The Tower of Pisa and the Surrounding Square: Recent Observations

La Tour de Pisa et la Place Autour: Observations Recentes

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SYNOPSIS The results of the observations made in the last decade on the Tower of Pisa and on the surrounding monuments give a general picture of the movements of the Tower and allow them to be considered in a more complex and broader context. The measurements concern the settlement of the Tower and of a number of points in the surrounding square, and the piezometric level in the main layers of the subsoil.
Since most of the measurements have been carried out by means of instruments installed in 1965 and their results span over a period long enough to be significant, they complete the observations made since the beginning of this century and allow a deeper insight of the Tower behaviour. In particular, possible correlations among the observed phenomena are pointed out.
The conclusions drawn seem to be of some use for a more suitable monitoring of the Tower and for a guidance towards perspective stabilization of the monument.

INTRODUCTION

The Commission set up by the Italian Ministry of Public Works for preparing an international tender for consolidating the Leaning Tower of Pisa terminated its studies on the movements and on the foundation soils about 12 years ago. At that time, a new series of measurements was initiated for a monitoring of the Tower, the near-by monuments, the surrounding square and some environmental conditions, as the ground water level.
The various proposal submitted for the tender were not accepted, and the consolidation works have been no longer carried out; the observations made since then, however, shed light on some aspects of the complex and unique phenomenon of the relentless movement of the Tower.

In this paper the main data collected after the publication of the Commission Report (1971) are reported and analysed, seeking possible connections between the recent movements of the Tower and the changes in environmental conditions.

RECENT MOVEMENTS OF THE TOWER

Only from 1965 onward the settlement of the Tower has been monitored; until 1965, the rotation of the Tower had been the sole concern of the many people who studied its behaviour.

Since 1911 the inclination angle was measured (every six months since 1923) through a geodethic method known as Pizzetti' s method. Since the Tower axis is curved, the angle ϑ formed by the line connecting the centers of the first and the seventh cornices, C_1 and C_7, with the vertical, is being used to express tilting.
In 1911 this angle was 5°14'46", while the angle formed by the basis plane with the horizontal was about 11' greater.
The plane of maximum inclination was almost coincident with the N-S direction.
The values of ϑ measured from 1911 to 1934 are plotted against time in fig. 1a (dotted curve).

In 1934 a pendulum (known as Girometti-Bonechi's inclinometer) was installed between the first and the sixth cornice. By means of this apparatus, the Tower rotation has been measured daily with great accuracy (1/100") and referred to two vertical planes, one of which coincides with the 1934 plane of maximum inclination and forms an angle of only 2°26' with the N-S direction. The two components of the Tower rotation are being therefore indicated as α_{NS} and α_{EW}(fig. 1).

The inclination of the Tower from 1934 onward, reported in fig. 1, has been obtained by adding these results to the geodethic measurement result in that year (ϑ = 5°16'50").

The inclination increments per year since 1934, in both direction, are plotted in fig. 2. The diagrams clearly show the fluctuation of rotation velocities around an almost constant and positive value, which is a characteristic of the Tower behaviour.

Two more pronounced phenomena marked its life since 1934: a sudden increase of tilting rate which occurred in 35 and lately, starting in the sixties, a progressive and long lasting increase

