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Stabilisation de la tour penchée de Pise

Die Stabilisierung des schiefes Turmes von Pisa

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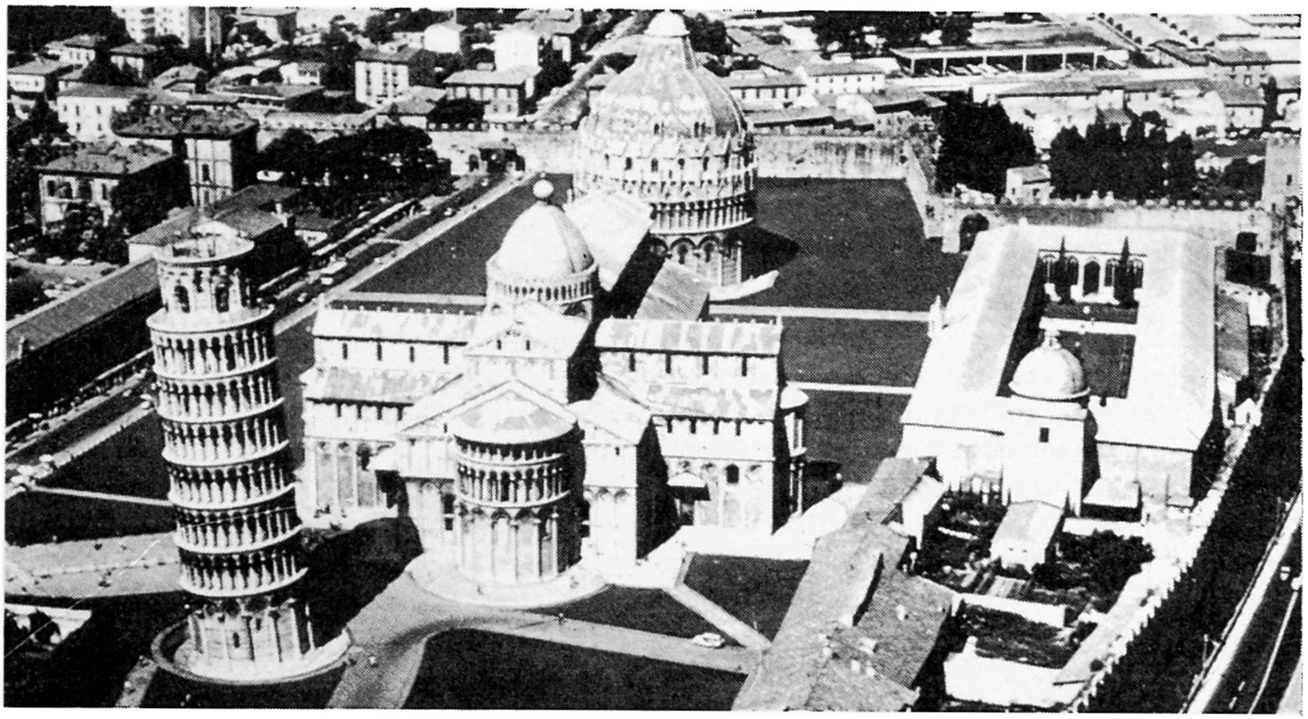

SUMMARY
After a brief historical outline and a concise description of the structure and soil foundation of the Leaning Tower of Pisa, conceptual trends for proposed stabilization design are explained.

RÉSUMÉ
Après un aperçu historique et une description de la structure et du sol de fondation de la Tour Penchée de Pise, on expose les principes du projet proposé pour la consolidation du monument.

ZUSAMMENFASSUNG
Nach einem Ausblick auf die Geschichte des schiefen Turmes von Pisa und einer kurzen Beschreibung des Bauwerks und der Bodeneigenschaften werden die Prinzipen des Projektes zur Stabilisierung des Turmes dargelegt.

