tower.

Some important observations can be made from the measurements on the masonry layers. For most of the storeys, construction took place using parallel sided blocks of masonry. With one or two notable exceptions adjustments only took place close to each floor using tapered blocks. The most important exception can be seen in Fig. 3 where there is an obvious kink one quarter the
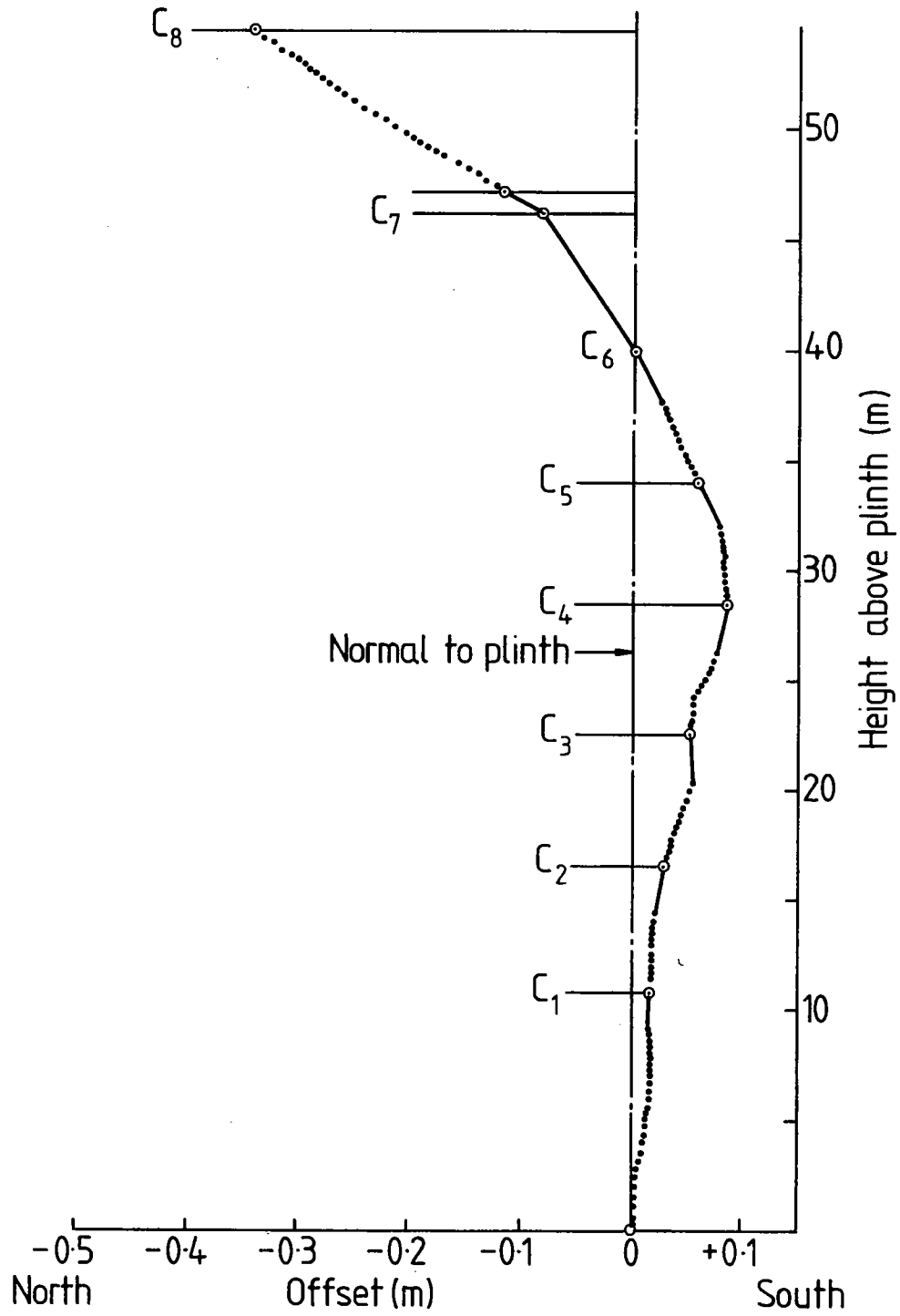
Fig. 3    Shape of axis of Tower deduced from relative inclinations of masonry layers

way up the fourth storey. It will be recalled that the construction remained at this level for about 100 years. Evidently the Tower was tilting significantly when work recommenced and the masons made adjustments to correct it.

We see that the history of the tilting of the Tower is tantalisingly frozen into the masonry layers. If only we knew the rules that the masons followed in adjusting for the tilt we would be able to unravel the history. We have to put ourselves in the place of a mason or architect in the 12th or 13th Century and ask ourselves:
    'What is the most practical thing to do when you
    arrive at a given floor and find that the tower
    is out-of-plumb?'
A widely accepted hypothesis is that the masons would always try to keep the masonry layers horizontal and the Polvani Commission adopted this. Although this seems reasonable for a low aspect ratio building like a cathedral, it does not make sense for a tower since it would tend to perpetuate the overall out-of-plumb. After a few trials, a child building a tower of bricks on a carpet will soon learn to compensate for any tilt by attempting to place successive bricks over the centre of the base of the tower i.e. by bringing the centre of the tower back vertically over the centre of the foundations (or possibly even further, away from the direction of tilt). Therefore an alternative hypothesis is one in which the masons aimed to bring the centre line of the tower back, vertically over the centre of the foundations at the end of each storey. The architectural historians on the Commission were satisfied that the masons would have had the technology to make such an adjustment, particularly as the stones for each storey were carved and assembled on the ground prior to hoisting into position.

Fig. 4 shows the re-constructed history of inclination of the foundations of the Tower using the alternative hypothesis [2]. In this figure the weight of the Tower is plotted against the deduced inclination. It can be seen that initially the Tower inclined slightly to the north amounting to about 0.2 degrees in 1272. As construction proceeded the Tower began to move towards the south at an increasing rate. In 1278, when construction had reached the seventh cornice, the tilt was about 0.6 degrees. During the 90 year pause, the tilt increased to about 1.6 degrees. After the completion of the bell chamber in about 1370 the inclination of the Tower increased dramatically. The point dated 1817 is based on measurements made by two British architects Cressy and Taylor using a plumb line. A further measurement was made by the Frenchman Ruhault de Fleury in 1859 which showed that the excavation of the catino by Gherardesca in 1838 caused a significant increase of inclination. The history of tilting depicted in Fig. 4 has been used to calibrate numerical and physical models of the Tower and underlying ground.
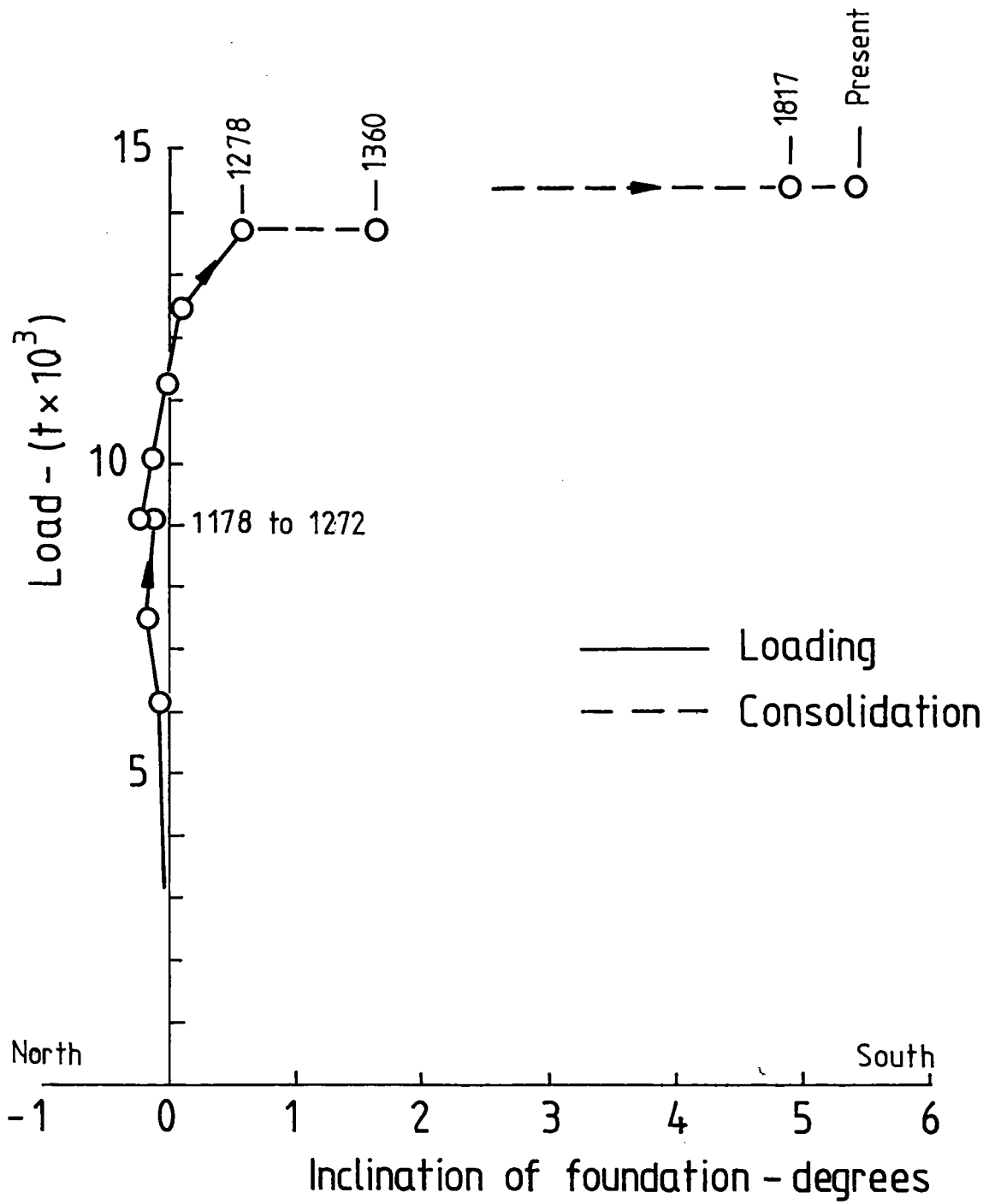
Fig. 4    Deduced history of inclination of Tower during and
          subsequent to construction

## COMPUTER MODELLING OF THE MOVEMENTS OF THE TOWER

The analysis was carried out using a suite of finite element geotechnical computer programs developed at Imperial College and known as ICFEP [3]. The constitutive model is based on Critical State concepts [4] and is non-linear elastic work-hardening plastic. Fully coupled consolidation is incorporated so that time effects due to the drainage of pore water out of or into the soil skeleton are included.

It must be emphasised that the prime objective of the analysis was to develop an understanding of the mechanisms controlling the behaviour of the Tower [5]. Accordingly a plane strain approach was used for much of the work and only later was three-dimensional analysis used to explore certain detailed features.

The layers of the finite element mesh matched the soil sub-layering that had been established from numerous extensive soil exploration studies. Fig. 5 shows the mesh in the immediate vicinity of the foundation. In Layer B (see Fig. 2) the soil is assumed to be laterally homogeneous. However a tapered layer of slightly more compressible material was incorporated into the mesh for Layer A1 as shown by the shaded elements in Fig. 5. This slightly more compressible region represents the more clayey material found beneath the south side of the foundation as discussed in Section 2. In applied mechanics terms the insertion of this slightly more compressible tapered layer may be considered to act as an 'imperfection'. The overturning moment generated by the lateral movement of the centre of gravity of the Tower was incorporated into the model as a function of the inclination of the foundation as shown in Fig 5.

The analysis was carried out in a series of time increments in which the loads were applied to the foundation to simulate the construction history of the Tower. The excavation of the catino in 1838 was also simulated in the analysis. Calibration of the model was carried out by adjusting the relationship between the overturning moment generated by the centre of gravity and the inclination of the foundation. A number of runs were carried out with successive adjustments being made until good agreement was obtained between the actual and the predicted present day value of the inclination.

