Electro-osmosis to stabilise the leaning Tower of Pisa

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Abstract

The Tower of Pisa was affected by leaning instability, a phenomenon controlled by the stiffness of the subsoil, rather than by its strength. In order to permanently stabilise the monument, while keeping an absolute respect of its integrity, the International Committee appointed by the Italian government reduced its inclination by half a degree, that is less than 10% of the inclination in the early '90s, amounting to 5.5 degrees. Among the possible means to achieve this result, the Committee selected a controlled removal of soil from below the "high" side of the foundation (underexcavation). In an early stage, electroosmotic consolidation of a soft clay layer known as Pancone was considered.

The paper briefly reports the analyses and experimental investigation carried out to explore this solution, including a large scale field experiment. The reasons why the technique was rejected are finally outlined.

1. Introduction

A cross section of the leaning Tower of Pisa is shown in Fig. 1. The tower weight is 141.8 MN. The average foundation pressure is 497 kPa. In the early 1990's the foundation plane was inclined southwards at about 5.5° to the horizon, with an overhang of the seventh cornice above the first cornice (points V_7 and V_1) by about 4.1 m. The inclination of the tower was steadily increasing at a rate of 6 to 8 arc seconds per year.

Fig. 2 shows the ground profile underlying the tower. It consists of three distinct horizons. Horizon A is about 10 m thick and primarily consists of rather variable sandy and clayey silts, laid down under tidal conditions. At the bottom of Horizon A there is a 2 m thick layer of medium dense fine sand.

Horizon B consists mainly of marine clay and extends to a depth of about 40 m. It is subdivided into four distinct layers. The upper layer is a soft sensitive clay locally known as the Pancone. It is underlain by an intermediate layer of stiffer clay, which in turn overlies a sand layer. The bottom layer of horizon B is a normally consolidated clay. Horizon B is laterally very uniform in the vicinity of the tower, but the upper surface of the Pancone clay is dished beneath the tower, from which it can be deduced that the average settlement of the monument is approximately 3 m.

Horizon C is a dense sand which extends to considerable depth.

Fuller details about the tower, its history and its subsoil can be found elsewhere [e.g.: BURLAND *et al.*, 1999].

In 1990 the Italian Government appointed an International Committee for the safeguard and stabilisation of the Tower, the last of a long series. It was conceived as a multidisciplinary body whose components were experts of art, restoration, materials, structural engineers and geotechnical engineers. Over ten years the Committee has developed a detailed understanding of the behaviour of the tower since its construction in the Middle Ages and particularly from the beginning of the XX century, when a comprehensive instrumental monitoring has started.

The Committee has been exploring a number of approaches to permanently stabilise the Tower. The fragility of the masonry, the sensitivity of the underlying clay and the marginal stability of the foundation impose severe restraints. Any measures involving the application of concentrated load to the masonry or underpinning operations beneath the south side of the foundation have thus been ruled out. Moreover conservation considerations require that the impact of stabilising measures on the formal, historical and material integrity of the monument should be kept to an absolute minimum.

The behaviour of the Tower indicates that its equilibrium is affected by leaning instability, a phenomenon controlled by the stiffness of the subsoil rather than by its strength [GORBUNOV POSSADOV, SEREBRAJANYI, 1961; SCHULTZE, 1973; LANCELLOTTA, 1993; NOVA, MONTRASIO, 1995; DESIDERI *et al.*, 1997]. The analysis of the leaning instability, taking into account the non elastic and non linear restraint exerted by the foundation, shows that a limited decrease of the inclination of the tower would greatly increase its safety and stop the progress of inclination. After a long and detailed discussion the Committee decided to give priority to "very soft" solu-

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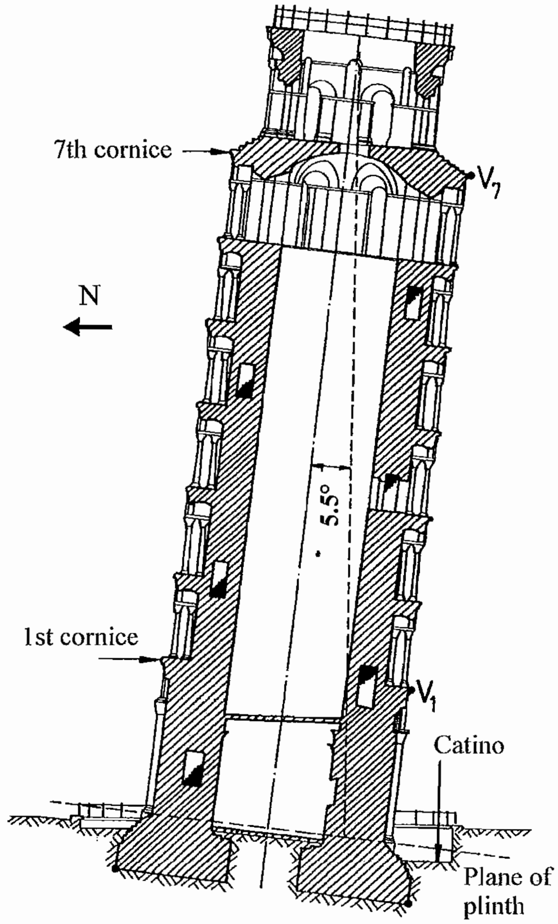

Fig. 1 – Cross section of the leaning Tower of Pisa in the plane of maximum inclination (i.e., very nearly, in the plane north – south).
Fig. 1 – Sezione della torre nel piano di massima pendenza.

tions, reducing the inclination of the tower by up to half a degree (i.e. by about 10% of the maximum inclination) by means of an induced settlement beneath the north side of the foundation, without even touching the structure of the Tower. The Committee gave careful consideration to a number of possible approaches to reach this goal, such as loading the soil surface north of the tower by means of a ground pressing slab loaded by tensioned ground anchors, or consolidating the Pancone clay by means of vacuum pumping or electro-osmosis. Eventually the choice was that of a controlled removal of small volumes of soil from beneath the north side of the foundation (underexcavation; see, e.g.: BURLAND *et al.*, 2000); at present (January 2002) this solution has been successfully completed.