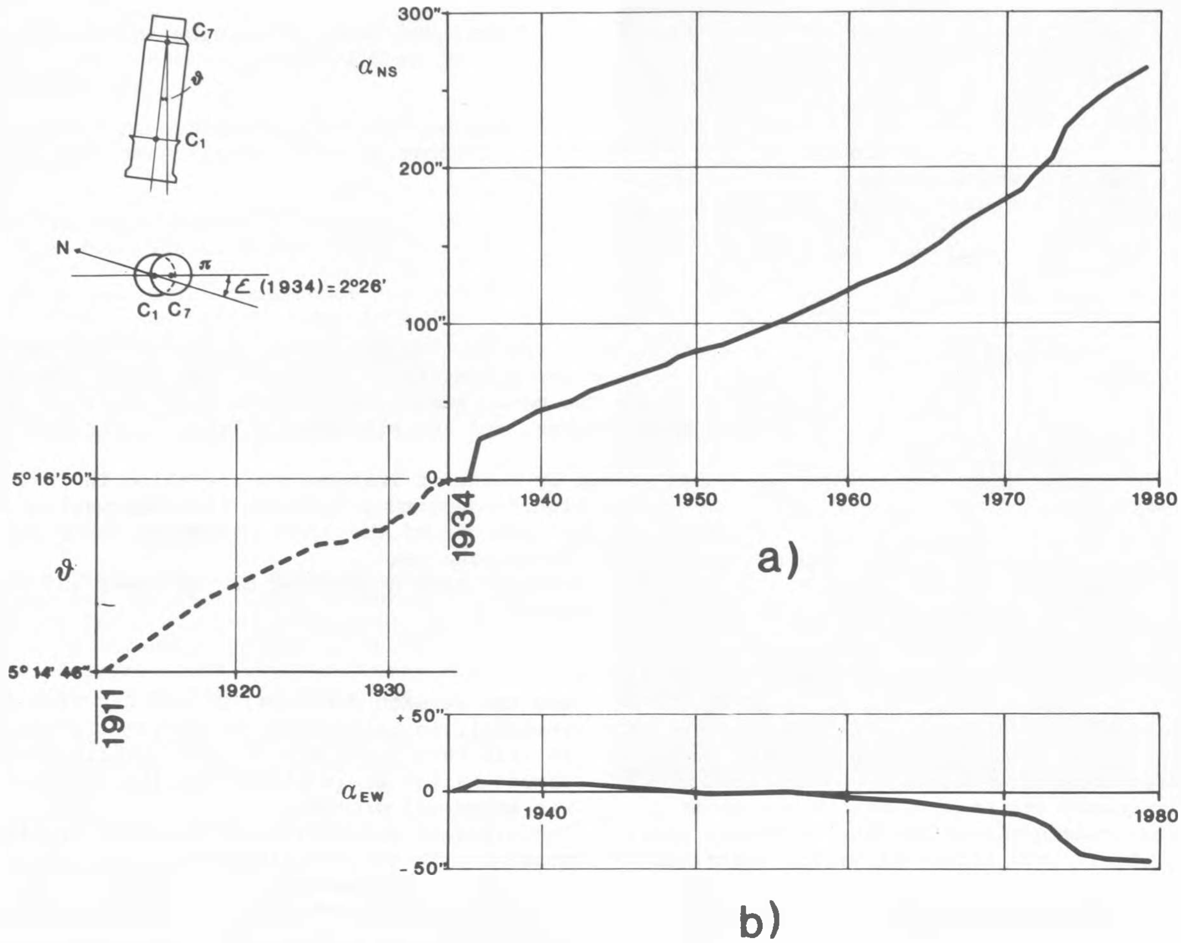

Fig. 1. Tower inclination measurements. a) Values of θ measured by Pizzetti's method from 1911 to 1934 (dotted line). After 1934, the inclination may be expressed as:

$$\vartheta = \sqrt{(\vartheta_{1934} + \alpha_{NS})^2 + \alpha_{EW}^2} \doteq \vartheta_{1934} + \alpha_{NS}$$

ϑ is assumed positive for southward inclination.

b) Values of α_{EW} since 1934; eastward inclination is assumed as positive.

of both components of the rotation velocity. The former was clearly due to the grouting of the foundation masonry and of the external ba= sin, which was carried out at that time. The induced rotation increment maintained the N-S direction and occurred in a few months.

On the contrary, the latter phenomenon introdu= ced a sensible change of the rotation plane and went on for a long time. For these reasons, the new trend of the Tower movement, as soon as it was firstly noticed, appeared of more concern and potentially dangerous as its possible causes remained undetected.
The analysis of this phenomenon and of its con= nections to the evolution of the environmental conditions forms the main object of this paper.

Finally, from the velocity diagrams of fig. 2 it seems that, when the first perturbation pe= riod ended, in 1936, the movement of the Tower reassumed its previous trend, without apparent memory of the preceding facts, except obviously the accumulated angle of tilting.

Whether the same occurs after 1978, on the con= trary, appears at present to be doubtful.

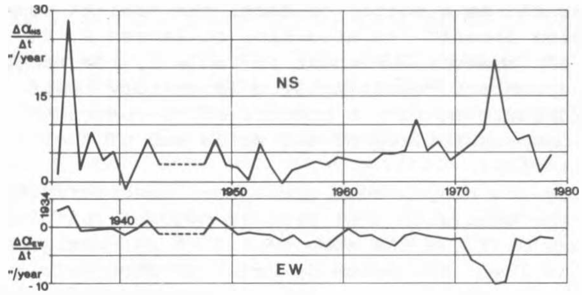

Fig. 2. Inclination increments per year since 1934; the sign convention is the same as in fig. 1

SUBSOIL PROPERTIES

The results of the geotechnical investigations carried out at different times, but mainly in 1965-66, on the Tower subsoil, have been already published (M.P.W. Commission, 1971).

In order to give a synthetic picture of the foundation soils with their main features, how= ever, the borehole profiles and the cone pene= tration diagrams, aligned on the N-S cross sec= tion through the Tower axis, have been composed in fig. 3. Table I summarizes the geotechnical characteristics of the various layers.

Two points, which clearly arise from fig. 3, are noteworthy. Firstly, the stratigraphic correla= tion of the various layers is very well under= lined by the sharp changes in the physical and

TABLE I. Geotechnical properties of the subsoil of the Tower

		Depth (m)	Nature of the soil	w_L (%)	I_P (%)	CF (%)	w (%)	State of consoli= dation	C_c	c_v (cm^2/s)	c_u (kN/m^2)	S_t
COMPLEX A		0-3	Made ground									
		3-8,5	Yellow sandy silt to silty clay, without stratification	38	13	15	25 to 32	heavy O.C.	0,3	3	63	--
		8,5-10	Uniform gray sand with interbed= ded clay layers and broken fossils	--	--	--	35	--	--	--	--	--
COMPLEX B	Upper clay (Pancone clay) B1	10-14	Highly plastic gray clay with fossils	75	42	61	53	slight O.C.	0,75	5 to 2	40	5
		14-16	Medium plastic gray clay with fossils	55	29	44	45	N.C.	0,5	2-15	45	5
		16-21	Highly plastic gray clay with fossils	85	45	66	57	N.C.	0,4-0,7	2-20	50	5
	Interm. clay B2	21-22	Dark gray organic clay	68	44	46	26	heavy O.C.	0,2	4-10	100	2
		22-25	Blue gray to yellow silty clay with calcareous nodules	45	21	32	25	heavy O.C.	0,15	40	160	2
	Interm. sand B3	25-27,5	Gray, sometimes yellow, sand and silty sand	--	--	10	30	--	--	--	--	--
	Lower clay B4	27,5-32	Medium to highly plastic clay, with fossils and thin sand lenses in the upper part	35 to 80	20 to 50	30 to 70	30 to 48	slight O.C. to N.C.	0,4 to 0,6	20 to 2	70	5
		32-33,5	Gray clay with frequent thin sand lenses	53	26	28	34	N.C.	0,35	8	140	3
		33,5-37	Blue gray silty clay with yellow spots; calcareous nodules; some dark organic clay at center	55	30	30	45 to 25	?	0,2-0,7	2-9	120	3
		37-40	Gray clay with yellow spots; fos= sils in the lower part	50	27	50	27-34	?	0,35	9	80	2
COMPLEX C		40-60	Medium uniform dense gray sand and silty sand	--	--	5 to 10	25 to 18	--	--	--	--	--

N.B. : 2-15 means a scatter; 30 to 48 means a gradual variation with depth.

mechanical properties of the soils. Apart from the apparent depression in the upper face of layer B1 (Pancone Clay) caused by the weight of the Tower, the separation surfaces are flat and the thickness of the layer constant.