1. HISTORICAL OUTLINE

The construction of the Tower of Pisa started in 1173. According to the tradition, its designer was the architect Bonanno Pisano, but more recent studies indicate its designer was Diotisalvi (Ragghianti, 1985). The works were interrupted in 1178, probably because the Tower was already leaning when the construction was at the fourth floor and its net weight approached 95 MN. Construction was resumed in 1272 by Giovanni di Simone, and after six years was completed up to the bell cell. At that time the net weight applied to soil reached the 138 MN and the leaning of the Tower became evident due to a differenzial settlement of about 90 cm. The construction of the bell cell started in 1360, by Tommaso d'Andrea and was completed in 1370.

The present situation of the Pisa Tower is summarized in Fig. 1.

The systematic measurement of the Tower movement started in 1911: at that time the rigid tilt approached 5° 14' 46" . During the 1900's the Tower continued to set and to tilt occurring in a North to South direction. The movement of the Tower is clearly some kind of self-driving instability phenomenon, causing the Italian Ministry of Public Works to establish, in the sixties, an International Commission which aim was to study the structural and soil mechanics aspects of the problem. In 1971 the Commission completed its work leaving in the hand of the Ministry a technical documentation suggesting the promotion of an international competition for the stabilization works. The analysis of the proposals by the competitors was completed during 1975. Despite the high quality of some of the proposals, the Commission and the Ministry were unable to take a decision, and the competition was then closed without a winner. During that period was stopped the pumping of water from deep wells in the surrounding areas, because they were found to be responsible for a general subsidence leading to an acceleration of the Tower tilt.

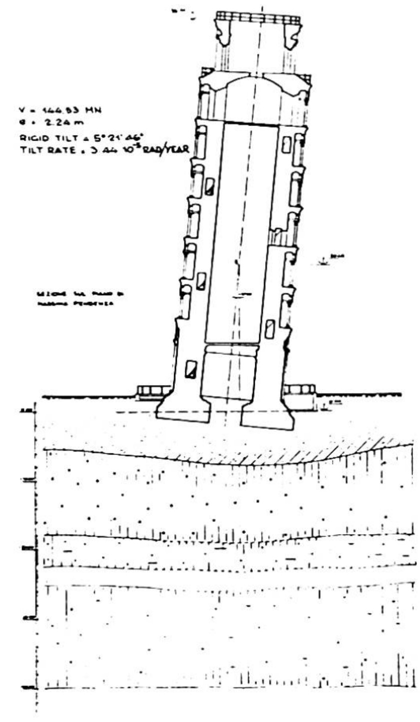

Fig. 1 Pisa Tower present situation

In 1984 the Ministry nominated the Authors as a design team whose duty was to establish a design for the stabilization work. They have supplemented the large amount of data already gathered by the Ministry by means of preliminary extensive experimental investigations both on the structure and on the foundation.

2. STRUCTURE OF THE TOWER

The cylindric wall is made of two square blocks, shells filled with mixed masonry of cobbles and very good hydraulic lime mortar. The foundation, made of stone masonry and hydraulic lime mortar has been extensively consolidated in 1935 by Rodio using cement grouting. The masonry max. stress, inferred by a theoretical analysis and supported by sophisticated measurements on the structure (doorstopper, flat jacks, dilatometer) are of about 7 N/mm^2 on the outer freestone with an ascertained resistance of 80 to 100 N/mm^2 and Young's modulus (E') of about 70.000

N/mm^2. In the inner masonry which has an E' about 6-8 times lower we can presume values around 1 N/mm^2 vs an ascertained resistance between 6 and 10 N/mm^2.

3. SOIL FOUNDATION

The soil profile and the geotechnical characterization of the soil foundation are based on the above set of investigation.