The present paper reports the analyses and experimental investigations carried out to explore the applicability of the electro-osmosis to the stabilisation of the Tower, outlining also the reasons why the technique was finally rejected.

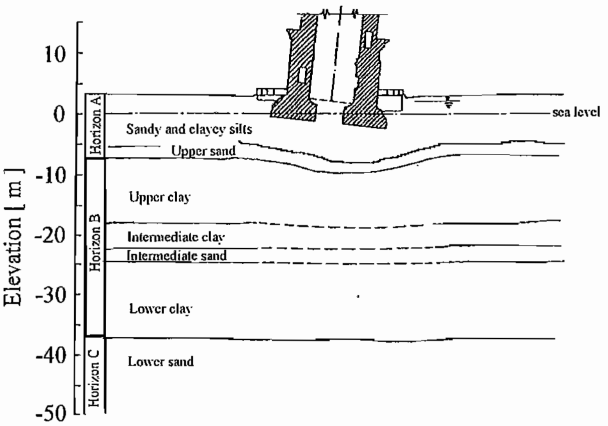

Fig. 2 – Subsoil profile below the tower.
Fig. 2 – Profilo stratigrafico in corrispondenza della torre.

2. Preliminary analyses

The application of electro-osmosis to the stabilisation of the Tower was originally proposed by CALABRESI *et al.* [1992] and by MITCHELL [1991]. The idea was to produce a volume reduction of the Pancone clay to the north of the Tower and beneath the north side of the foundation by electro-osmotic consolidation. Three aspects have been analysed: electrodes arrangement; possibility of reducing the tower inclination of the required value; energy consumption. Fig. 3 shows the arrangements investigated. In order to choose the most efficient arrangement, several numerical analyses have been carried out. These analyses were based on the Esrig's theory of one-dimensional electroosmotic consolidation with the electrodes modelled as continuous surfaces [CALABRESI *et al.*, 1992].

The results of the analyses in terms of time development of negative excess pore pressure at anodes are reported in Fig. 4. The layout of electrodes with cathodes along the arc of circumference C2 and anodes on the arc A2 revealed the most efficient one in terms of rate of development of negative excess pore pressure.

Since the development of negative excess pore pressure within a compressible medium is followed by a volume reduction by consolidation, a differential settlement results. Such a settlement may be used to obtain a decrease of the inclination of the tower.

A preliminary uncoupled analysis of the settlement induced by the electroosmotic consolidation [CALABRESI *et al.*, 1992] showed that a tilt reduction up to half a degree was possible, provided a pore pressure decrease within the Pancone clay of 150 kPa was reached (Fig. 5). The analysis was based on the assumptions that the tower behaves as a rigid body and the southern edge of the foundation does not settle; furthermore, the influence of Horizon A was neglected.

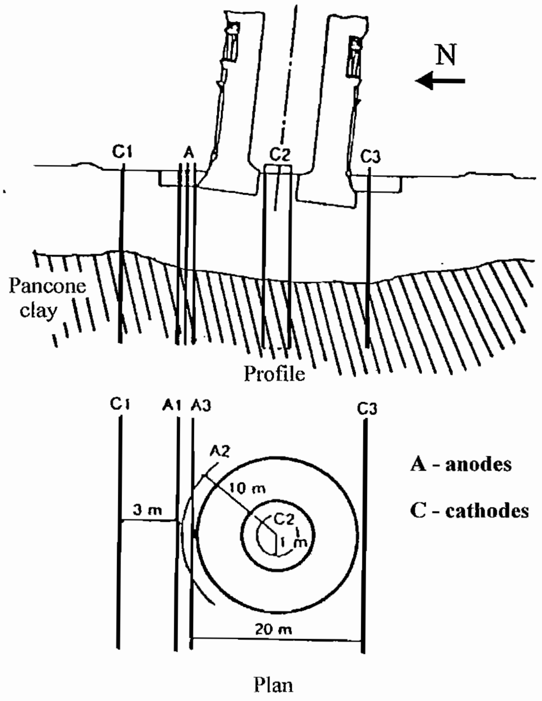

Fig. 3 – Electrodes arrangements considered in the preliminary analyses.
Fig. 3 – Disposizioni degli elettrodi considerate nelle analisi preliminari.