Secondly, single layers are not homogeneous. The differences among the cone penetration resistan= ces in layer B1 can be easily marked in tests P9 and P10 (which, being far from the Tower, are not influenced by the induced stress), or in the lower part of tests P7 and P8.

Unfortunately, the deeper layers (B3, B4 and C) were not reached by the penetration tests and their mechanical properties are not specified by laboratory tests with the same detail as for layer B1. As a matter of fact, the 1965-66 Com= mission focused its attention on layers A, B1 and B2; however, as shown in Table I, the range of parameters resulting from laboratory tests is adequate to give a picture of the strength and compressibility of all soils and of their scattering.

As regards clays, both geological considerations and the available test results suggest that layer B4 has at least the same degree of non-homogene= ity as layer B1, which is known in more detail. To what extent are the lower sands (layer C) ho= mogeneous is more difficult to assess. The bore= holes carried out in the Square detected some clay and silt generally diffused throughout the coarse sand; only one borehole crossed a silty

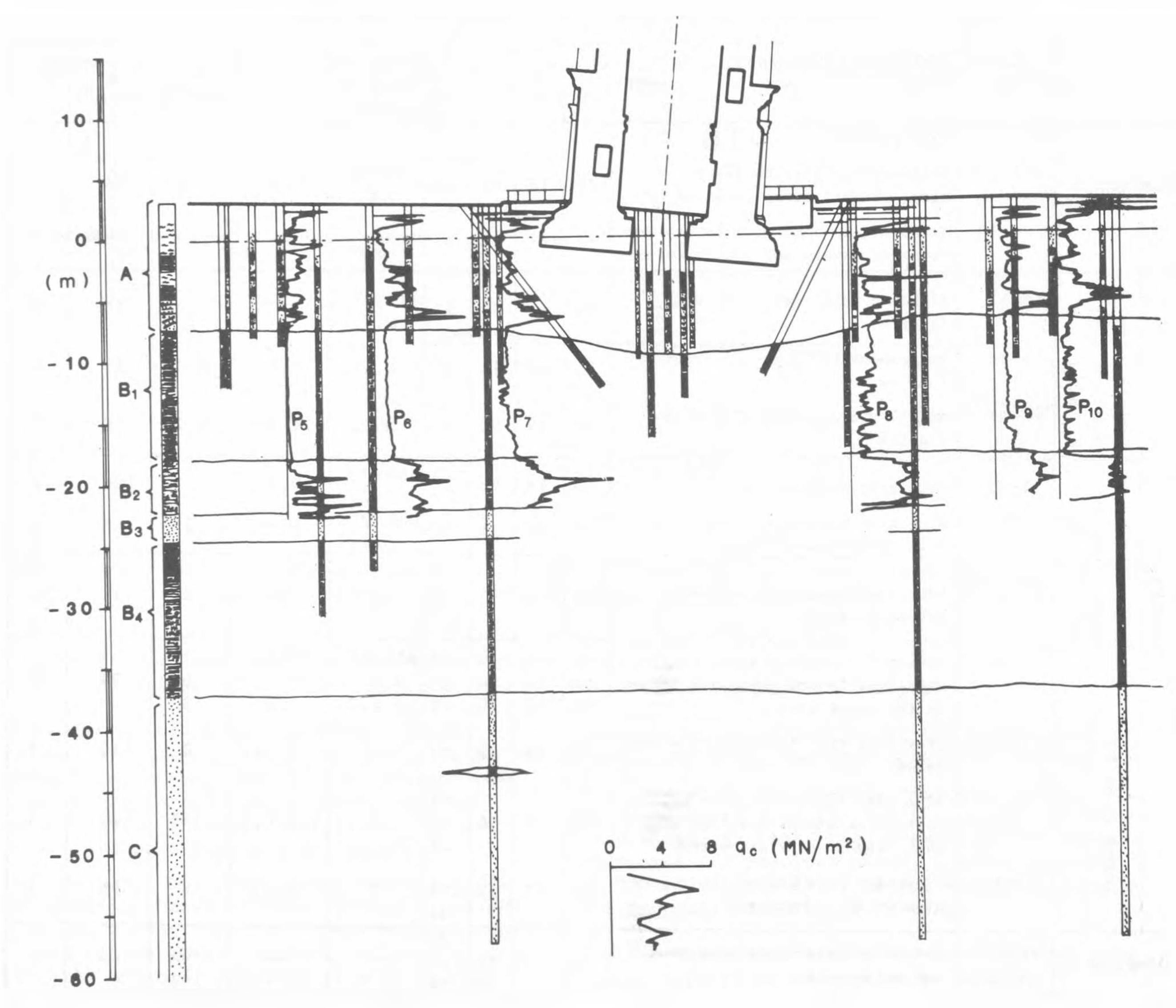

Fig. 3. Cross section of the subsoil of the Tower showing boreholes and cone penetration tests. Soils description and a summary of geotechnical properties are reported in Table I

clay lens, about 1 m thick, at a depth of 46 m.