Fig. 2 shows the soil profile and the stress history of the deposit. The lower clay extends to an elevation of -37 m below m.s.l., where a thick bearing layer of very dense sand is encountered. The results of oedometer tests performed on good quality undisturbed samples taken far from the Tower (representing free field

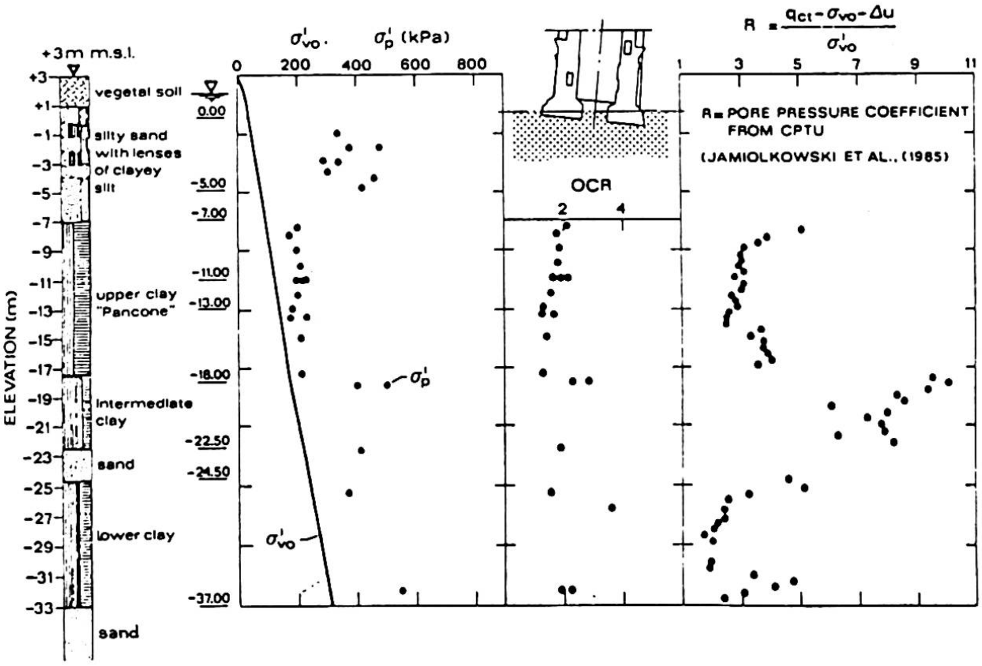

Fig. 2 Profile of soil underlaying Pisa Tower

values, hence not influenced by the stress induced by the Tower) indicated consistently that $\sigma'_p > \sigma'_{vo}$, leading to the OCR profile shown in the Figure. The preconsolidation mechanisms responsible for this are not known; probably they are linked with aging, ground water level oscillations and other environmental changes.

Fig. 3 presents the effective stress shear strength envelope of undisturbed Pisa clay, as obtained from drained compression tests performed on both isotropically and anisotropically consolidated specimens. The plot presents the mean effective stress (s') on the horizontal axis and one half of the deviatoric stress (t) on the vertical axis, both normalized with respect to the σ'_p.

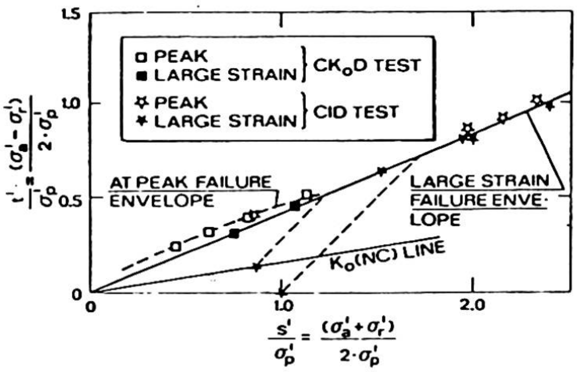

Fig. 3 Strength envelope of Pisa clay from drained tests

Fig. 4 takes us back to the Cambridge p' - q plane, in which the results of undrained triaxial compression and extension tests, performed on specimens reconsolidated to the in-situ initial stresses (σ'_{vo}, σ'_{ho}) in K_o conditions are summarized. Also in this case both p' and q have been normalized to in-situ σ'_p.