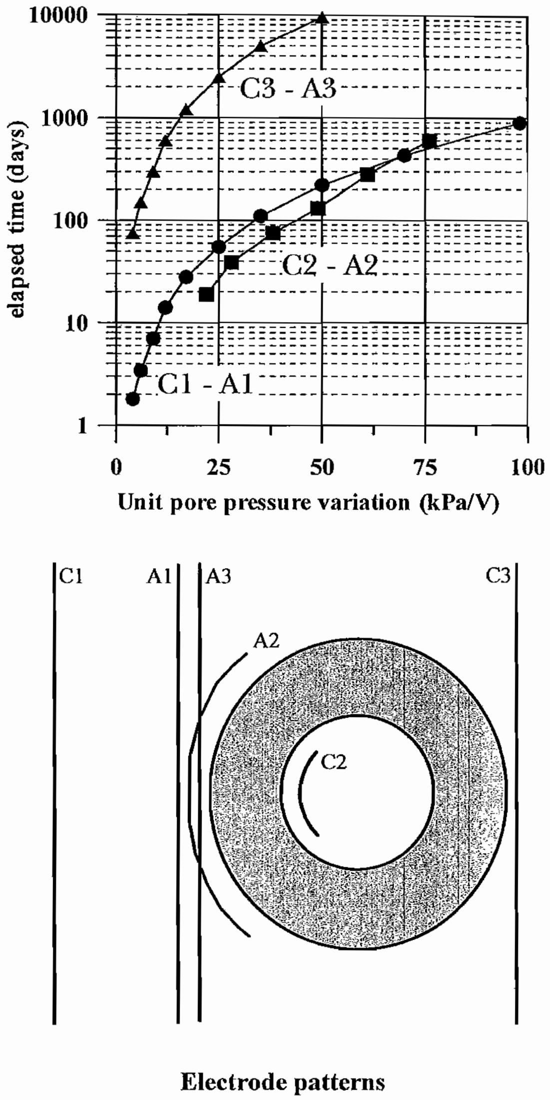

Fig. 4 – Variation of unit pore pressure with time and with different electrode patterns [after CALABRESI *et al.*, 1992].
Fig. 4 – Variazione unitaria della pressione neutra nel tempo per diverse disposizioni degli elettrodi [da CALABRESI et al., *1992].*

In order to predict the electrical current required and to design the electrical set up, the knowledge of soil resistivity was needed. Laboratory measurements of resistivity of the Pancone clay were carried out in a modified oedometer [TAMAGNINI, 1994]. The measured values of the resistivity were in the range between 9 and 17 ohm per meter (Ωm) depending on void ratio (Fig. 6).

The encouraging results of these preliminary evaluations suggested the implementation of a large scale electro-osmosis field test in order to assess the influence of the actual conditions and develop technological details.

3. Field experiment

The lay out of the field experiment is reported in Fig. 7. Electrodes of the same polarity are installed along four concentric circular arcs with an opening of 90°. Being the treatment intended only in the Pancone clay, the electrodes which were 24 m long, were electrically insulated from the surrounding soils between the ground surface and the depth of 11 m. They consisted of steel tubes with an outer diameter of 40 mm (Fig. 8). In the span corresponding to Pancone, between the depths of 11 and 24 m, the tubes were perforated to collect the water flowing to the cathodes as a consequence of electro-osmosis. The test program included the inversion of the polarity of the electrodes, since this is known to increase the effectiveness of the treatment [WAN, MITCHELL, 1976]; all the electrodes were thus equal. The electrical installation included three AC/DC converters and stabilising units. The total power installed was over 50 kW. The discharge at the electrodes could be collected and measured by means of a special system, or alternatively the drainage could be closed.

The instrumentation of the field test also included 36 pore pressure transducers, 36 thermocouples, 8 Casagrande type piezometers, 9 multipoint extensometers, 2 single point settlement meters, 18 surface settlement probes and 12 electrical potential measuring probes.

The electrodes could be connected in different patterns, in order to modify the boundary conditions of the electro-osmosis experiment.

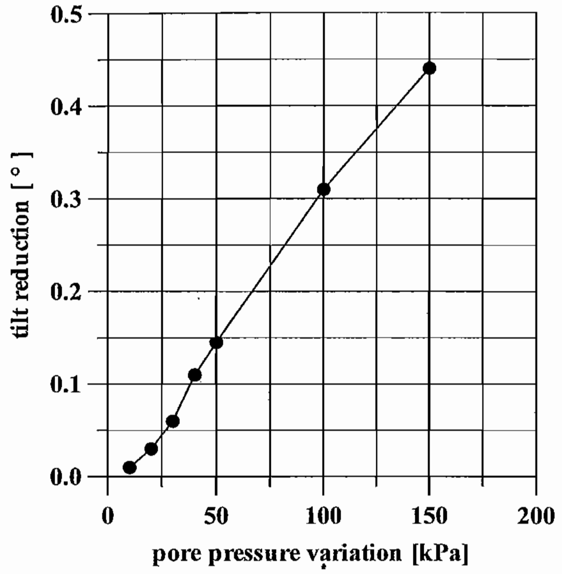

Fig. 5 – Tilt reduction with pore pressure variation [after CALABRESI *et al.*, 1992].

Fig. 5 – Riduzione della pendenza in funzione della variazione di pressione neutra [da CALABRESI et al., *1992].*

Two main tests have been carried out. The overall duration of the tests, including the preparatory work, was about one year. The original test program was to apply a potential difference up to 60 V connecting the electrodes in different patterns. The first test involved 30 electrodes out of the 33 installed. The arcs B and D (Fig. 7) were the sealed anodes and arc C was the draining cathode. It was soon realised that the resistivity in situ was lower than that measured in laboratory tests. In fact, a maximum potential difference of 26 V has been attained instead of 60 V planned. During the first 12 hours of the test a flow rate of about 850 dm^3/d has been measured (Fig. 9). After this short period the flow rate dropped to about 80 dm^3/d. In the mean time a leakage of mud from cathodes has been observed. After a period of about 15 days, since the flow rate dropped to 30 ÷ 40 dm^3/d, the test was interrupted.