Fig. 6 shows a graph of the predicted changes in inclination of the Tower against time, compared with the deduced historical values. It is important to appreciate that the only point that has been pre-determined in the analysis is the present-day value. The model does not simulate the initial small rotation of the Tower to the north. However, from about 1272 onwards there is remarkable agreement between the model and the historical inclinations. Note that it is only when the bell chamber

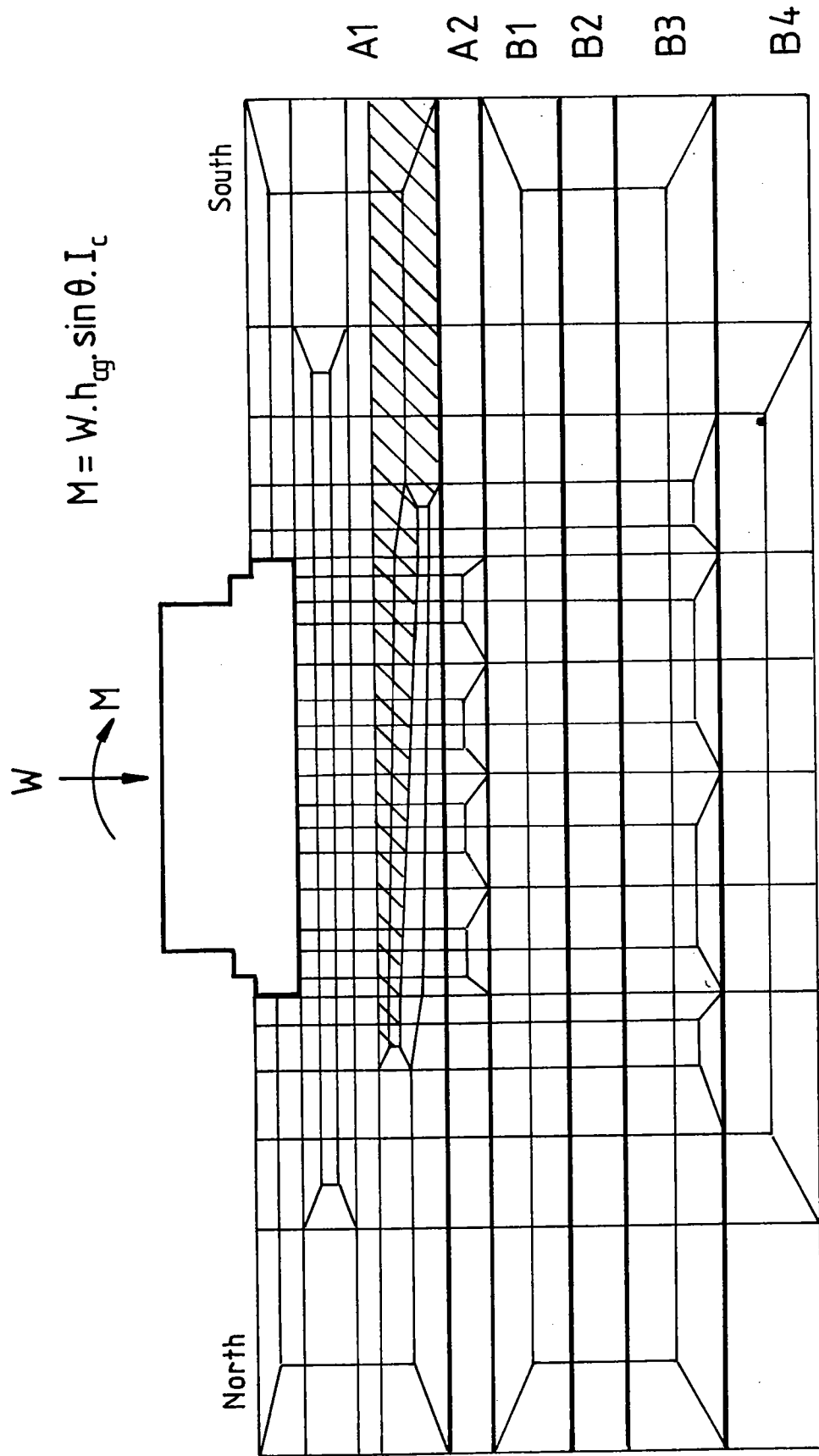$$M = W.h_{cg}.\sin\theta.I_c$$

Fig. 5    Finite element mesh in the vicinity of the tower foundation
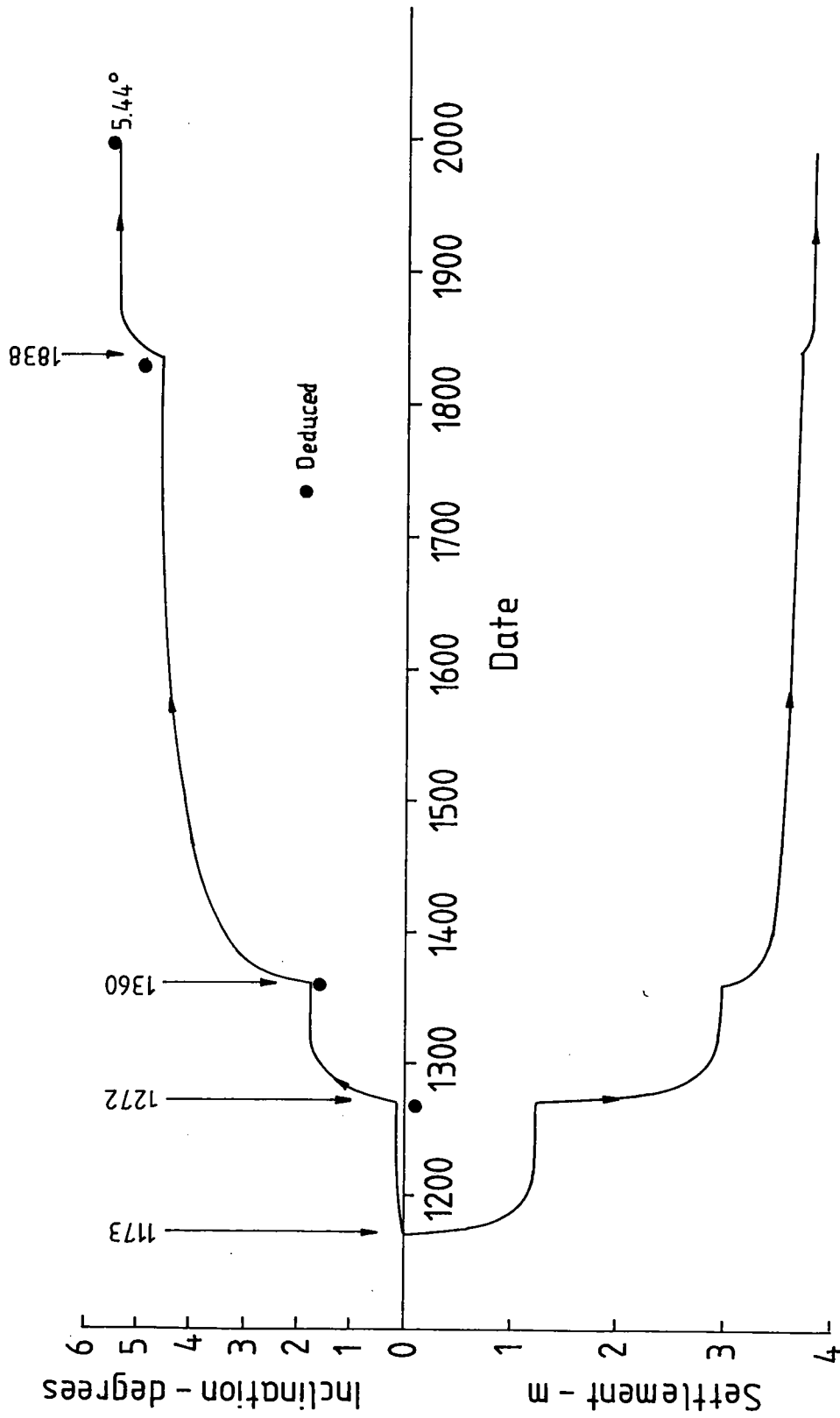
Fig. 6    Relationship between time, inclination and settlement
          for the plane strain Finite Element simulation of the
          history of the Pisa Tower

-11-

was added in 1360 that the inclination increases dramatically. Also of considerable interest is the excavation of the catino in 1838 which results in a predicted rotation of about 0.75 degrees. It should be noted that the final imposed inclination of the model tower is 5.44 degrees which is slightly less than the present-day value of 5.5 degrees. It was found that any further increase in the final inclination of the model tower resulted in instability - a clear indication that the Tower is very close to falling over.

Burland and Potts [5] concluded from a careful study of the computer model that the impending instability of the Tower foundation is not due to a shear failure of the ground but can be attributed to the high compressibility of the Pancone Clay. This phenomenon was called 'leaning instability' by the late Edmund Hambly [6] who used it to explain the lean of the Pisa Tower. No matter how carefully the structure is built, once it reaches a 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, i.e. too much settlement under load'. Children building brick towers on a soft carpet will be familiar with this phenomenon!

In summary, the Finite Element model gives remarkable agreement with the deduced historical behaviour of the Tower. It is important to emphasise that the predicted history of foundation inclinations and overturning moments were self generated and were not imposed externally in a pre-determined way. The only quantity that was used to calibrate the model was the present-day inclination. The analysis has demonstrated that the lean of the Tower results from the phenomenon of leaning instability due to the high compressibility of the Pancone Clay. The role of the layer of slightly increased compressibility beneath the south side of the foundations is to act as an 'imperfection'. Its principal effect is to determine the direction of lean rather than its magnitude. The main limitation of the model is that it is a plane strain one rather than fully three-dimensional. Also, the constitutive model does not deal with creep so that no attempt has been made to model the small time-dependent rotations that have been taking place this century and which are described in the next Section. Nevertheless the model provides important insights into the basic mechanisms of behaviour and has proved valuable in assessing the effectiveness of various proposed stabilisation measures. Its role in evaluating the effectiveness of the temporary counterweight solution is described later.

## OBSERVED BEHAVIOUR OF THE TOWER THIS CENTURY
*Change of inclination*

For most of this century the inclination of the Tower has been increasing. The study of these movements has been important in developing an understanding of the behaviour of the Tower and has profoundly influenced the decisions taken by the Commission. It is important to appreciate that the magnitudes of the movements are about three orders of magnitude less than the movements that occurred during construction. Thus changes in inclination are measured in arc seconds rather than degrees (one arc second equals 1/3600th of a degree).

Fig. 7 is a plan view of the *Piazza dei Miracoli* showing the location of the Baptistry, Cathedral and Tower. Since 1911 the inclination of the Tower has been measured regularly by means of a theodolite. The instrument is located at the station marked E and the angles between station D and the first cornice (V1 in Fig. 1) and between station D and the seventh cornice (V7) are measured. The difference between these two angles is used to calculate the vertical offset between the seventh and first cornice and hence the inclination of the Tower.

In 1928 four levelling stations were placed around the plinth level of the Tower and were referred to a bench mark on the Baptistry. Readings were taken in 1928 and 1929 but not again until 1965. In 1965, fifteen levelling points were installed around the Tower at plinth level and about seventy surveying monuments were located around the Piazza.

In 1934 a plumb line was installed in the Tower, suspended from the sixth floor and observed in an instrument room whose location is shown in Fig. 1. The instrument was designed by the engineers Girometti and Bonechi and is known as the GB pendulum. Also in 1934 a 4.5m long spirit level was installed within the instrument room. The instrument rests on brackets embedded in the masonry and can be used to measure both the north-south and the east-west inclination of the Tower. The instrument was designed by the officials of the Genio Civile di Pisa and is known as the GC level.