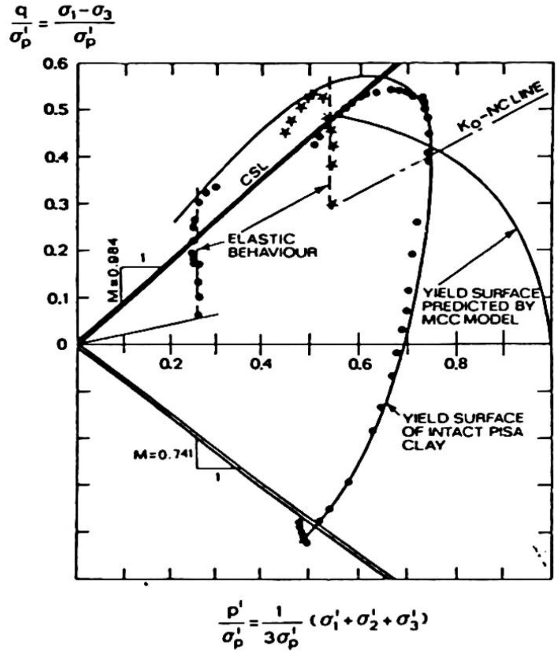

Fig. 4 Yield locus of Pisa Clay

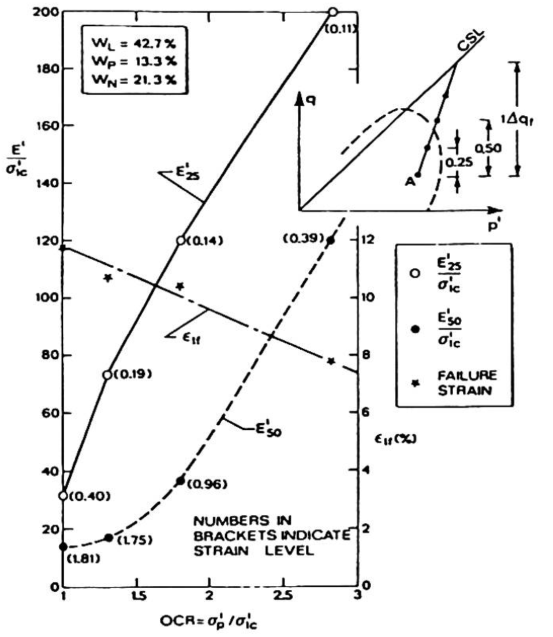

Fig. 5 Stifness of natural Pisa clay from TX-CK_oD compression tests

Fig. 5 shows the variation of normalized drained Young's modulus (E') of Pisa Clay versus OCR. The E'_{25} and E'_{50} correspond to the secant moduli evaluated at one fourth and one half the increment of the deviator stress at failure respectively.

4. CONCEPTUAL TRENDS IN STABILIZATION OF PISA TOWER

The conceptual trends of the design proposed by the Authors in 1985 with the aim to stop the movements of the Tower are shown in Fig. 6.

The basic idea of the geotechnical solution proposed by the design team in 1985 consists of the application of a stabilizing moment to the Tower and is linked qualitatively to the Critical State Soil Mechanics (CSSM) concept as visualized in Fig. 7. The effect of the application of the stabilizing moment will be to change the existing stress distribution below the Tower's foundation; unloading the soil under the Southern part and reloading the soil under the Northern part. This, at least in principle, will lead to a situation as shown in Fig. 7, in wich all relevant soil elements will be subjected to the stress state falling inside the stress space delineated by the current yield locus. In order to quantify

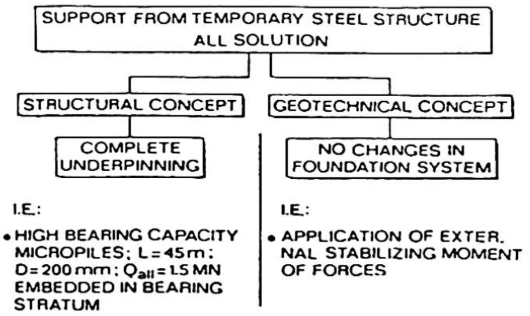

Fig. 6 Stabilization of Pisa Tower: conceptual trends

this concept, the application of the stabilizing moment to the Tower has been modelled by FEM analyses incorporating an elasto-plastic model belonging to the family of modified Cam Clay Models (CCM's).