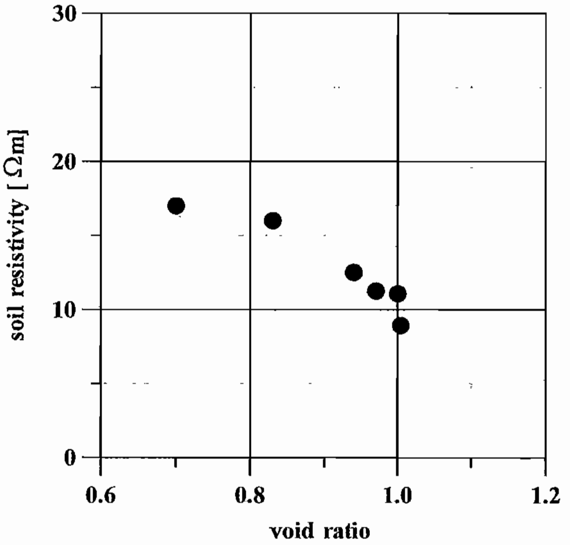

Fig. 6 – Soil resistivity as function of void ratio from laboratory measurements in a special oedometer (after CALABRESI *et al.*, 1992).

Fig. 6 – Resistività del terreno misurata in laboratorio con un edometro modificato in funzione dell'indice dei vuoti (da CALABRESI et al., *1992).*

Figure 10 shows some excess pore pressure measurements and the location of the instruments. Contrary to the predictions based on Esrig's theory, the pore pressure actually decreased by up to 80 kPa only in a restricted zone close to the anodes, and it unexpectedly increased by up to 30 kPa in the remaining volume of soil. As the current was switched out, the excess pore pressures tended to dissipate. Piezometers installed externally to the treated volume of soil, indicate that the influence of electrical current is not confined to the space between the electrodes.

Numerical simulations carried out after the first test [SQUEGLIA, 1995] revealed that the spacing between the electrodes along an arc is too large to confine the effects of the electro osmosis to the volume of soil between the electrodes of different polarity (i.e., each arc behaves as a grid of electrodes, not as a continuous surface). Another consequence of the large spacing of the electrodes is the low

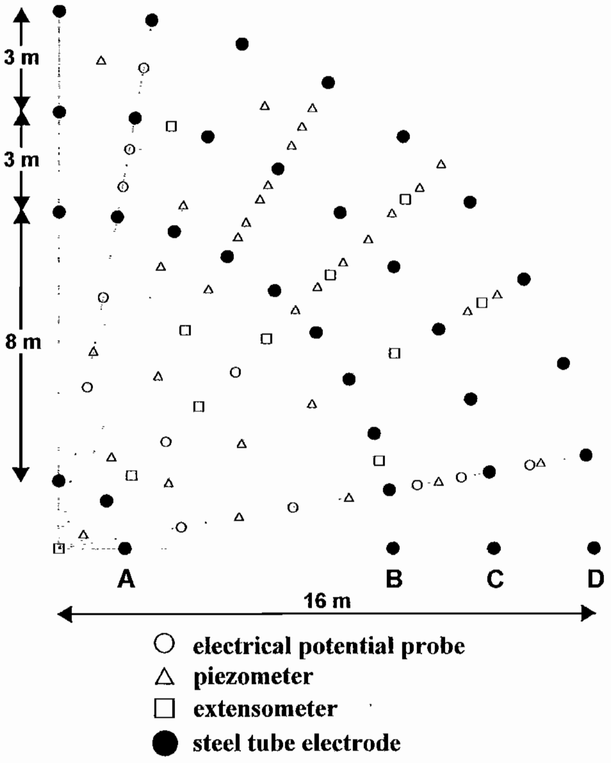

Fig. 7 – Lay out in plan of the field experiment of electro-osmosis.

Fig. 7 – Disposizione della strumentazione e degli elettrodi del campo sperimentale.

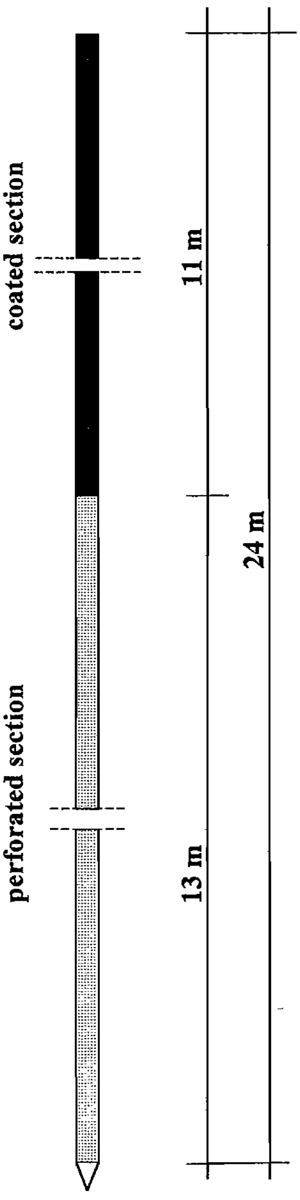

Fig. 8 – Scheme of electrodes.
Fig. 8 – Schema dell'elettrodo.

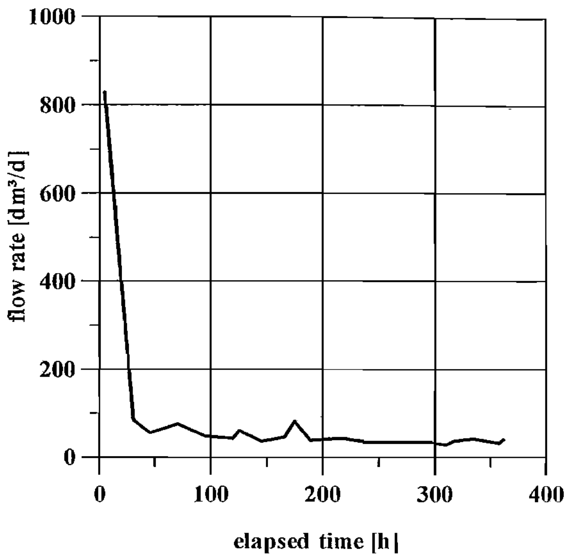

Fig. 9 – Flow rate at the cathodes during test no. 1.
Fig. 9 – Portata totale misurata ai catodi durante la prima prova.

electrical gradient in the soil mass. In fact, the same simulations showed that the greater is the spacing between the electrodes of the same polarity the lower is the electrical gradient in the soil mass. The phenomenon has been observed during the first test. In figure 11, which shows the measurements carried out during the first test, the reduction of electrical potential gradient in the soil mass between arc B and arc C is quite clear.