Boreholes 302, 303 and 304, later carried out at a greater distance from the Tower (Fig. 4), allowed to ascertain that the main soil comple= xes A, B and C have a substantial continuity over a large area and the separation surface between B and C is almost plane. On the contra= ry, the stratigraphic subdivision of layer B which very uniformly applies to all the boreho= les in the Square was not generally found in the surroundings.

CHANGES IN THE ENVIRONMENT CONDITIONS

Possible connections between the behaviour of the Tower and changes of physical factors in its environment had been already considered in the past. Accordingly, at the end of 1965 a geodetic grid (Fig. 4) was set up in the surrounding Square (Piazza dei Miracoli) and on other monuments (Cathedral, Baptistry, ancient walls). Only since 1973, however, a systematic surveying was started at six months intervals.

Since all the measurements have been referred to a benchmark placed on the Baptistry (point ϕ' in fig. 4), only relative settlement can be inferred from them.

It has only recently been discovered that the whole Pisa plain is subjected to an extensive subsidence movement, the amount of which, how= ever, has been estimated only approximately (Palla, 1978). It should be presumed, therefore, that the Square is settling just as the surroun= ding area is but, since the level changes of the benchmark are unfortunately unknown, so are the total settlements of the Tower and the Squa= re. Taking apart the subsidence of Pisa plain, the results of the repeated surveying clearly

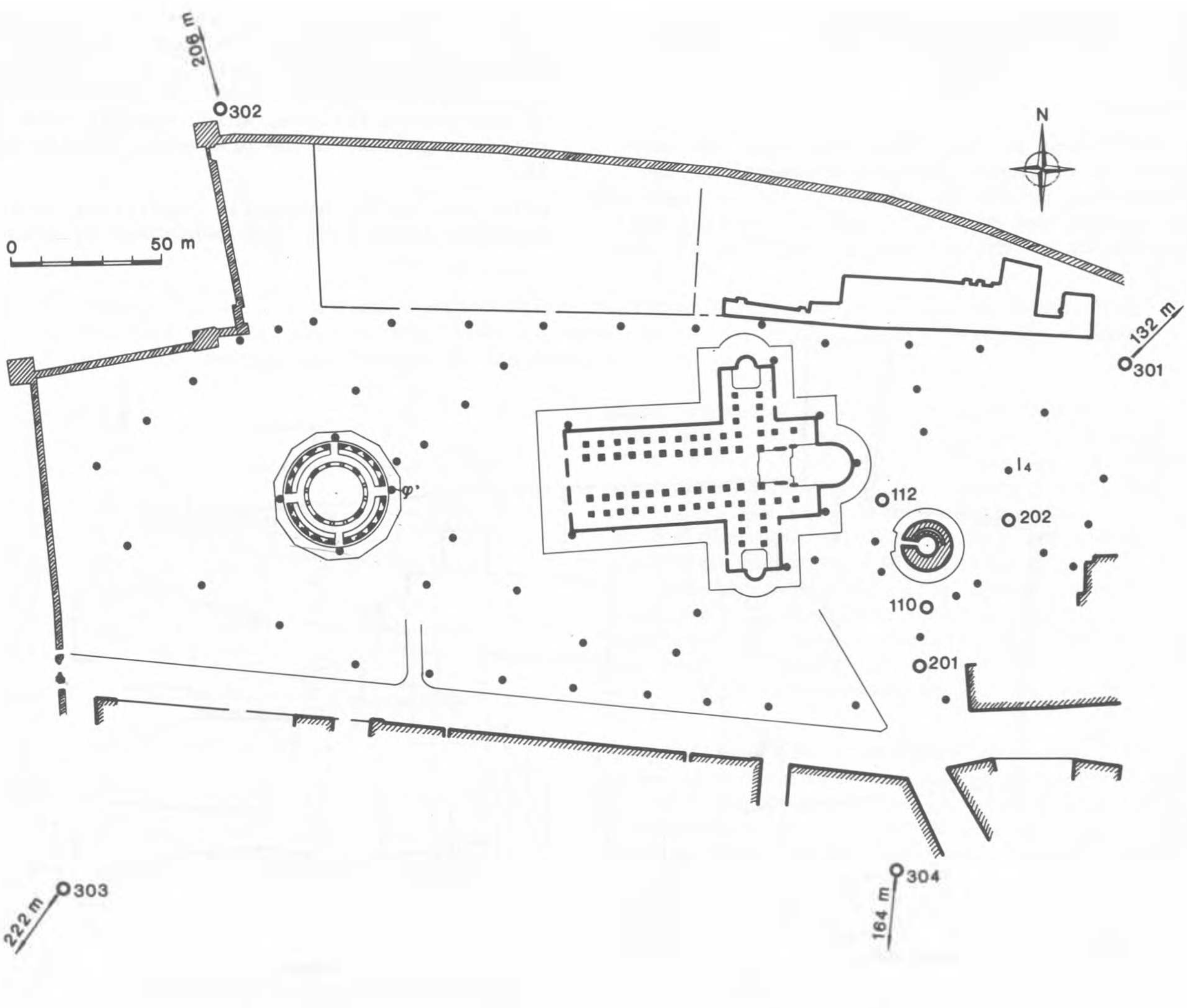

Fig. 4. Geodetic grid for settlement measurements (heavy dots) and location of piezometers (open dots). Fifteen measuring points on the tower basis are included in the grid, but are not shown in the figure

show that the Square is affected by some local phenomenon from which differential settlement arises.

In order to get a better picture of the beha= viour of the Square, the survey data from de= cember 1965 to may 1979 have been referred to the point of minimum settlement (point I_4 in fig. 4). The settlements relative to point I_4 are reported in fig. 5 as proportional vectors and clearly show the irregular deformation of the ground surface. The points which settle less are located in the northeastern part of the Square, close to the Tower, while the maximum settlement occurs along the southern boundary, between the Cathedral and the Baptistry.