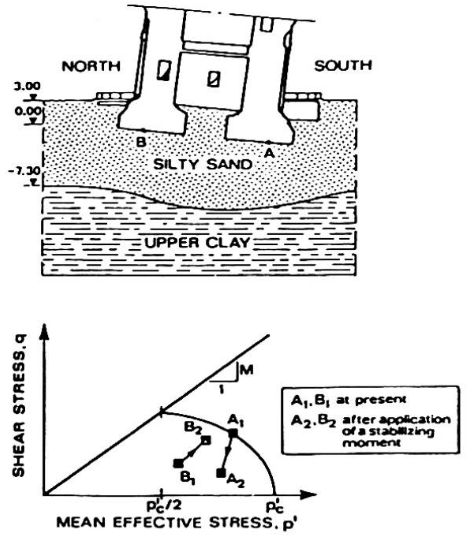

Fig. 7 Stabilization of Pisa Tower: geotechnical solution

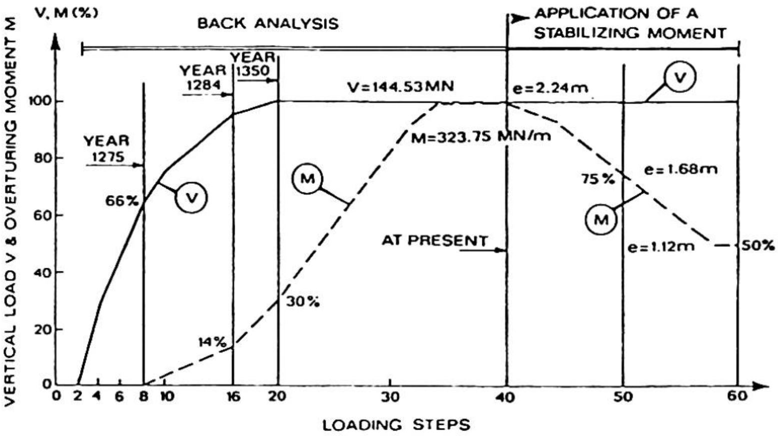

Fig. 8 Loading history of Pisa Tower

Fig. 8 shows the numerical simulation of the loading history. The loading step 20 corresponds to the end of construction. From this point, in the time the vertical load remains constant and the overturning moment increases as a consequence of the increase of the load eccentricity (e) caused by the Tower tilt in time. The loading step 40 coincides with the beginning of the application of the stabilizing moment of force, wich assumes that the final moment reduces by one half the existing value. According to the theory, the application of the stabilizing moment to the Tower would reduce its tilt within the limits allowed by the Ministry.

5. PROPOSED DESIGN

The proposed final solution for the stabilization of the Tower of Pisa consists in two distinct steps. The first providing the application of a stabilizing moment of force to the Monument, and the second one consisting in the complete underpinning of the existing foundation. The final acceptance of the first solution or the move to the second one is subordinated to the observed behaviour of the Tower after the application of the stabilizing moment of force.

A temporary steel structure will be the preliminary step. It will be placed on a prestressed concrete annular beam located far enough from the Tower and founded on high bearing capacity micropiles. The steel structure has been designed in order to: a) assure stability of the Tower during the works; b) apply the stabilizing moment to the Tower up to 320 MNm; c) support a vertical load of 150 MN. The above load on the masonry structure imply stresses compatible with the masonry resistance, previously consolidated by grouting. The schematic cross-section of the temporary steel structure is shown in Fig. 9. The structure will be used to apply the temporary stabilizing moment to the Tower (160 MNm). This will be followed by an adequate period of monitoring and possible adjustment of the moment according to the principle of the observational method. During this period of time, if the observed behaviour is satisfactory, proving the effectiveness of the soil model and of input data utilized, then a permanent structure embedded in the ground will be built, as shown in Fig. 10, and subsequently the temporary steel structure dismantelled. The permanent structure will incorporate a number of hydraulic jacks to permit adjustment to the stabilizing moment with time if necessary. By means of this solution, the Tower would still be laying on the foundation ground with a 8 centuries applied load but with a reduced eccentricity and therefore with a state of stress much more favourable than the present one.