In order to increase the electrical gradient in the soil, a second test involving only 9 out of 33 electrodes was planned (Fig. 12). Eight Casagrande type piezometers and fifteen electrical potential probes were added in the vicinity of the electrodes in the test area, to obtain more detailed information. In the mean time the in situ soil resistivity was measured by means of a special probe along 4 vertical. Figure 13 reports one of the measured resistivity profiles; the remaining ones are practically equal to the one shown. Field measurements showed thus that the resistivity of Pancone clay was in the range from 2 to 3 Ωm instead of about 15 Ωm previously obtained by laboratory tests.

In the configuration of the second test it was possible to apply an electrical potential difference of 55 V in both circuits, and the average gradient was 0.19 V/cm. As in the previous test, the flow rate was very high during the first hours of the experiment, and again it dropped to negligible values in a few days (Fig. 14).

Figure 15 shows the values of excess pore pressure recorded by some electrical piezometers and their locations. Once more the excess pore pressures were positive and reached the remarkable value of 100 kPa. Negative values of excess pore pressures were again measured in the vicinity of the anodes, reaching the value of 150 kPa. Measurements by Casagrande type piezometers were meaningless, being attacked by the occurrence of a foam in the cells.

Measurements of the electrical potential confirmed that a high loss of potential occurs in the vicinity of the electrodes, both for anodes and cathodes, and hence a reduction of the electrical gradient in the bulk of the treated soil. At the beginning of the second test, the intensities of current which circulates in the two circuits were in the range from 400 to 450 A. As a consequence the current density at the cathode-soil interface reached the remarkable value of 170 A/m^2. These high current induced a considerable heating of the soil. Figure 16

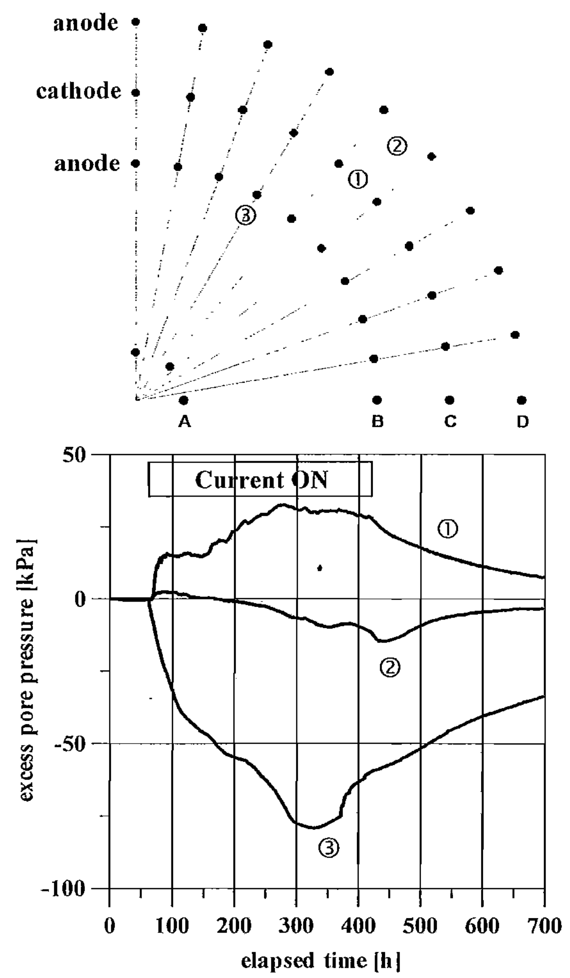

Fig. 10 – Excess pore pressure generated during the test n. 1.

Fig. 10 – Sovrappressioni neutre generate durante la prima prova.

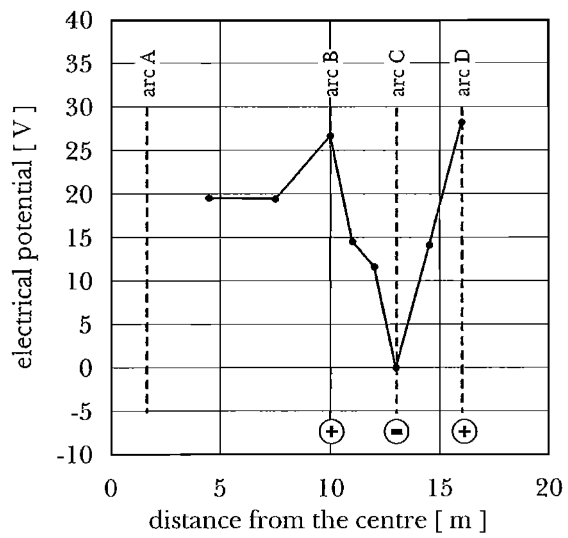

Fig. 11 – Measurement of electrical potential along a radius.

Fig. 11 – Misura del potenziale elettrico lungo un allineamento radiale.