Fig. 6 reports the progressive settlement from december 1965 to september 1973 and may 1979 along the three cross sections of the Square indicated in fig. 5.
It can be noticed that the settlement has an almost homogeneous increase: the points which settle less between 1965 and 1973 show the mini= mum increase also in the subsequent period, and viceversa.

The settlement of the Tower axis has been cal= culated by averaging the displacements of the 15 measuring points on its base, and is reported with a heavy dot in fig. 6. It may be seen that the presence of the monuments, particularly the Tower, with their very different structural cha= racteristics, has no apparent influence on the surface deformations; actually, both the lowest and the highest settlement occur in unloaded zones.

From sections Q-Q and R-R across the Tower, it becomes clear that, as a consequence of the ge= neral trend of the surrounding area, the Tower is subject to tilt both in the N-S and E-W di= rections, as was previously pointed (fig. 1). This fact results from fig. 7 too. Here the set= tlement of some significant point of the Square (Fig. 7a) and the rotation angles of two ortho= gonal alignements joining the points H-L and I-M across the Tower base (Fig. 7b) are plotted aga= inst time for the short period over which the Square has been surveyed at regular intervals. All these points, which include the Tower axis (T), the East Baptistry door (ϕ'), the Cathedral apse (20) and the point of maximum settlement (IV_5), like the others not shown in the figure, show a regular increase of settlement with time. Meanwhile, the average settlement of the Tower is accompanied by an almost proportional tilting of the ground surface, which results from the rotation angles in the orthoganal planes HL and IM.

Going now to the hydraulic conditions in the subsoil, these have been monitored by means of

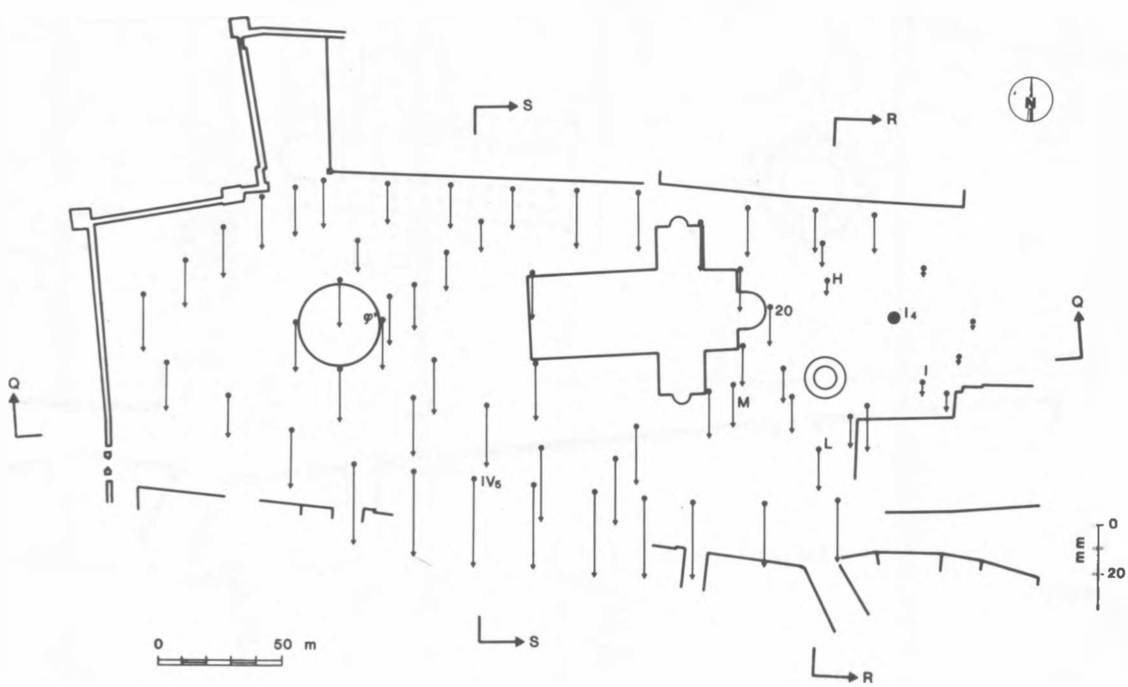

Fig. 5. Relative settlement referred to the benchmark I_4 from december 1965 to may 1979