Fig. 8 shows the change of inclination with time since 1911. From 1934 to 1969 the GC level was read regularly once or twice a year except during the second world war. For some reason readings with the GC level ceased in 1969 but fortunately precision levelling on the fifteen points around the Tower began in 1965 and continued regularly until 1985. In 1990 Professor Carlo Viggiani and I read the GC level again and found that the inclination agreed to within a few seconds of arc with that derived from the precision levelling around the plinth.
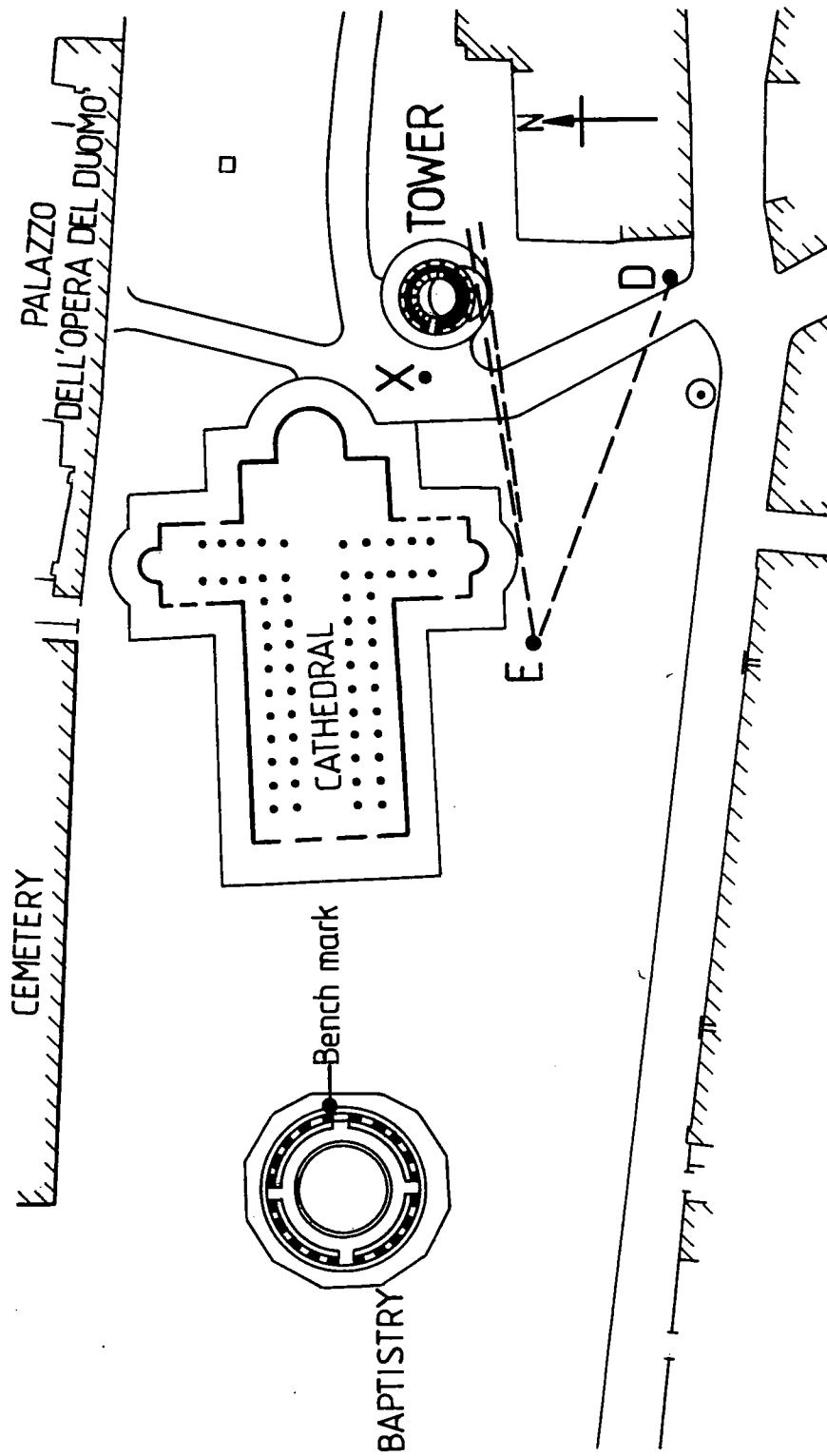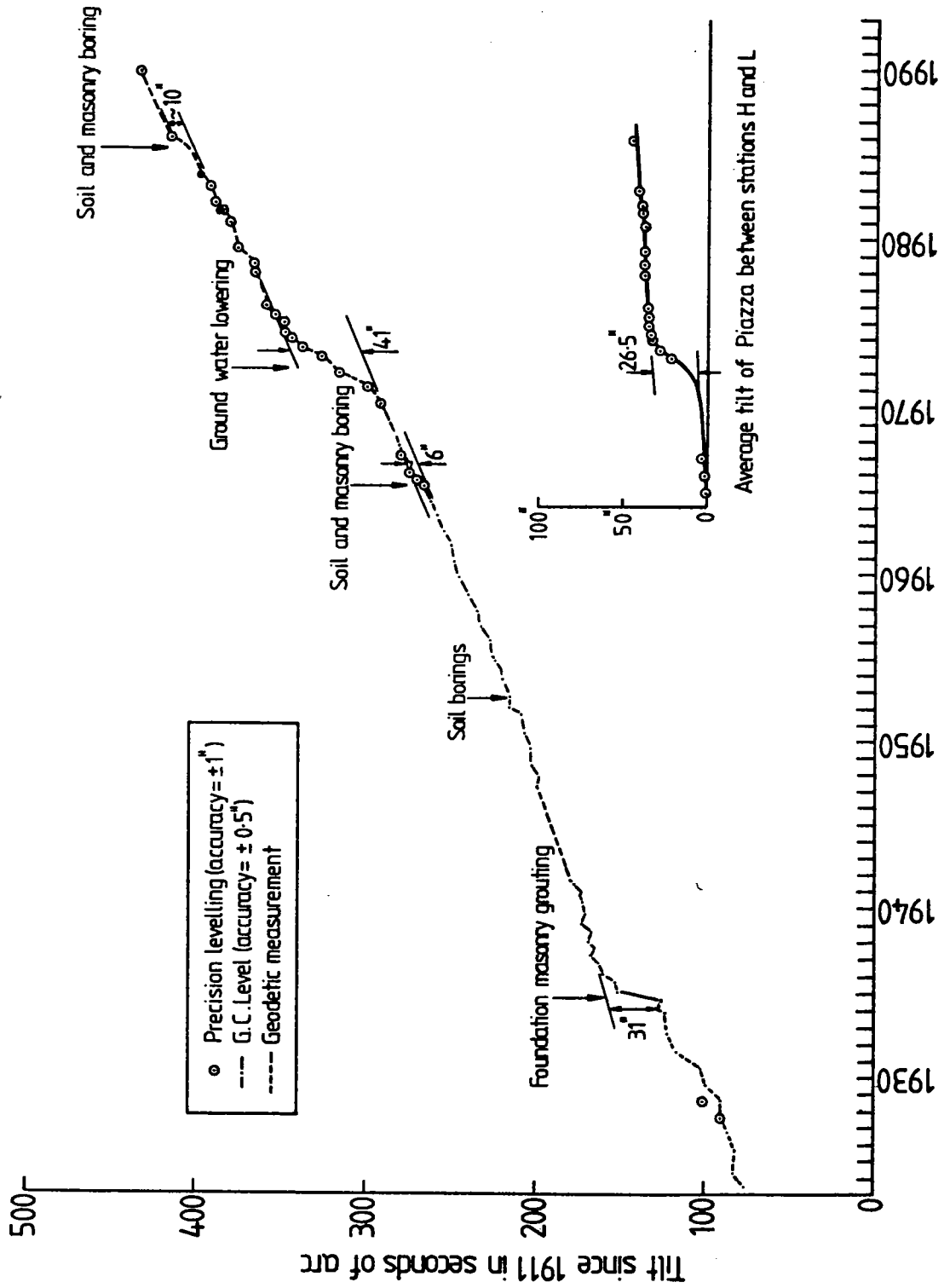
Fig. 7    Plan of the Piazza dei Miracoli

Fig. 8    Change in inclination of the foundations since 1911

It can be seen from Fig. 8 that the inclination-time relationship for the Tower is not a smooth curve but contains some significant 'events'. In 1934, Girometti drilled 361 holes into the foundation masonry and injected about 80t of grout with a view to strengthening the masonry. This activity caused a sudden increase in tilt of 31 arc seconds. Like Gherardesca, Girometti also left us an unpleasant surprise as is described later. In 1966 some soil and masonry drilling took place and caused a small but distinct increase of tilt of about 6 arc seconds. Again, in 1985 an increase in tilt of 10 arc seconds resulted from masonry boring through the foundations. In the late 1960's and early 1970's pumping from the lower sands caused subsidence and tilting towards the south-west of the *Piazza*. This induced a tilt of the Tower of about 41 arc seconds. When pumping was reduced the tilting of the Tower reduced to its previous rate. It is clear from these events that the inclination of the Tower is very sensitive to even the smallest ground disturbance. Hence any remedial measures should involve a minimum of such disturbance. The rate of inclination of the Tower in 1990 was about 6 seconds of arc per annum or about 1.5mm at the top of the Tower.

*The motion of the Tower foundation*
Previously, studies have concentrated on the changes of inclination of the tower. Little attention has been devoted to the complete motion of the foundations relative to the surrounding ground. The theodolite and precision levelling measurements help to clarify this. It will be recalled from Fig. 7 that angles were measured relative to the line ED. Hence it is possible to deduce the horizontal displacements of the tower relative to point D. Fig. 9 shows a plot of the horizontal displacement of point $V_1$ on the first cornice relative to point D since 1911. Also shown, for comparison, is the relative vertical displacements between the north and south sides of the foundation (points $F_N$ and $F_S$). It can be seen that up to 1934 the horizontal movement of $V_1$ was very small. Between 1935 and 1938, following the work of Girometti, point $V_1$ moved southwards by about 5mm. No further horizontal movement took place until about 1973 when a further southward movement of about 3mm to 4mm took place as a result of the ground water lowering. A further small horizontal movement appears to have taken place in about 1985 as a result of masonry drilling at that time. These observations reveal the surprising fact that during steady state creep-rotation point $V_1$ on the first cornice does not move horizontally. Horizontal movements to the south only take place when disturbance to the underlying ground takes place.

Study of the precision levelling results shows that between 1928 and 1965 the centre of the foundations at plinth level rose by 0.3mm relative to the Baptistry - a negligible amount. Between 1965 and 1986 the relative vertical
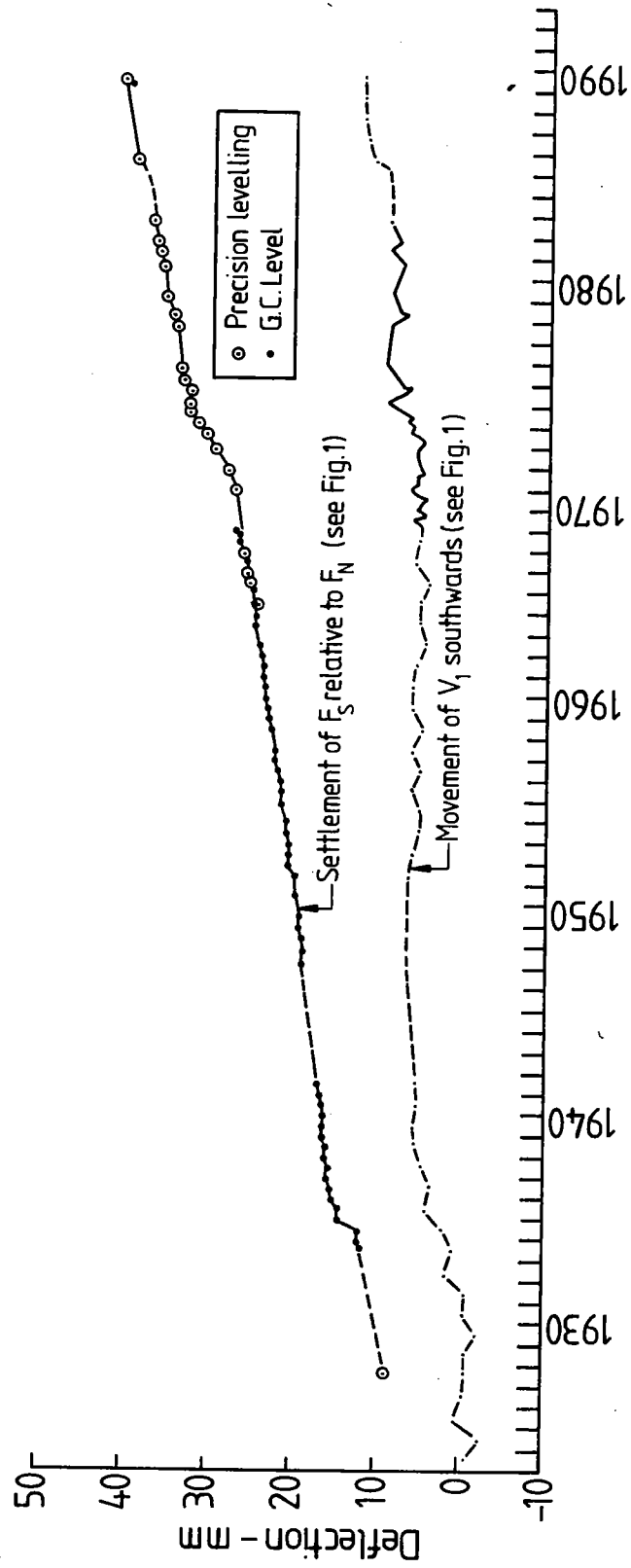
Fig. 9    Horizontal displacement of V1 (see Fig. 1) on the
         first cornice since 1911

displacement between the centre of the plinth and a point
a few metres away from the tower was again negligible.
Thus, not only does point $V_1$ not move horizontally during
steady-state creep, but also negligible average settlement
of the foundations has taken place relative to the
surrounding ground.