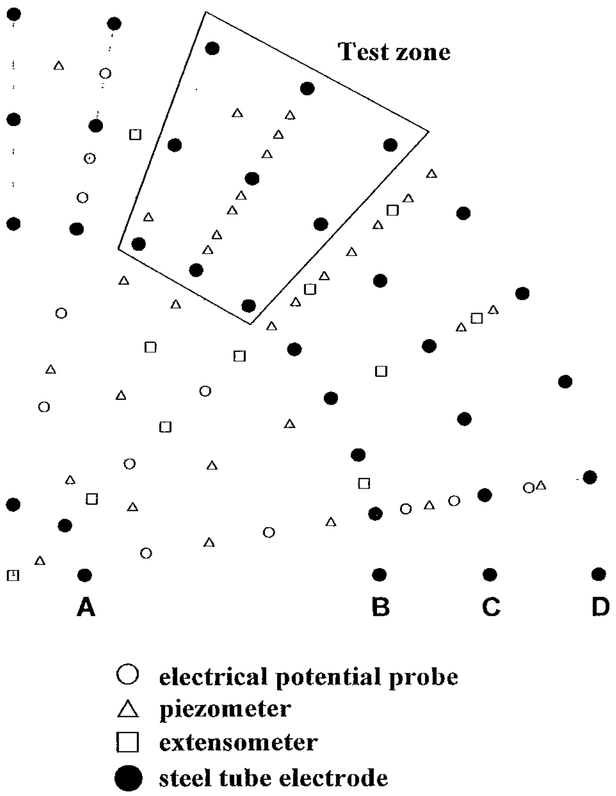

Fig. 12 – Layout of test no. 2.

Fig. 12 – Disposizione della strumentazione per la prova n. 2.

shows the temperature values recorded by a thermocouple installed in the vicinity of an electrode; the average temperature variation in the treated soil was about 10 °C.

The settlements measured during both tests at the surface and in the soil mass were negligible. Besides, measurements at the surface were affected by some disturbance due to archaeological excavation and subsequent re-filling carried out earlier. The negligible amount of settlements had to be expected since the discharge of water at cathode has been very small in both tests in comparison to the treated volume of soil (i.e. less than 0.15%).

Discussion

On the whole, the results of the field experiments were rather disappointing in terms both of the agreement with predictions and the efficiency of the process.

The main factor responsible for the disagreement between predictions and performance has been the actual electrical resistivity of the soil in situ, which is almost one order of magnitude lower than that evaluated by laboratory tests. As a consequence, the current density during the tests reached values much hi-

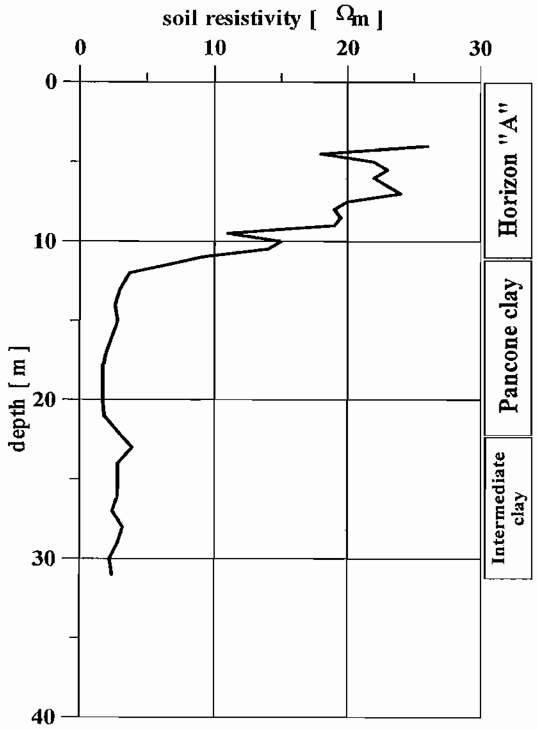

Fig. 13 – Field measurements of the electrical resistivity of the soil.
Fig. 13 – Misura in sito della resistività elettrica del terreno.

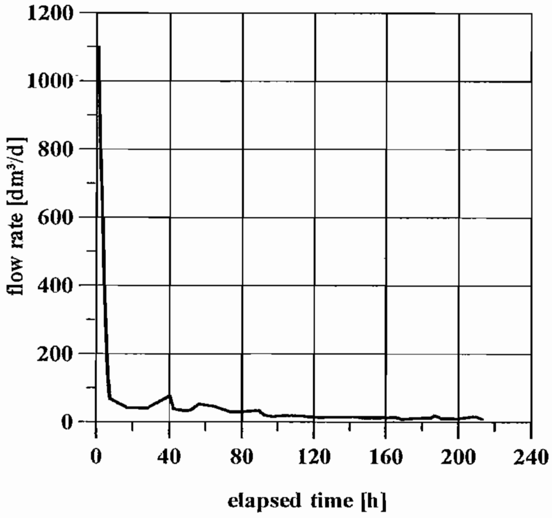

Fig. 14 – Flow rate at cathodes during the test no. 2.
Fig. 14 – Portata totale misurata ai catodi durante la seconda prova.

gher than foreseen, and greatly exceeding the limits indicated in literature [BJERRUM *et al.*, 1967].