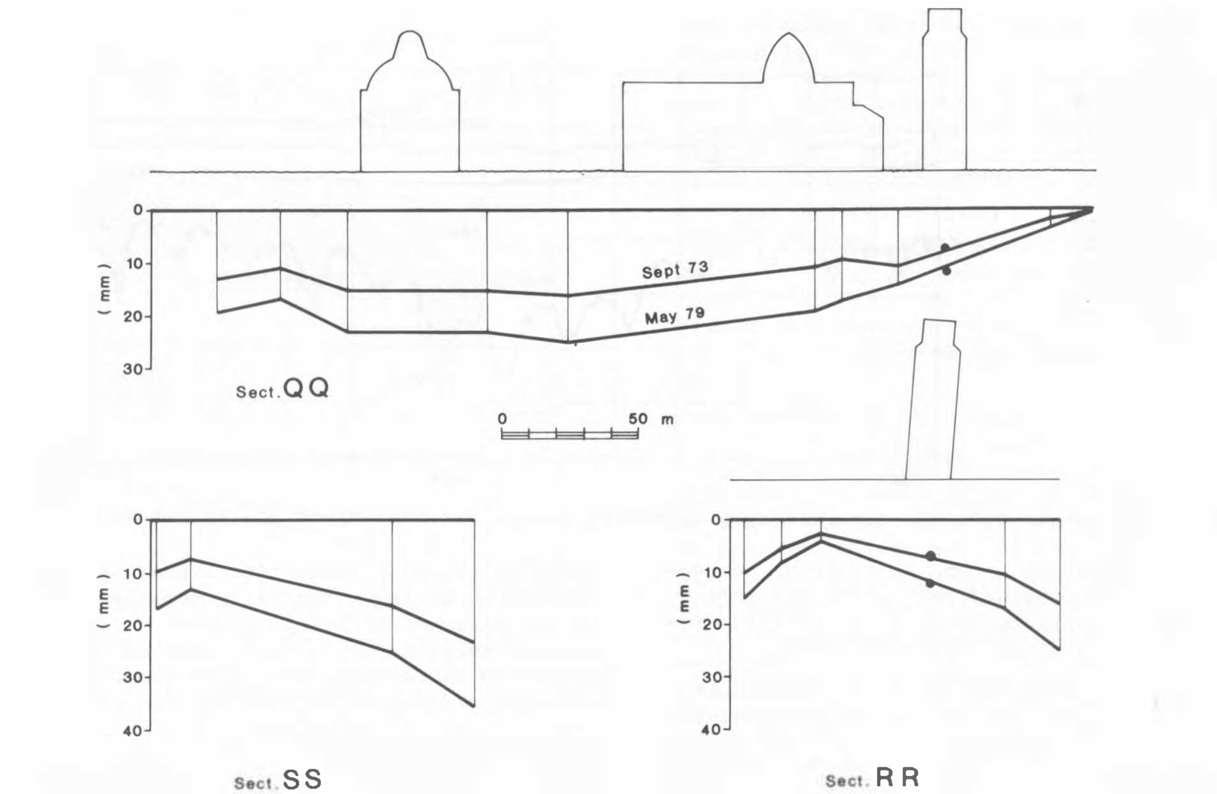

Fig. 6. Distorsion of the ground surface in the directions N-S and E-W since december 1965. The location in plan of the cross sections is shown in fig. 5. The heavy dots repre= sent the average settlement of the Tower.

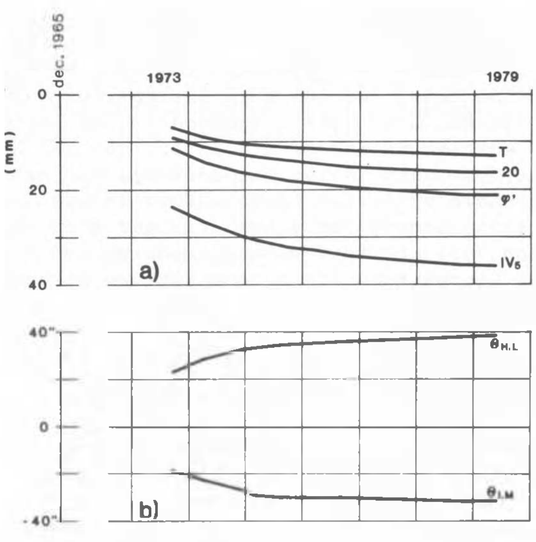

Fig. 7. Ground surface movements since decem= ber 1965. a) Relative settlement re= ferred to the benchmark I_4. b) Rota= tions.
The sign convention is the same as in fig. 1.

piezometers in the various soil layers. Piezometers 110 and 112 have been installed in 1966 (M.P.W. Commission, 1971); the remaining ones have been placed some years later. The lo= cation of all piezometers is reported in fig. 4. As the diagrams relating to all the piezometers placed in the Square (110, 112, 201, 202) are practically identical, only those installed in borehole 112 have been reported in fig. 8 to represent all them, together with the one loca= ted in layer A (201/1) and the two later instal= led in layer C outside the Square (301/3 and 304/3).

The diagrams are a condensed picture of the hy= draulic situation which characterizes the sub= soil of the Square. They show that the average piezometric level in the different layers decre= ases as their depth increases, passing from a constant value of about + 2,1 m above datum in layer A (201/1) to a variable level in layer C (112/3), always below the mean sea level. In layer B1 (112/1) the piezometric level is al= most constant at + 1,7 m, while in layer B3 (112/2) a smooth, long term variation occurs which seems to follow, at a greatly reduced sca= le, the mean trend of layer C. Here (112/3) the piezometric level has a marked