The observations described above can be used to define the
rigid-body motion of the tower during steady-state creep-
rotation as shown in Fig. 10. It can be seen that the
Tower must be rotating about a point approximately located
level with point $V_1$ and vertically above the centre of the
foundation. The direction of motion of points $F_N$ and $F_S$
are shown by vectors and it is clear that the foundations
are moving northwards with $F_N$ rising and $F_S$ sinking.

*Conclusions from the observed motion of the Tower
foundations*
The discovery that the motion of the Tower is as shown in
Fig. 10 has turned out to be a most important finding in
a number of respects. Previously it had been believed that
the foundations were undergoing creep settlements with the
south side settling more rapidly than the north. However,
the observation that the north side had been steadily
rising led to the suggestion that the application of load
to the foundation masonry on the north side could be
beneficial in reducing the overturning moment [7].

The form of foundation motion depicted in Fig. 10 leads to
the very important conclusion that the seat of the
continuing long-term tilting of the Tower lies in Horizon
A and not within the underlying Pancone Clay as had been
widely assumed in the past. It can therefore be concluded
that this stratum must have undergone a considerable period
of ageing since last experiencing significant deformation.
Thus, in developing the computer model, it is reasonable
to assume that the clay has an increased resistance to
yield subsequent to the excavation of the catino in 1838.
This conclusion has proved of great importance in the
successful analysis of the effects of applying the lead
counterweight [5].

The continuing foundation movements tend to be seasonal.
Between February and August each year little change in the
north-south inclination takes place. In late August or
early September the Tower starts to move southward and this
continues through till December or January amounting to an
average of about 6 arc seconds. In the light of the
observed motion of the Tower foundations, the most likely
cause of these seasonal movements is thought to be the
sharp rises in ground-water level that have been measured
in Horizon A resulting from seasonal heavy rainstorms in
the period September to December each year. Thus,
continuing rotation of the foundations might be
substantially reduced by controlling the water table in
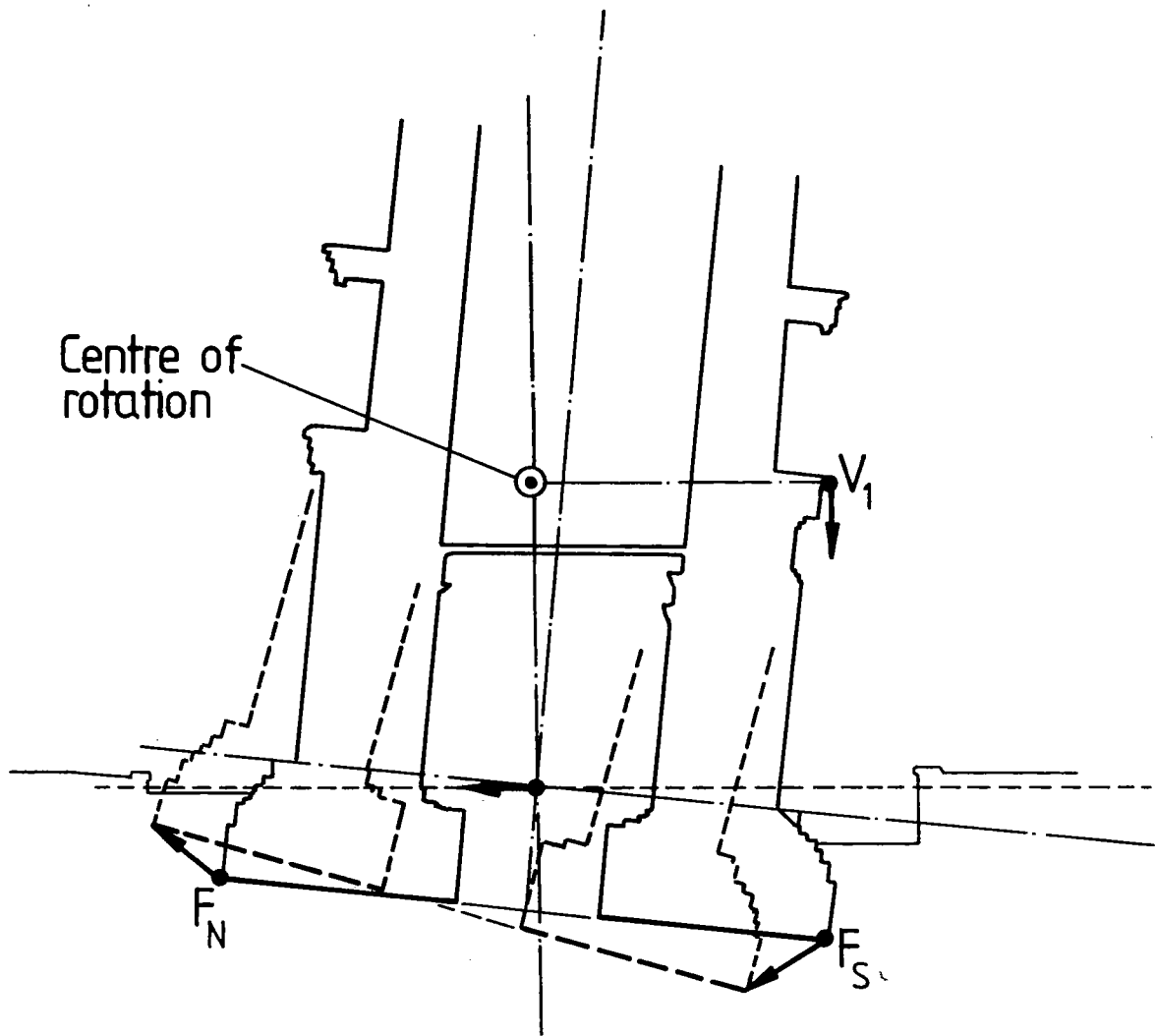Horizon A in the vicinity of the Tower.

Fig. 10    Motion of the Tower during steady state creep-rotation

**TEMPORARY STABILISATION OF THE TOWER**
There are two distinct problems that threaten the stability of the Tower. The most immediate one is the strength of the masonry. It can be seen from the cross section in Fig. 1 that at first floor level there is a change in cross section of the walls. This gives rise to stress concentrations at the south side. In addition to this, the spiral staircase can be seen to pass through the middle of this change in cross section giving rise to a significant magnification in the stresses. The marble cladding in this location shows signs of cracking. It is almost impossible to assess accurately the margin of safety against failure of the masonry, but the consequences of failure would be catastrophic. The second problem is the stability of the foundations against overturning.

The approach of the Commission to stabilisation of the Tower has been a two stage one. The first stage has been to secure an increase in the margin of safety against both modes of failure as quickly as possible by means of temporary measures. Having achieved this, the second stage is to develop permanent solutions recognising that these would require time to carry out the necessary investigations and trials. Significant progress has been made with the first stage. It is a prerequisite of restoration work that temporary works should be non-destructive, reversible and capable of being applied incrementally in a controlled manner.

*Temporary stabilisation of the masonry*
The masonry problem has been tackled by binding lightly pre-stressed plastic covered steel tendons around the Tower at the first cornice and at intervals up the second storey as shown in Fig. 11. The work was carried out in the summer of 1992 and was effective in closing some of the cracks and in reducing the risk of a buckling failure of the marble cladding. The visual impact has proved to be negligible.

*Temporary stabilisation of the foundations*
As mentioned previously, the observation that the northern side of the foundation had been steadily rising for most of this century led to the suggestion that application of load to the foundation masonry on the north side could be beneficial in reducing the overturning moment. Clearly such a solution would not have been considered if it had not been recognised that leaning instability rather than bearing capacity failure was controlling the behaviour of the Tower or if the north side of the foundation had been settling.

Before implementing such a solution it was obviously essential that a detailed analysis should be carried out. The purpose of such an analysis was two-fold: (i) to ensure that the proposal was safe and did not lead to any undesirable effects and (ii) to provide a best estimate of

~10 cm

~20 cm

~40 cm
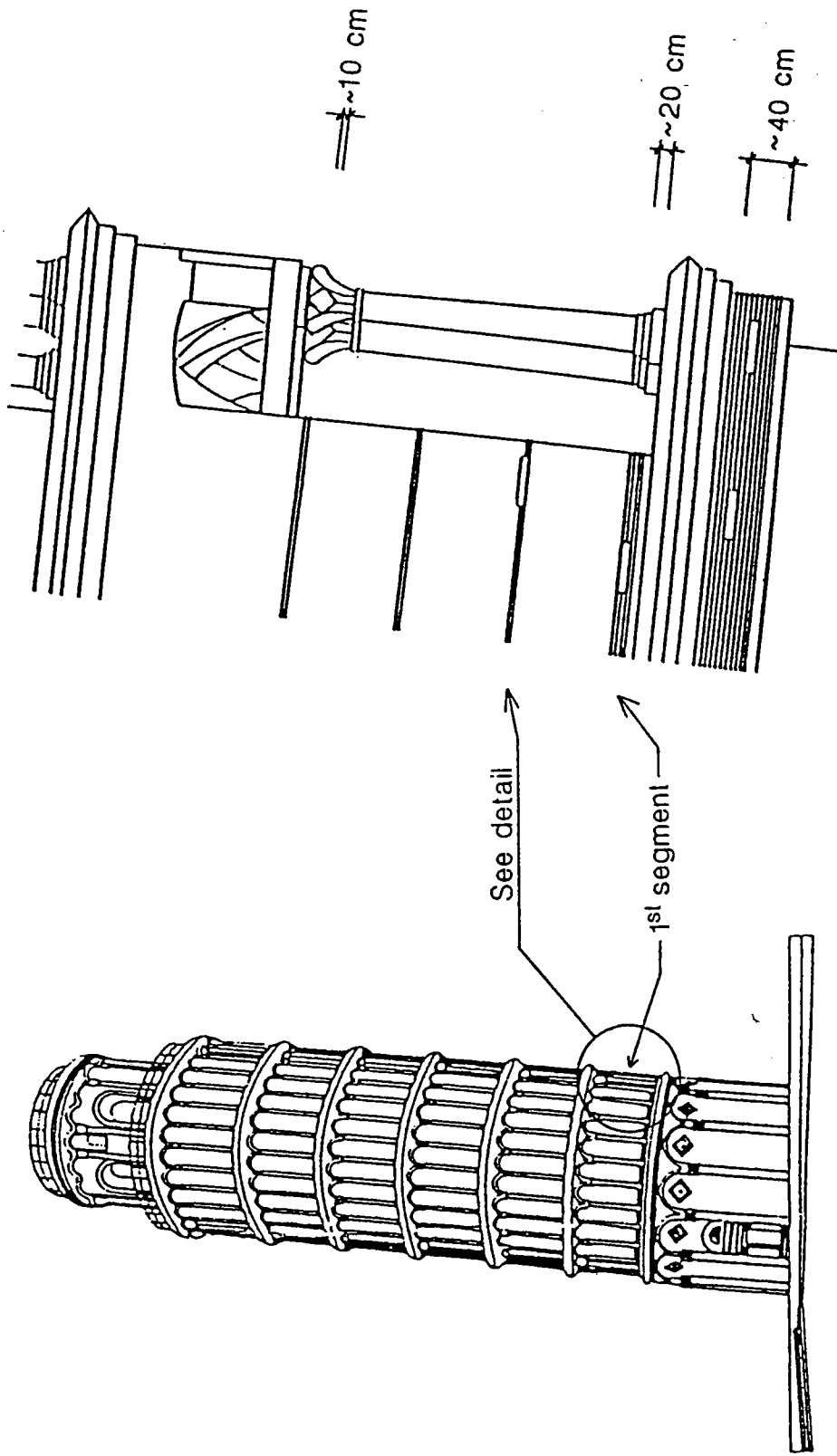
See detail

1st segment

Fig. 11    Temporary stabilisation of the masonry with light circumferential pre-stressing

the response against which to judge the observed response of the Tower as the load was being applied. A detailed description of the analysis is given by Burland and Potts [5] who found that a satisfactory result was only forthcoming if the effects of ageing of the underlying Pancone Clay was incorporated in the computer model. The justification for such ageing lay in the observed motion of the foundations depicted in Fig. 10 as described in the previous section. The computer analysis indicated that it was safe to apply up to a maximum of 1400t load to the north side of the foundation masonry. Above that load there was a risk that the underlying Pancone Clay would begin to yield resulting in a southward rotation of the Tower and excessive settlement of the foundations.