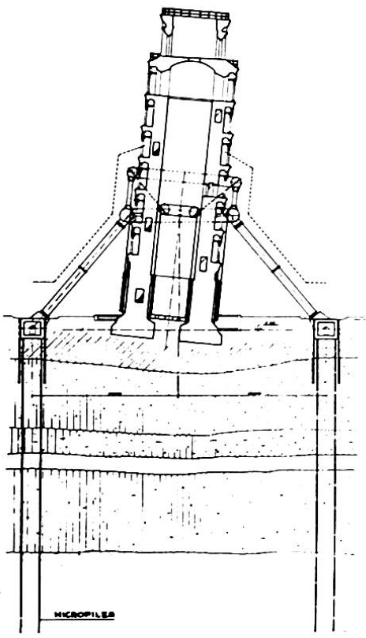

Fig. 9 Temporary support

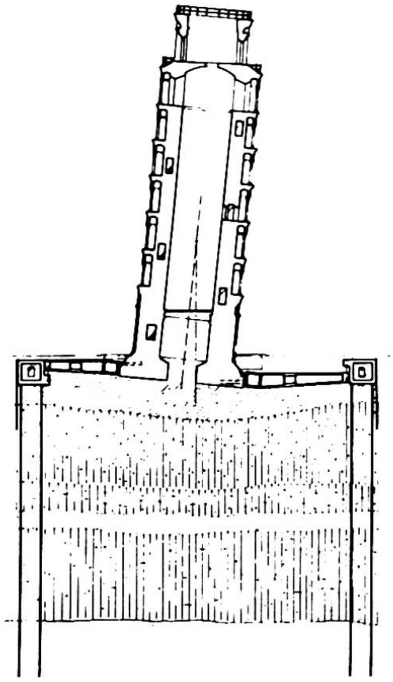

Fig. 10 Permanent structure for stabilizing moment

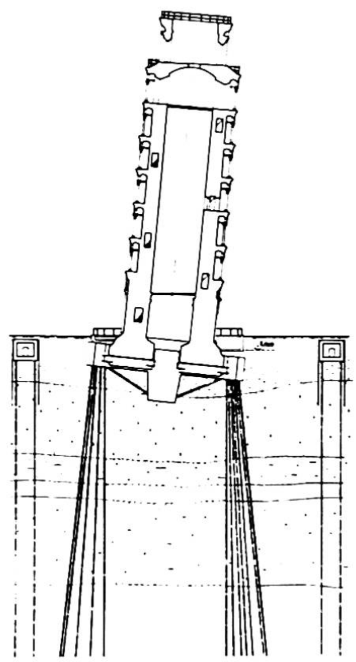

Fig. 11 Structure for complete underpinning

A complete underpinning has been exhaustively designed and will be applied shouldn't the application of the corrective moment give the predicted effects. Such an alternative method consists in the construction of a group of micropiles 45 m long, D 200 mm which penetrate the dense sand layer and with a bearing capacity of 1,5 MN, all located outside the foundation block (Fig. 11). Steel radial connected beams will transfer the load from the present foundation to the micropiles group. The beams are supported externally by the prestressed reinforced concrete ring overlaying the piles, while internally they lay on a concrete block sustained by 8 prestressed anchors. During construction before the operating of such anchors, the provisional structure will sustain the internal ends of the radial beams.

The two methods have been studied in order to maintain the historical-artistic integrity of the Monument, since after the completion of the construction no piece of work will be visible nor any super-structure of the Tower will have experienced any kind of modifications. Both designs have had the outstanding approval by late Prof. C. Ludovico Ragghianti, a great historical art expert and member of the Commission established by the Ministry of Public Works.