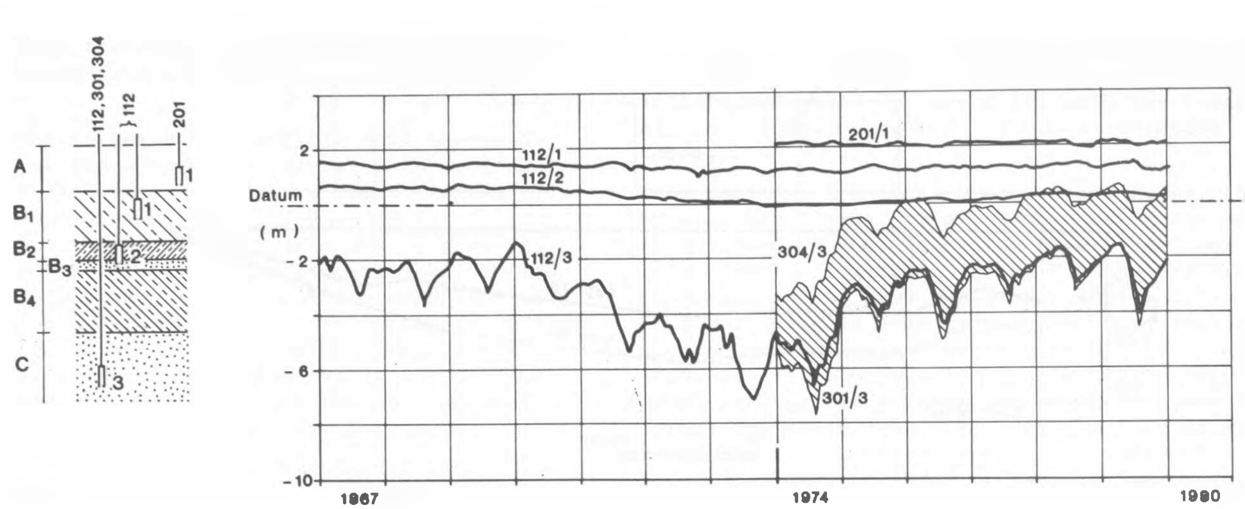

Fig. 8. Piezometric levels observed by piezometers in the various layers of the subsoil.

seasonal fluctuation around an unsteady average value. This one progressively decreases from about - 2 m in 1967 to about - 6 m in 1973, returning to the previous values in 1978.

The trend of piezometric levels in layer C is related to pumping from deep wells all over the Pisa plain. It is noteworthy that all the piezometers in layer C, including those at a great distance from the Square (301/3, 302/3, 303/3, 304/3), show the same fluctuation and maintain an almost constant difference, as could be expected given the permeability and continuity of layer C. However, the piezometers close to the Tower measure almost the lowest levels in the considered area.

MOVEMENTS OF THE TOWER AND SETTLEMENT OF THE SQUARE

An overall examination of the changes occurred in the environment of the Tower and the Square since 1967 clearly suggests the existence of a tight connection among the observed phenomena. The variations of the piezometric level in the lower sand, uniform over a large area, involve a one-dimensional consolidation of the overlying soil layers. Being their thickness constant, the differential settlement must be due to soil non-homogeneity.

The process has been simulated by means of an analytical consolidation model, which is one-dimensional, non linear and accounts for creep. The model has been described elsewhere (Burghignoli, 1979); it assumes that:

1. the effective stress-strain behaviour of the soil skeleton is represented by a viscoelastic logarithmic law;
2. the swelling index C_s is ten times smaller than the compression index C_c;
3. the permeability is related to the porosity by a logarithmic law.

Assuming the soil properties listed in Table I and taking as input the daily measured values of the piezometric level in layer C, a finite element solution was used to analyse the response of the overlying layers in terms of pore pressure at various points and settlement.

Taking into account that the deep wells identified near the Tower (M.P.W. Commission, 1971) began to operate at the end of fifties and that the majority of industries asking for pumped water underwent substantial developments in the same period, it has been supposed that the lowering of the piezometric level in layer C began in 1960.
Since the piezometric measurements are available only from 1966 onward, an assumption about the evolution of the process from 1960 to 1966 had to be done. Various such assumptions have been tested, but their influence on the calculated settlement increments after 1967 has been found to be very small. Accordingly, the assumption shown by dotted line in fig. 9a has been finally selected, featuring a linear decrease between 1960 and 1966 with a superimposed sinusoidal fluctuation having the same amplitude of the seasonal variations observed in the following years.

The piezometric level in the lower sand, as assumed from 1960 to 1966 and recorded from 1967 onward, is reported in fig. 9a. Corresponding piezometric levels at different depths in the lower clay, and settlement, as predicted by the model, are plotted respectively in figs. 9b and 9c. Since the compressibility of the layer B4 has a significant effect on the computed settlement, the calculation has been repeated for two values of $CR = C_c/(1+e_o)$, which bound the range of experimental data.

It has been already noticed that the piezometric level in the upper layers is not affected by the seasonal fluctuations in the lower sand, while

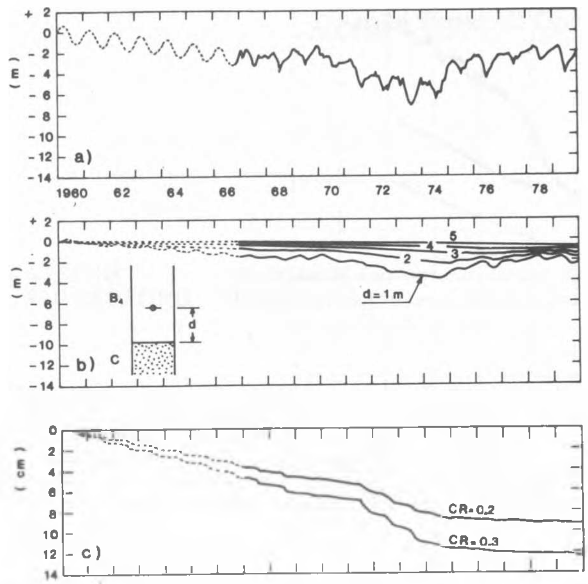

Fig. 9. Results of one-dimensional consolidation analysis. a) Piezometric levels in lower sand, used as input in the analysis. b) Piezometric levels (in m above datum) within lower clay. c) Settlement of ground surface for two different values of CR of layer B4

is slightly influenced by the long term trend (fig. 8). For the examined conditions, the model predicts a rapid smoothing down of the head variation at a very short distance from the layer boundary (fig. 9b). Therefore, as already said, only the bottom part of the lower clay should have been influenced by the piezometric level changes in the lower sand.

Similar conclusions can be drawn for the settlement. By incorporating soil inelasticity and creep effects, the consolidation model predicts the irrecoverable strain produced by a closed loop change of pore pressure. Therefore, the increase of piezometric level in layers C and B4, that occurred after 1974 (figs 9a and 9b) is not followed by a reverse deformation (fig. 9c). The same trend has been observed in the Square settlement (fig. 7).