Accordingly a design was developed by Professors Leonhardt and Macchi for the application of a north counterweight and the details of construction are shown in Fig. 12. It consists of a temporary prestressed concrete ring cast around the base of the tower at plinth level. This ring acts as a base for supporting specially cast lead ingots which were placed one at a time at suitable time intervals. The movements experienced by the tower are measured with a highly redundant monitoring system consisting of the following: (i) precision inclinometers and levellometers installed on the wall of the ground floor room, (ii) high precision levelling of 8 survey stations mounted on the wall of the above room and (iii) external high precision levelling of 15 bench marks located around the tower plinth and 24 bench marks located along north-south and east-west lines centred on the tower. All the levels are related to a deep datum installed in the Piazza dei Miracoli by the Commission.

*Observed Response*
Burland et al [7] describe the response of the Tower to the application of the counterweight. Construction of the concrete ring commenced on 3rd May 1993 and the first lead ingot was placed on 14th July 1993 (see Fig. 13). The load was applied in four phases with a pause between each phase to give time to observe the response of the tower. Fig. 14 shows the application of one the lead ingots. The final phase was split in two either side of the Christmas break. The last ingot was placed on 20th January 1994.

Fig. 15 shows the change of inclination of the tower towards the north during the application of the lead ingots as measured by the internal high precision levelling and the inclinometer placed in the north-south plane. The agreement between the two independent monitoring systems is excellent. (Note that Fig. 15 does not include the inclination induced by the weight of the concrete ring which amounted to about 4 arc seconds). It can be seen that the amount of creep between the phases of load is small. However, subsequent to completion of loading, time dependent northward inclination continued. On 20th
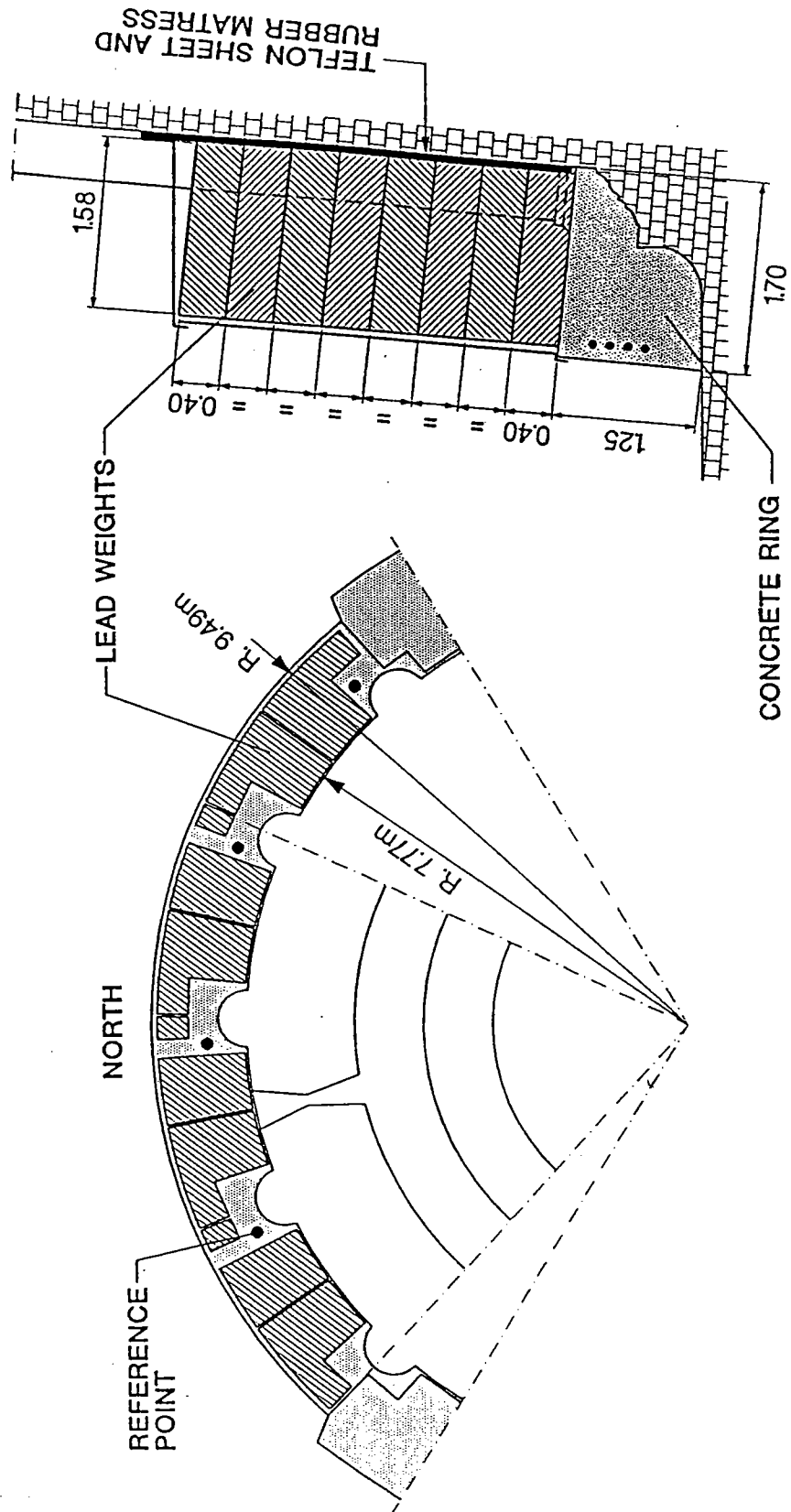
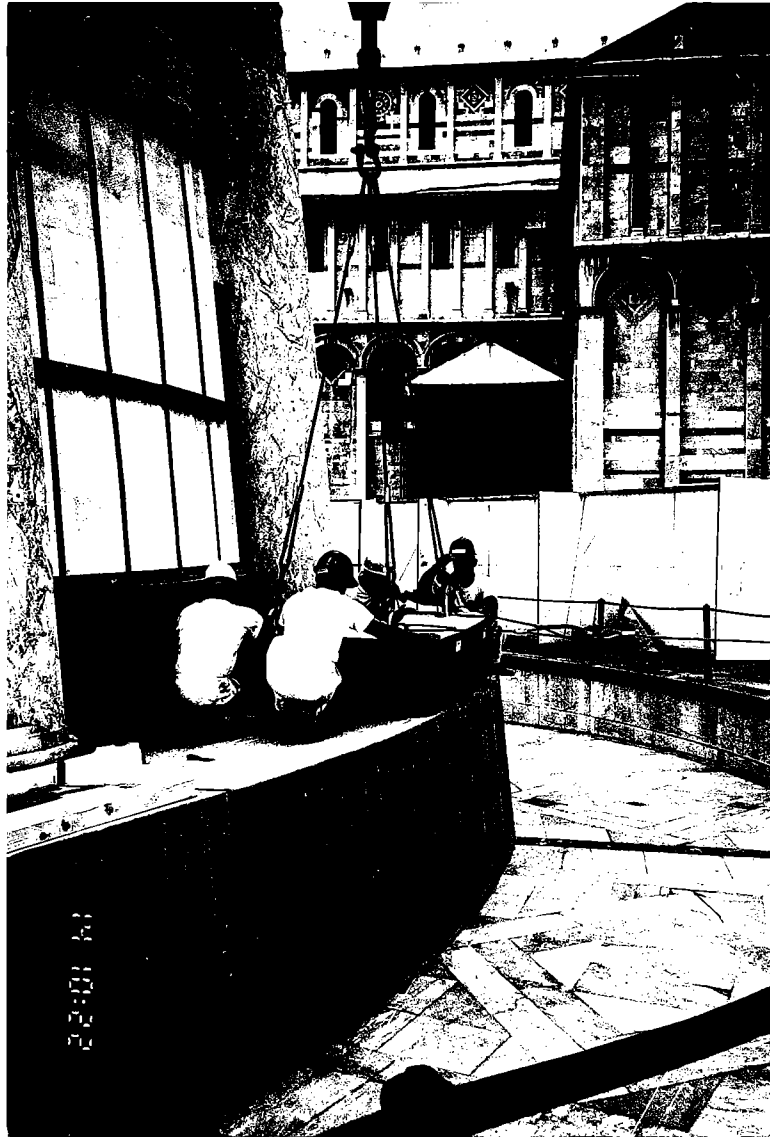Fig. 12 Details of the north counterweight