As it is well known, in any electroosmotic process a number of electrochemical phenomena occur at the interface between the soil and the electrodes, such as gas generation at the electrodes and subsequent desaturation of the soil, dissolution of the electrodes' metal, strong variation of the pH due to

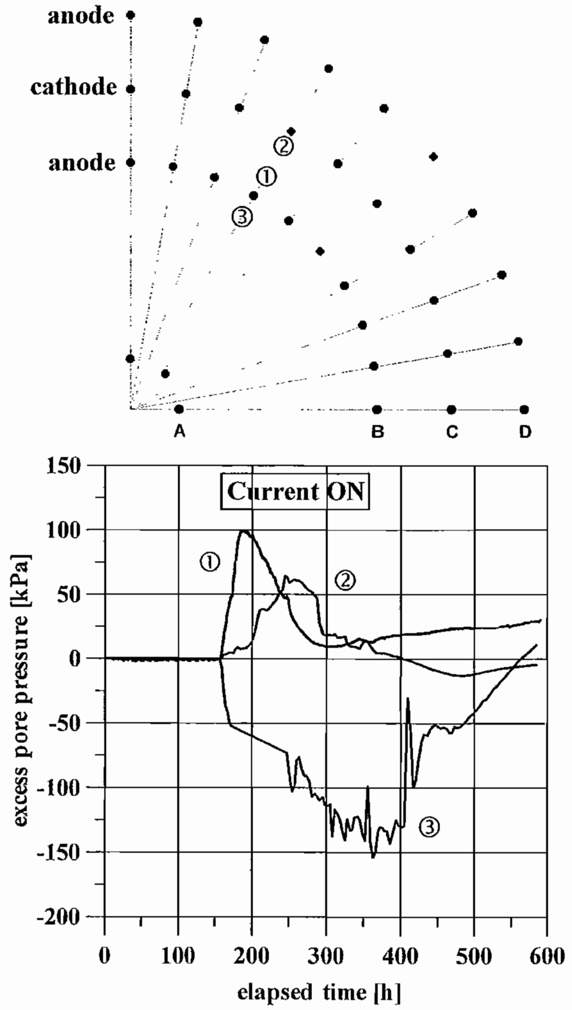

Fig. 15 – Excess pore pressure generated during the test no. 2.
Fig. 15 – Sovrappressioni neutre generate durante la seconda prova.

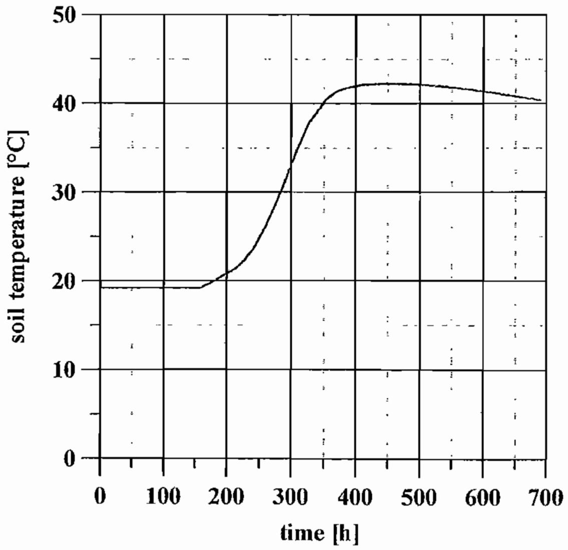

Fig. 16 – Temperature measurement during the test no. 2.
Fig. 16 – Temperatura misurata nel terreno durante la seconda prova.

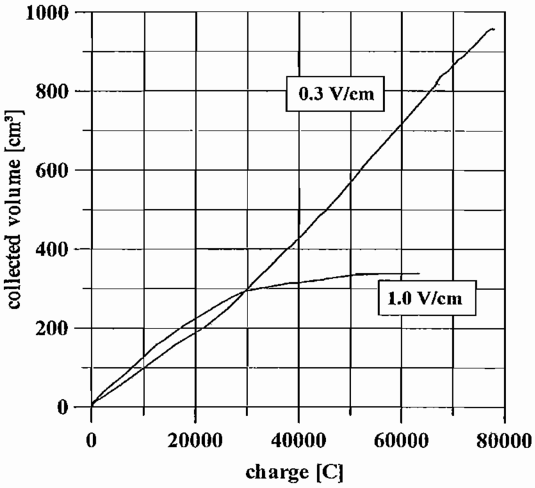

Fig. 17 – Laboratory experiments of electro-osmotic filtration. Variation of flow rate with different electrical gradients [after Squeglia, 1998].

Fig. 17 – Prove di filtrazione elettroosmotica. Variazione del flusso in funzione del diverso gradiente elettrico applicato [da Squeglia, 1998].

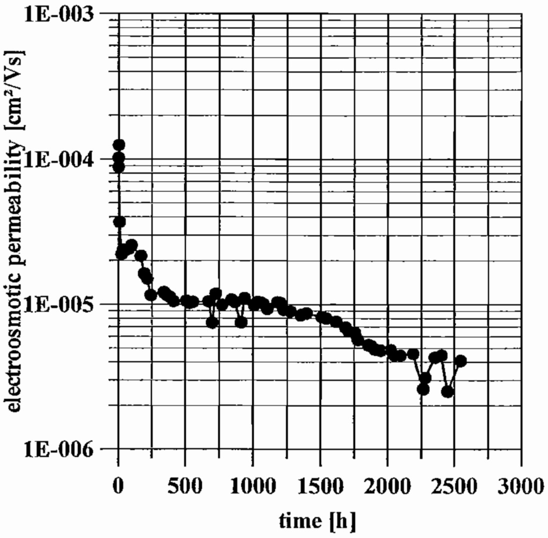

Fig. 18 – Variation of the electro-osmotic permeability in the laboratory experiments [after Squeglia, 1998].

Fig. 18 – Variazione della permeabilità elettroosmotica durante una prova di laboratorio [da Squeglia, 1998].

electrolysis, heating by Joule effect; their intensity is roughly proportional to the circulating current. The variation of concentration of ionic species in the ground water due to the above phenomena leads to a change in electro-kinetic properties of soil [Williams, Williams, 1977; Eykholt, Daniel, 1994; Squeglia, 1998]. In the field experiment at Pisa, such phenomena played a substantial role since they are all opposing the electro-osmotic flow, eventually bringing it to a complete stop.