Since only the bottom part of layer B4 is involved in the consolidation process, the differential settlement recorded at the ground surface should be ascribed to its non-homogeneities. These could arise from differences in the average compressibility among different verticals and/or from a different position of more compressible or permeable levels within layer B4. Anyway, it may be noted that the difference between the settlement calculated with the range limits of layer B4 compressibility (fig. 9c) is nearly equal to the maximum differential settlement recorded from 1965 to 1979 (between points IV_5 and I_4, fig. 7).

In this connection, it is noteworthy that a series of finite elements calculations has shown that, for the geometry and the properties of Pisa subsoil, a distortion occurring at a depth of 40 m is transmitted to the surface with no sensible attenuation.

Finally, coming back to the rotation of the Tower, an attempt has been done to isolate the effects of differential settlement of the surrounding ground from the long term rotation increase, characteristic of the Tower behaviour (Croce, 1978).

The rotations of the ground surface in N-S and E-W directions, across the base of the Tower (θ_{HL} and θ_{IM}, fig. 7b), have been subtracted from the corresponding rotations α_{NS} and α_{EW} of the Tower, measured by the pendulum inclinometer. The results are plotted in fig. 10.

It can be easily remarked that the corrected E-W tilt diagram is parallel to the line extrapolating the trend of the period 1950-1960, and very close to it. It seems, therefore, that the ground surface rotation is simply added to the Tower rotation.

On the contrary, in the N-S plane the correction results in a line somewhat diverging from the corresponding extrapolation of the 1950-1960 trend. The corrected tilt diagram seems rather to fit the trend of the Tower inclination in the late sixties.

The type of data available and the relative brevity of the period of observation do not allow a definite conclusion; however, it seems that, in the direction of the maximum Tower inclination, the rotation of the ground has an amplifying effect on the inclination of the Tower.

SUMMARY AND FINAL REMARKS

The results of the observations made in the last decade on the Tower of Pisa and the surrounding Square and monuments have been reported and discussed.

Particular relevance is to be ascribed to the changes of piezometric level occurring in the lower sand because of pumping from deep wells. The observation period, though relatively short, appears to be rather significant from this viewpoint, since it includes a sensible decrease of the piezometric level, followed by an increase.

A simple one-dimensional consolidation analysis points out that the pore pressure decrease affects only the bottom part of the lower clay.

Although the piezometric level variations are fairly uniform in the Square area, they give rise to differential settlement at the ground surface, due to soil non-homogeneities.

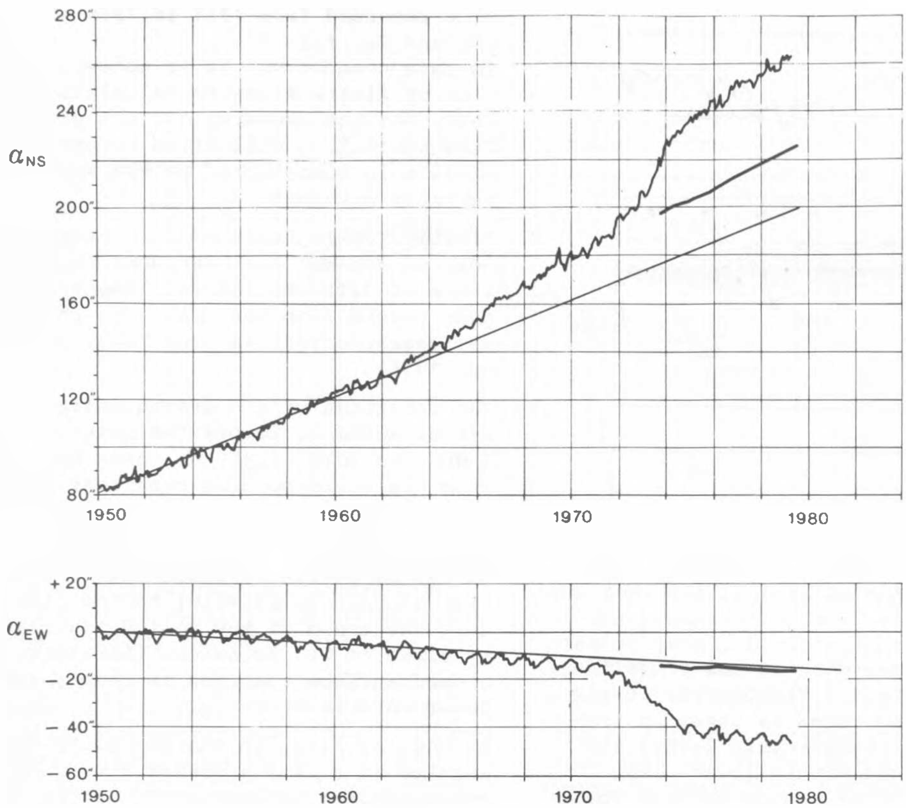

Fig. 10. Influence of the changes of environment conditions on the movements of the Tower. The thin straight lines extrapolate the 1950-1960 trend; the thick lines between 1973 and 1979 are the corrected tilt diagrams.

The results of the analysis, in terms of pore pressure and settlement, seem to agree with the available data on the behaviour of the Square.

As a consequence of the differential settlement, an increase of the Tower inclination rate oc= curs, together with a change of its kinematic characteristics.

The prompt response of the Tower to changes in the environment conditions should be pointed out. Accordingly, a tighter control of the pie= zometric level in the lower sand, still affec= ted by pumping from deep wells, is of the utmost importance; initiatives on this line are being taken by the Ministry of Public Works.

On the other hand, the preceding analysis sug= gests that a positive correction of the present trend could be possibly achieved by means of slight adjustments of the environment conditions.

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