Fig. 13    Placing the first lead ingot on 14th July 1993
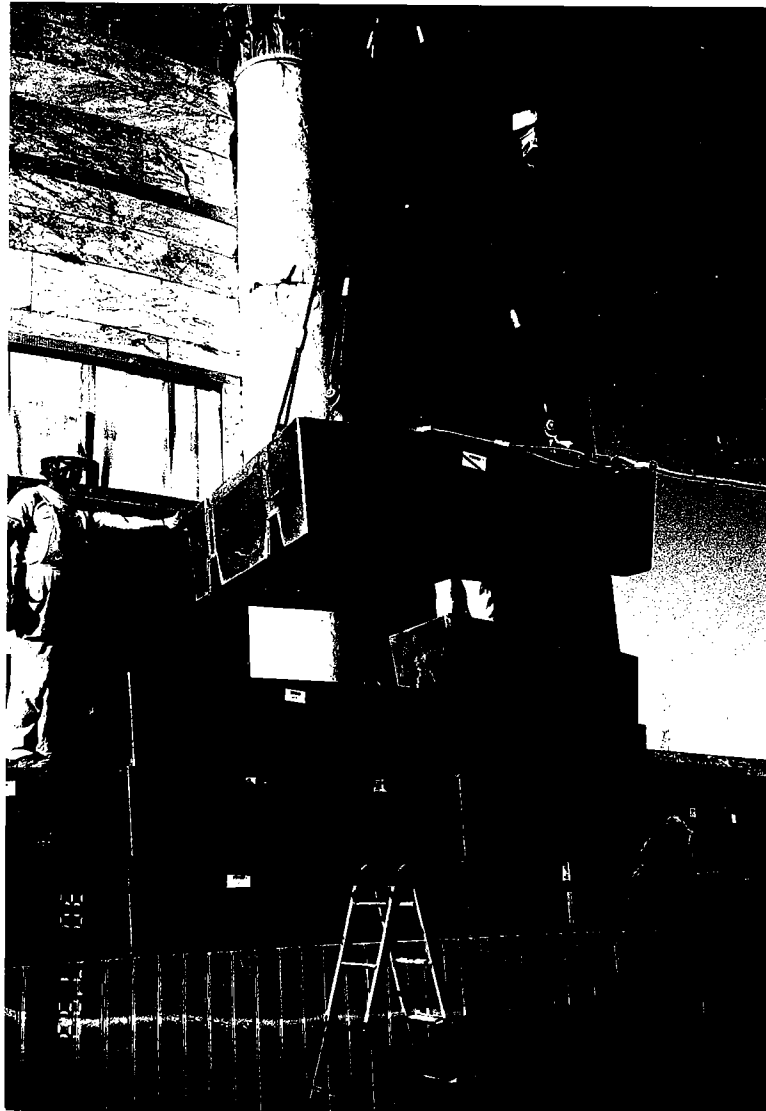
Fig. 14    Construction of the north counter-weight
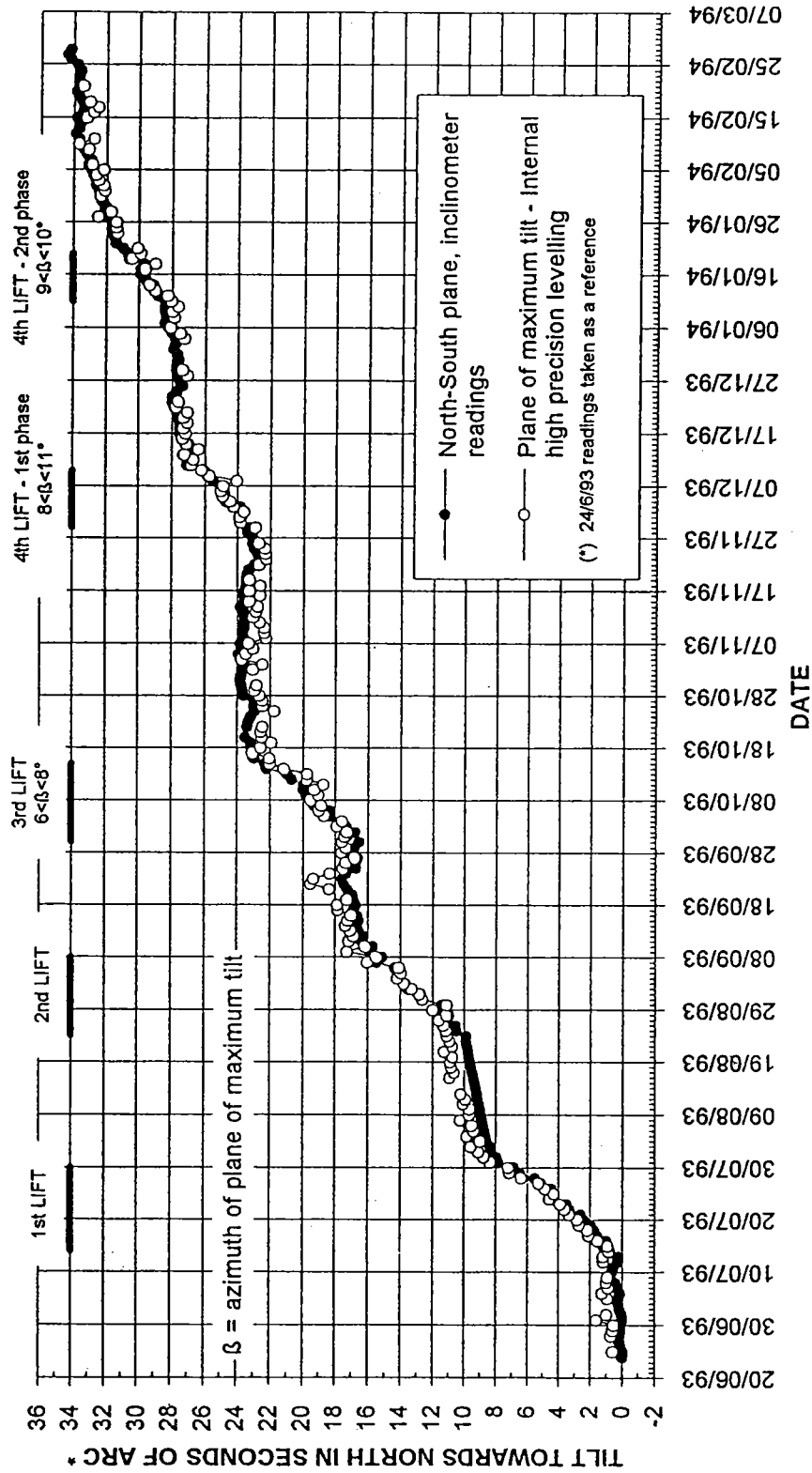
Fig. 15   Observed change of inclination of the tower during
          application of the counterweight

February 1994 (one month after completion of loading) the northward inclination was 33 arc seconds. By the end of July 1994 it had increased to 48 arc seconds giving a total of 52 arc seconds including the effect of the concrete ring. On 21st February 1994 the average settlement of the tower relative to the surrounding ground was about 2.5mm.

*Comparison Between Predictions and Observations*
Fig. 16 shows a comparison of the predictions from the computer model and measurements of (a) the changes in inclination and (b) the average settlements of the tower relative to the surrounding ground during the application of the lead ingots. The points in the upper part of Fig 16 represent the measured rotations at the end of each phase of loading and the vertical lines extending from them show the amount of creep movement between each phase. For the final phase the creep after one month is shown. It can be seen that the predictions of the computer model give changes in inclination which are about 80% of the measured values. However the predicted settlements are in excellent agreement with the measurements.

It is perhaps worth emphasising that the purpose of the computer model was to clarify some of the basic mechanisms of behaviour and it was calibrated against inclinations measured in degrees. The use of the model in studying the effects of the counterweight was to check that undesirable and unexpected responses of the tower did not occur. In this respect the model has proved to be very useful. It has led to a consideration of the effects of ageing and it has drawn attention to the importance of limiting the magnitude of the load so as to avoid yield in the underlying Pancone clay. It is perhaps expecting too much of the model for it to make accurate quantitative predictions of movements which are three orders of magnitude less than those against which it was calibrated and the fact that it has done as well as it has is remarkable. The observed movements due to the application of the counterweight have been used to further refine the model.

## PERMANENT STABILISATION
For bureaucratic and financial reasons work on the temporary stabilisation of the Tower has taken longer than had been hoped. In parallel with these operations the Commission had been exploring a variety of approaches to permanently stabilising the Tower. The fragility of the masonry, the sensitivity of the underlying clay and the very marginal stability of the foundations has already been referred to. Because of these severe restraints, any measures involving the application of concentrated loads to the masonry or underpinning operations beneath the south side of the foundation have been ruled-out. Moreover aesthetic and conservation considerations require that the visible impact of any stabilising measures should be kept to an absolute minimum.
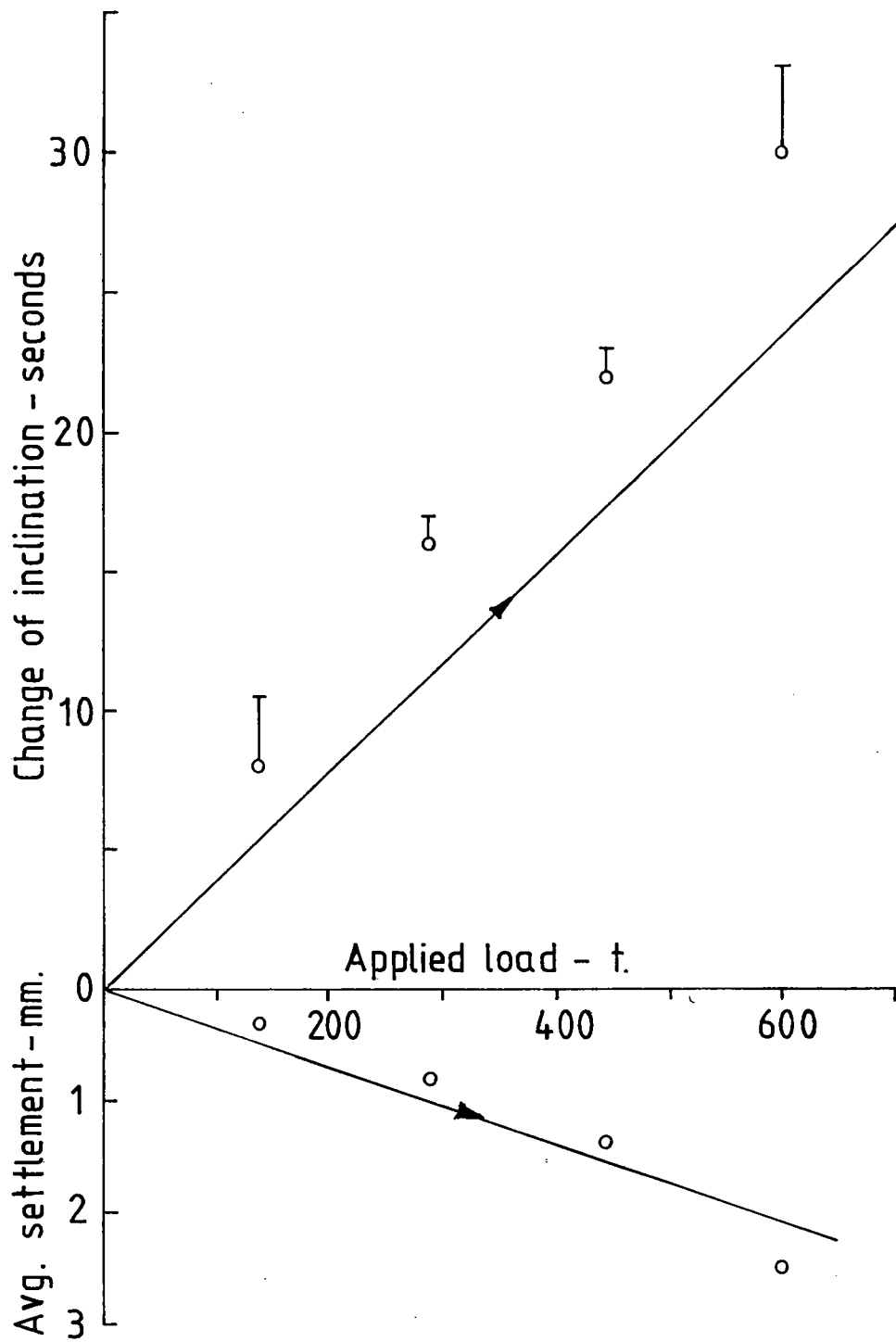
Fig. 16    Plane strain prediction and observed response of the
           tower due to the application of the counterweight

The Commission decided to give priority to so called 'very soft' solutions aimed at reducing the inclination of the Tower by up to half a degree by means of induced subsidence beneath the north side of the foundation without touching the structure of the Tower. Such an approach allows the simultaneous reduction of both the foundation instability and the masonry overstressing with a minimum of work on the Tower fabric itself.

Some of the key requirements of stabilisation by reducing inclination are as follows:
1. The method must be capable of application incrementally in very small steps.
2. The method should permit the Tower to be 'steered'.
3. It must produce a rapid response from the Tower so that its effects can be monitored and controlled.
4. Settlement at the south side must not be more than 0.25 of the north side. This restriction is required to minimise damage to the catino and disturbance to the very highly stressed soil beneath the south side.
5. There must be no risk of disturbance to the underlying Pancone clay which is highly sensitive and upon whose stiffness, due to ageing, the stability of the Tower depends.
6. The method should not be critically dependent on assumed detailed ground conditions.
7. The impact of possible archaeological remains beneath the Tower must be taken into account.
8. Before the method is implemented it must have been clearly demonstrated by means of calculation, modelling and large scale trials that the probability of success is very high indeed.
9. It must be demonstrated that there is no risk of an adverse response of the Tower.
10. Any preliminary works associated with the method must have no risk of impact on the Tower.
11. Methods which require costly civil engineering works prior to carrying out the stabilisation work are extremely undesirable for a number of reasons.

After careful consideration of a number of possible approaches the Commission chose to study three in detail:
a. The construction of a ground pressing slab to the north of the Tower which is coupled to a post-tensioned concrete ring constructed around the periphery of the foundations.
b. Consolidation of the Pancone Clay by means of carefully devised electro-osmosis.
c. The technique of soil extraction as postulated by Terracina [9] for Pisa and widely used in Mexico City to reduce the differential settlements of a number of buildings due to regional subsidence and earthquake effects. This technique involves the controlled removal of small volumes of soil from the sandy silt formation of Horizon A beneath the north side of the foundation.

All three approaches have been the subject of intense investigation. Numerical and centrifuge modelling of the north pressing slab have shown that the response of the Tower is somewhat uncertain and, if positive, is small while the induced settlements are large. Full scale trials of the electro-osmosis showed that the ground conditions at Pisa are not suited to this method. Both these methods require costly civil engineering works prior to commencement of the stabilisation work. Work on the method of soil extraction is proving much more positive but before describing it a major set-back took place in September 1995 and first this will be described.

## A SET-BACK

It is not widely appreciated that the decree establishing the Commission has never been ratified. The position in Italian law is that a decree has to be ratified by the Italian Parliament within two months of publication or else it falls. Thus, every two months, the decree relating to the Commission had to be renewed. On a number of occasions the Commission had been suspended because of delays in the renewal of the decree. Such an arrangement made the Commission very vulnerable to media and political pressures. Moreover, long-term planning becomes very difficult.