Laboratory tests have been carried out later on the Pancone clay [Squeglia, 1998], to clarify the matter; they confirmed that the electro-osmotic flow rapidly ceases when the electrical gradient is high (Fig. 17). In the samples subjected to electro-osmotic filtration tests with a low electrical gradient, the phenomenon is rather stable in time, while it is rapidly evolving when the potential difference is high. The same experiments have revealed that the distribution of the electrical potential within the sample changes in time, with the gradient increasing in the vicinity of the electrodes.

The electro-osmotic permeability, i.e. the ratio between the velocity of filtration and the electrical gradient, is not a constant soil characteristic, as assumed by Esrig [1968] and Mitchell [1993]; actually it varies during the process (Fig. 18) as a consequence of the phenomena associated to the electro-osmosis [Eykholt, Daniel, 1994; Squeglia, 1998].

Concluding remarks

The analyses carried out after the tests revealed that a more efficient configuration of electrodes was indeed possible. The model applied in the analyses, however, was not able to take into account the electrochemical phenomena associated to electroosmosis. This was the reason why a field tests was believed to be indispensable.

A more efficient configuration of the electrodes and different boundary conditions would have improved the efficiency of the process. In any case, with reference to the stabilisation of the leaning tower, the occurrence of phenomena such as an increase in pore pressure is extremely dangerous. It appears that the process is not yet sufficiently understood to be completely controllable, and therefore no further investigations have been carried out and the use of electro-osmosis as a means to stabilise the leaning Tower has been ruled out.

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L'elettroosmosi per la stabilizzazione della Torre di Pisa

Sommario

La stabilità della Torre di Pisa era legata ad un fenomeno di instabilità dell'equilibrio, noto come "leaning instability" e controllato dalla rigidezza, e non dalla resistenza, dei terreni di fondazione. Per la stabilizzazione del monumento nel rispetto dei criteri del restauro, il Comitato preposto agli interventi di consolidamento e restauro ha operato riducendone l'inclinazione di circa mezzo grado. Tra le diverse proposte prese in esame per ottenere questo risultato, come è noto, dopo approfondite analisi e verifiche sperimentali fu selezionata la sottoescavazione; inizialmente venne però approfondito lo studio anche di altre possibilità, fra le quali l'impiego dell'elettroosmosi.

L'articolo descrive gli studi e le prove sperimentali effettuati per verificare l'efficacia della consolidazione elettroosmotica come mezzo per la riduzione della pendenza della Torre di Pisa, ed illustra i motivi per i quali la tecnica fu infine scartata.

L'applicazione dell'elettroosmosi per produrre un cedimento controllato al di sotto del bordo nord della fondazione della torre fu proposta in origine da Calabresi et al. *[1992] e da* Mitchell *[1991]. Analisi preliminari su schemi semplificati furono condotte per studiare la più opportuna disposizione degli elettrodi e per verificare la possibilità di ridurre la pendenza di una quantità sufficiente. L'approfondimento dello studio venne affidato ad un campo sperimentale, comprendente 33 elettrodi costituiti da tubi in acciaio del diametro di circa 40 mm, isolati elettricamente dai terreni presenti nei dieci metri più superficiali. Il tratto di tubo, attraverso le argille che si intendeva consolidare, era dotato di fori per permettere il passaggio dell'acqua estratta per elettroosmosi.*

La sperimentazione è consistita nell'esecuzione di due prove. La prima ha coinvolto l'intera installazione, mentre la seconda ha interessato solo 9 dei 33 elettrodi con correnti più elevate. I risultati di entrambe le prove sono stati, nel complesso, deludenti. Sia nel primo che nel secondo caso, infatti, nelle prime fasi di prova sono state osservate portate affluenti al catodo molto elevate; esse si riducevano poi rapidamente a valori tanto bassi da consigliare in entrambi i casi l'interruzione della sperimentazione. Nello stesso tempo si osservava una significativa variazione del regime delle pressioni neutre. Come previsto dalla teoria della consolidazione elettroosmotica, nelle vicinanze degli anodi si verificava una riduzione della pressione neutra mentre nelle zone più distanti sono stati registrati inattesi incrementi, che nella seconda prova hanno raggiunto i 100 kPa.

*Il motivo principale della difformità dei risultati ottenuti rispetto a quelli attesi è da ricercare nel valore della resistività del terreno, che è risultata di un ordine di grandezza inferiore rispetto ai valori determinati in laboratorio. Di conseguenza, il valore della densità di corrente agli elettrodi è stato molto elevato, eccedendo di molto i limiti consigliati in letteratura [*Bjerrum et al., *1967].*

I fenomeni elettrochimici che si sviluppano agli elettrodi durante un trattamento elettroosmotico sono direttamente legati alla densità di corrente e, generalmente, si oppongono all'evoluzione del trattamento stesso. Nel caso in esame, il valore molto elevato della densità di corrente ha reso preponderante l'effetto di questi fenomeni rispetto al trasporto elettroosmotico, fino a provocarne l'arresto.

L'influenza della densità di corrente sull'evoluzione del fenomeno elettroosmotico è stata in seguito messa in evidenza da Squeglia *[1998] con indagini di laboratorio.*

Ulteriori prove ed analisi avrebbero probabilmente permesso di sviluppare una configurazione più efficiente del campo sperimentale. Tuttavia l'insorgere di fenomeni non ancora completamente giustificati, quale ad esempio l'incremento delle pressioni neutre, ha sconsigliato per motivi di sicurezza l'applicazione della tecnica elettroosmotica per la stabilizzazione della Torre di Pisa.