Shortly after the successful application of the temporary counterweight a view emerged that the Commission was politically vulnerable and that something needed to be done that would clearly demonstrate the effectiveness of the work so far. There was also considerable concern amongst some members that, should the Commission cease to exist, the unsightly lead counterweight would be left in position for many years. Therefore a scheme was developed to replace the lead weights with ten tensioned cables anchored in the lower sands at a depth of about 45m as shown in Fig. 17. Additional benefits of this proposal were seen to be that the increased lever-arm would give a slightly larger stabilising moment than the lead counterweight and tensions in the anchors could be adjusted to 'steer' the Tower during implementation of induced subsidence. It is important to appreciate that this ten anchor solution was always intended to be temporary.

The major problem with the ten anchor solution is that the anchors have to react against a post-tensioned concrete ring around the Tower foundation and this involves excavation beneath the catino at the south side - an operation of the utmost delicacy since it is below the water table. Various schemes for controlling the water were considered and it was decided to employ local ground freezing immediately beneath the catino floor but well above foundation level. The post-tensioned concrete ring was to be installed in short lengths so as to limit the length of excavation open at any time.
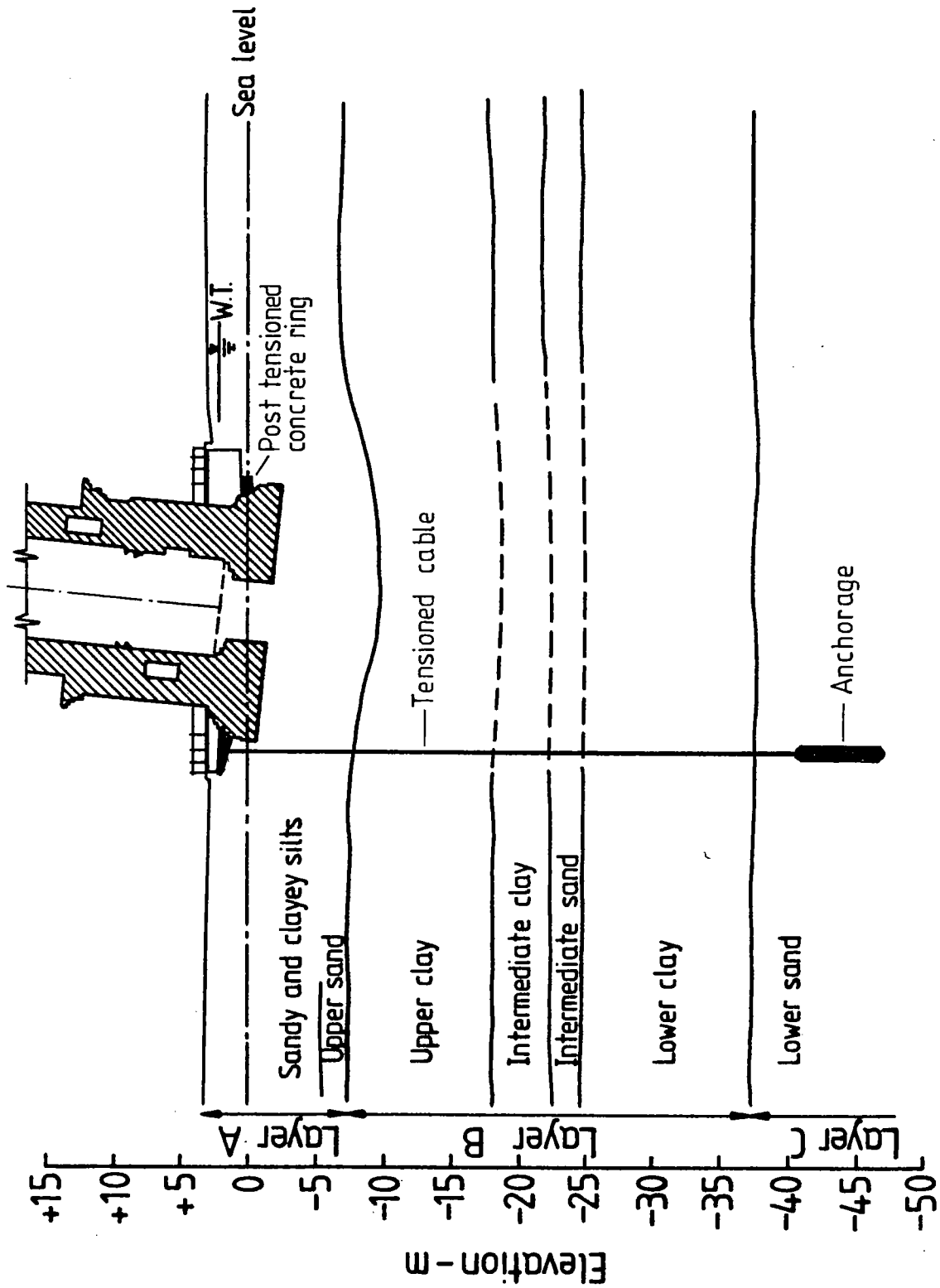
Fig. 17 Schematic diagram of the temporary ten anchor solution

Shortly before commencement of the freezing operation exploratory drilling through the floor of the catino revealed the existence of an 80cm thick ancient concrete (conglomerate) layer which had evidently been placed by Gherardesca in 1838. There are no archaeological records of this conglomerate and its discovery came as a complete surprise. A key question was whether it was connected to the Tower. Exploratory drilling was carried out to investigate the interface between the conglomerate and the masonry foundation. A circumferential gap was found all around the foundation and it was concluded that the conglomerate was not connected to the masonry. Work then started on installing the post-tensioned concrete ring.

Freezing commenced on the north side and the northern sections of the ring were successfully installed. The freezing operations consisted of 36 hours of continuous freezing using liquid nitrogen followed by a maintenance phase when freezing was carried out for one hour per day so as to control the expansion of the ice front. Some worrying southward rotation of the Tower did take place during freezing at the north but this was recovered once thawing commenced. Of far greater concern was the discovery of a large number of steel grout-filled pipes connecting the conglomerate to the masonry foundation. These were installed by Girometti in 1934 when the foundation masonry was grouted. In none of the engineering reports of the time is there any reference to these grout pipes or of the conglomerate.

In September 1995 freezing commenced on the south-west and south-east sides of the foundation. During the initial 36 hours of continuous freezing no rotation of the Tower was observed. However, as soon as the freezing was stopped for the maintenance phase the Tower began to rotate southward at about 4 arc seconds per day. The operation was suspended and the southward rotation was controlled by the application of further lead weights on the north side. The resulting southward rotation of the Tower was small, being about 7 arc seconds, but the counterweight had to be increased to about 900t. The main concern was the uncertainty about the strength of the structural connection between the conglomerate and the masonry formed by the steel grout pipes. In view of this uncertainty the freezing operation was abandoned and work on developing the permanent solution was accelerated.

## INDUCED SUBSIDENCE BY SOIL EXTRACTION

Figure 18 shows the proposed scheme whereby small quantities of soil are extracted from Layer A below the north side of the Tower foundation by means of an inclined drill. The principle of the method is to extract a small volume of soil at a desired location leaving a cavity. The cavity gently closes due to the overburden pressure causing a small surface subsidence. The process is repeated at various chosen locations and very gradually the inclination
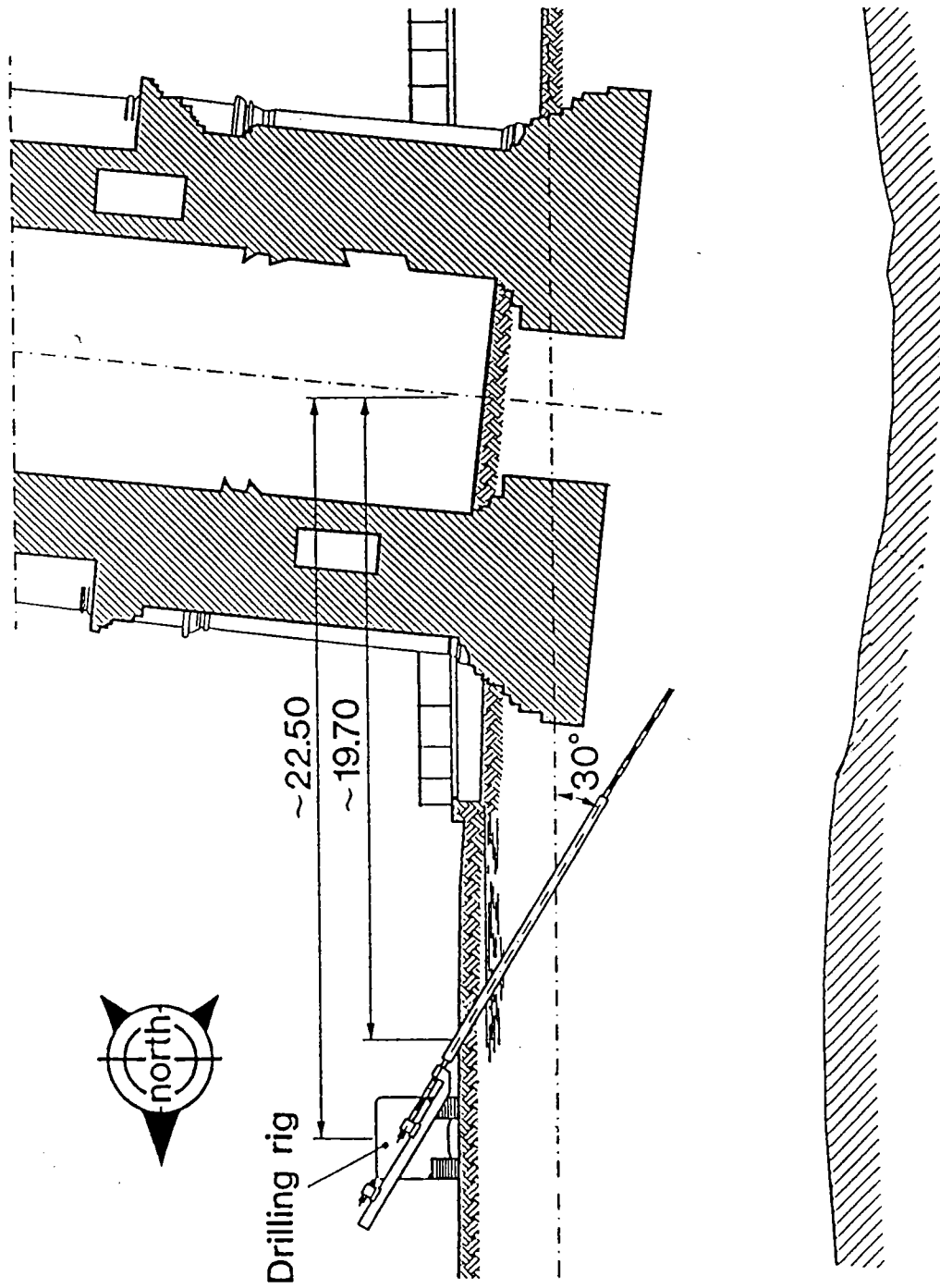
~22.50

~19.70

30°

Drilling rig

north

Fig. 18  Schematic representation of the underexcavation process

of the Tower is reduced.

Two key questions had to be addressed:
1. Given that the Tower is on the point of leaning instability, is there a risk that extraction of small quantities of soil from beneath the north side will cause an <u>increase</u> in inclination?
2. Is the extraction of small volumes of ground in controlled manner feasible, will the cavities close and what is the response at the soil/foundation interface?

The first issue has been studied in great detail using two independent approaches - numerical modelling and physical modelling on the centrifuge. The numerical model described previously was used to simulate the extraction of soil from beneath the north side of the foundation. Even though the tower was on the point of falling over it was found that, provided extraction takes place north of a critical line, the response is always positive. The Moreover the changes in contact stress beneath the foundations were small. Advanced physical modelling was carried out on a centrifuge at ISMES in Bergamo. As for the numerical modelling, the ground conditions were carefully reproduced and the model was calibrated to give a reasonably accurate history of inclination. The test results showed that soil extraction always gave a positive response.

The results of the modelling work were sufficiently encouraging to undertake a large scale development trial of the drilling equipment. For this purpose a 7m diameter eccentrically loaded instrumented footing was constructed in the Piazza north of the Baptistry as shown in Fig. 19. The objectives of the trial were:
1. To develop a suitable method of forming a cavity without disturbing the surrounding ground during drilling.
2. To study the time involved in cavity closure.
3. To measure the changes in contact stresses and pore water pressures beneath the trial footing.
4. To evaluate the effectiveness of the method in changing the inclination of the trial footing.
5. To explore methods of 'steering' the trial footing by adjusting the drilling sequence.
6. To study the time effects between and after the operations.
It must be emphasised that the trial footing was not intended to represent a scale model of the Tower.

The results of the trial have been very successful. Drilling is carried out using a hollow-stemmed continuous flight auger inside a contra-rotating casing. When the drill is withdrawn to form the cavity an instrumented probe located in the hollow stem is left in place to monitor its closure. A cavity formed in the Horizon A material has been found to close smoothly and rapidly. The stress
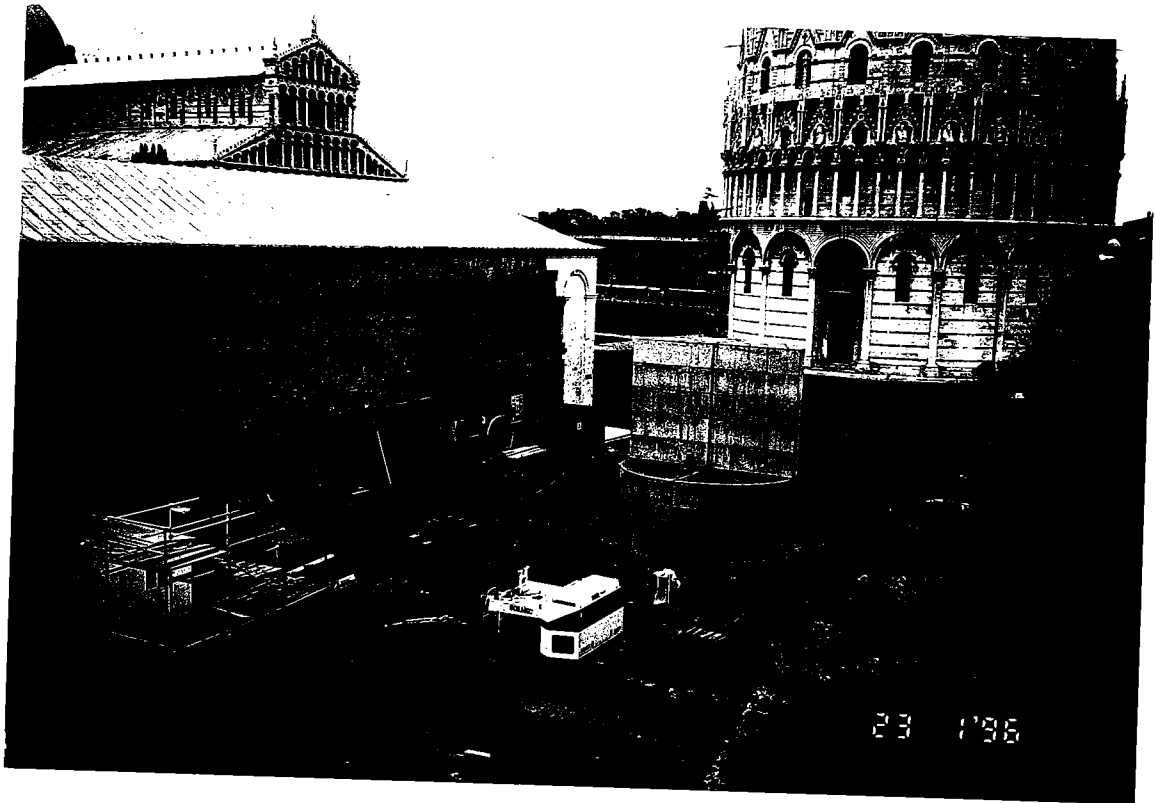
Fig. 19    Soil   extraction   trial   showing   7m   diameter
           eccentrically loaded footing and inclined drill

changes beneath the foundation were found to be small. The trial footing 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. Very importantly, an effective system of communication, decision taking and implementation was developed.

**CONCLUDING REMARKS**

Both numerical and physical modelling of the response of the Tower to soil extraction has proved positive. The large-scale trials of the drilling technology has shown that the method works for the soil in Layer A. As a result of these extensive and detailed studies a decision was taken by the Commission in the summer of 1996 to carry out preliminary soil extraction beneath the north side of the Tower itself. The objective was to observe the response of the Tower to a limited and localised intervention. Prior to undertaking this work a safeguard structure was to be constructed in the form of a horizontal cable stay attached to the Tower at the third storey.

Before work on the preliminary underexcavation could commence the Commission was dissolved by the Italian Government in late 1996. In March 1997 a new Commission was established (the seventeenth) with a significant change of membership. This new Commission met for the first time in July 1997. Understandably it was necessary for the new members to become fully informed about all the background work relating to the behaviour of the Tower. Also the opportunity was taken to re-examine possible alternative solutions. The proposals developed and agreed by the old Commission had to be re-submitted to the new Commission for detailed examination and debate.

For the members of the old Commission who had worked so hard and so long on the Tower this has proved a taxing and frustrating period. But it was absolutely right that a new Commission should be seen to be taking a fresh look at all the problems. In November 1998 the new Commission finally approved the carrying out of preliminary‛soil extraction alongside the north side of the Tower in conjunction with the use of safeguard cable stays as described above. A limited amount of masonry strengthening has also been approved in principle. It is important to emphasise that the purpose of the cable stays is simply to hold the Tower steady in the event of a negative response to the soil extraction. There is no intention to use the cable stays as a means of pulling the Tower northwards. Not to have such a safety system would be highly irresponsible. The Contractor calls the cable stays his 'parachute'!

If the preliminary soil extraction proves successful it is estimated that it will take about two years to reduce the inclination of the Tower by approximately half a degree. This will bring the Tower back to its inclination prior to

the intervention by Gherardesca in 1838 and will be barely visible to the casual observer. It is intended that the lead weights will be removed and it is also anticipated that, in the longer term, it will be necessary to stabilise the ground water level in the vicinity of the Tower.

In recent months the question has frequently been asked whether eight years of work has achieved anything. Fig. 20 provides the simple answer to this. It shows the seasonal north/south rotation of the Tower since 1985 as measured by the GB pendulum. The beneficial effects of the application of the temporary counterweight in 1993/94 are graphically illustrated by bringing the Tower back to its 1985 value. It is also clear that, apart from the events of September 1995, the annual rate of rotation has been dramatically reduced. Moreover, the temporary stabilisation of the masonry by the steel tendons appears to have been effective. Numerous other studies have been carried out on the fabric and history of the Tower resulting in considerable advances in our understanding of its history, construction and character.

The work on the Tower now enters a new and very delicate phase and only time will tell the outcome. The Tower has always been an enigma as have the institutions and organisations responsible for it. The more one studies and works on the Tower the greater the enigma.
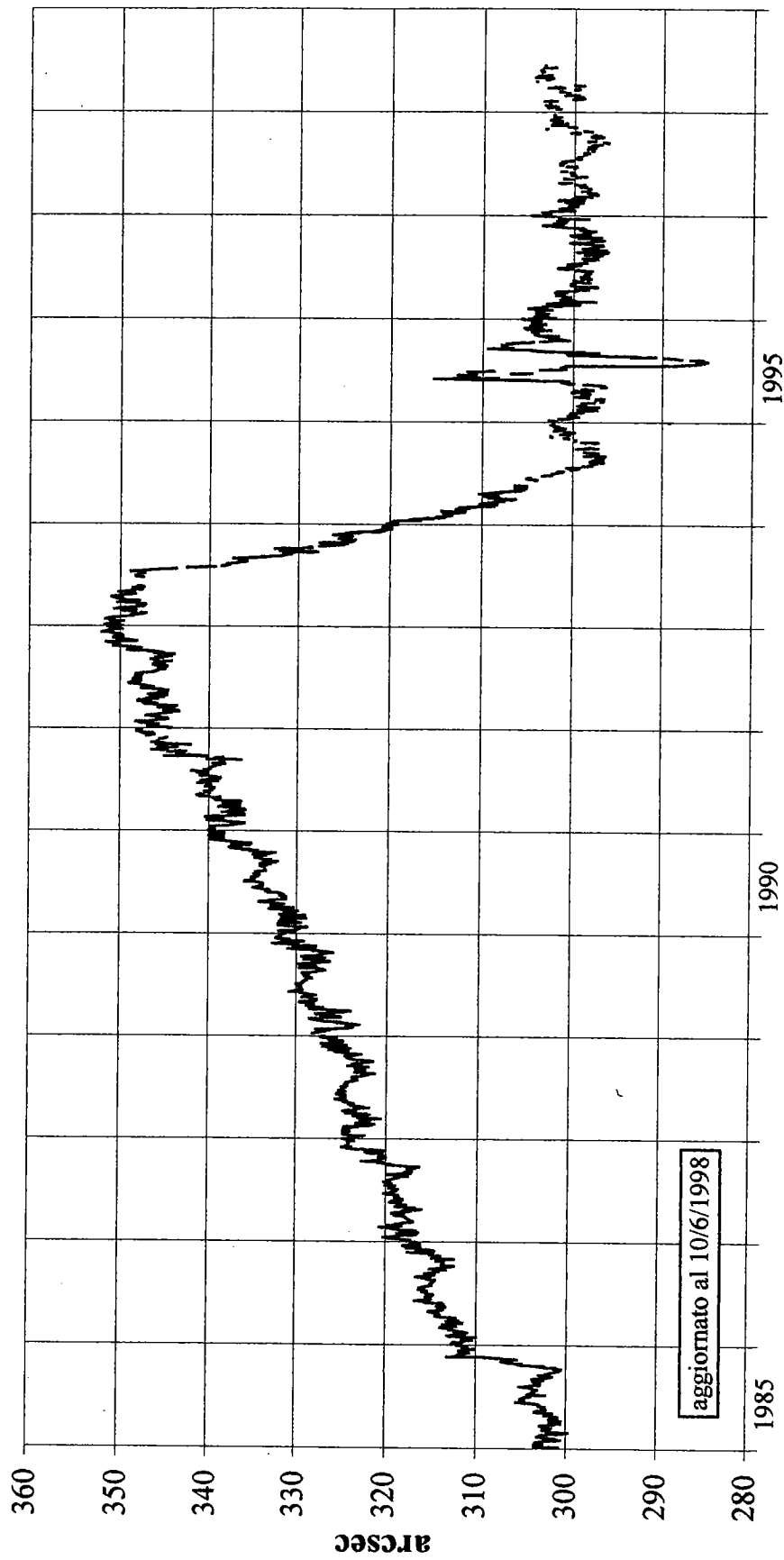
Fig. 20    Change in north-south inclination since 1985 as
           measured with the Girometi-Bonechi pendulum

**REFERENCES**

1.  Ministero dei Lavori Pubblici (1971). *Ricerche e studi sulla Torre di Pisa ed i fenomeni connessi alle condizione di ambiente.* 3 Vol., I.G.M., Florence.

2.  Burland, J.B. and Viggiani, C. (1994). Observazioni sulcomportamento della Torre di Pisa. *Rivista Italiana di Geotecnica*, 28; 3; 179-200.

3.  Potts, D.M. and Gens, A., (1984). The effect of the plastic potential in boundary value problems involving plane strain deformation. *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol 8;259-286.

4.  Schofield, A.N. and Wroth, C.P., (1968). Critical State Soil Mechanics. *McGraw-Hill Book Co.*, London.

5.  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 Geo-materials.* IS-Hokkaido '94, Japan, Vol 2,715-738.

6.  Hambly, E.C. (1985). Soil buckling and the leaning instability of tall structures. *The Structural Engineer*, Vol 63A, No 3, 77-85.

7.  Burland, J.B., Jamiolkowski, M., Lancellotta, R., Leonards, G.A. and Viggiani, C. (1994). Pisa update - behaviour during counterweight application. *ISSMFE News*, Vol 21, No 2.

8.  Burland, J.B. (1990). Pisa Tower. A simple temporary scheme to increase the stability of the foundations. *Unpublished report to the Commission.*

9.  Terracina, F., (1962). Foundations of the Tower of Pisa. *Geotechnique*, Vol 12;4;336-339.