International Conference on Case Histories in Geotechnical Engineering

(1988) - Second International Conference on Case Histories in Geotechnical Engineering

03 Jun 1988, 10:00 am - 5:30 pm

Damage to Masonry Structures in the Historic Center of Arezzo (Tuscany, Italy) Following the Excavation of a Sewer Tunnel

A. Ghinelli
University of Florence, Italy

G. Vannucchi
University of Florence, Italy

Proceedings: Second International Conference on Case Histories in Geotechnical Engineering, June 1-5, 1988, St. Louis, Mo., Paper No. 6.05

Damage to Masonry Structures in the Historic Center of Arezzo (Tuscany, Italy) Following the Excavation of a Sewer Tunnel

A. Ghinelli
Department of Civil Engineering, University of Florence, Italy

G. Vannucchi
Department of Civil Engineering, University of Florence, Italy

ABSTRACT: The work carried out in the 1983-84 period for the building of a sewer line at a shallow depth in the historic center of Arezzo (Tuscany - Italy) caused serious damage to many of the masonry structures.
For a depth of 6-7 m., the foundation underground is made of a thick deposit of eterogeneous soils, mainly clayey silt of medium or soft consistency, including elements of gravel, boulders and organic sediment.
The tunnel has a circular section, its external diameter being 1.90 m, cover 3.40-5.20 m, and the work was carried out using a shield. The method of excavation and the subsequent operation of the tunnel brought about a prolonged disturbance and resettling of the ground in contact with the casing and thus, where fairly large boulders came into contact with the outside edge, gaps formed which were not injected with plastic concrete.
On the basis of the geotechnical data available, the surface subsidence has subsequently been calculated and has been compared with what is allowable without damaging the overhead structures.

Introduction

Arezzo is a town in Tuscany about 60 Km south-east of Florence.

The original layout is from the Etruscan-Roman period (4th century B.C.), and the present urban configuration is the result of an uninterrupted and millenary building and urbanistic transformation. The historic center is enclosed within the pentagonal ring of the Medicean city walls, and is crossed in a SE-NW direction by the Castro creek. In Roman times, once it had reached the city, the Castro most probably pursued its straight and artificial course, wich it already had, for a kilometer and a half (Fatucchi, 1969). It made its way from east to west, passing to the south of the amphitheatre and, immediately afterwards, bending towards the northwest (Figure 1).

The creek was covered over in different times for its entire city lenght: already in the 13th. century, the bed was covered in the section included between the present Corso Italia and Via Madonna del Prato, in corrispondence with the ancient "Ospedale di S. Maria del Ponte"; around 1870, the stretch included between Via Madonna del Prato and Via Guido Monaco; in the second post-war period, the remaining urban sections were covered over.

The most important building operation which involved the historic center of Arezzo was consequent on the building of the Florence-Arezzo-Perugia-Roma railway line, inaugurated in 1866.

In the immediate subsequent years, within the sphere of a vast program of expansion and re-ordering of the old building plan, were realized the large circular Piazza Guido Monaco, the widening of streets and squares (with the demolition of numerous buildings, among which in part the 15th-century "Convento dei Minoriti"), the opening of new passages in the city walls, and the covering over of the bed of the Castro creek with a large barrel vault, for a distance of about 80 m.

In the years 1983-84 at Arezzo, the fourth section of a large sewer line was built which, at shallow depth of few meters for several hundreds of meters, brushes the historic center of the city (figure 2), travelling along Via Garibaldi in the vicinity of the covered over bed of the Castro.

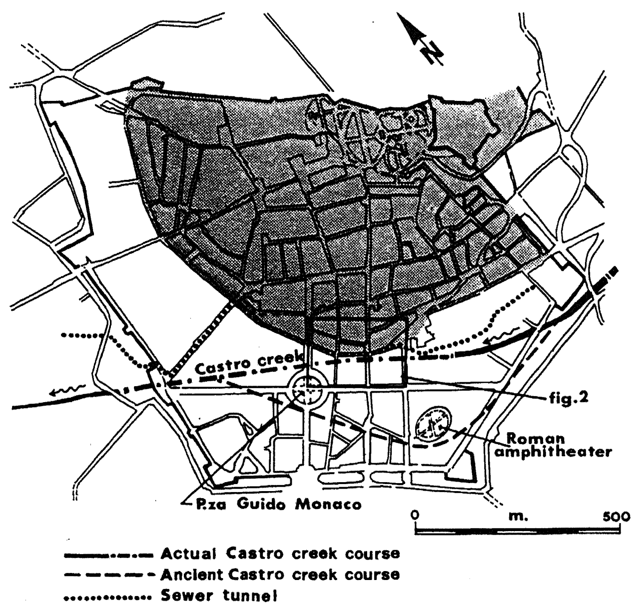

Fig. 1: Plan of historic center of Arezzo

During the excavation of the tunnel, several buildings in the historic center suffered damages of varying extents.

The walled city is divided into two clearly distinct zones, from Via Sacra, now Via Garibaldi, which has semicircular layout (figure 1). The Castro, whose course in the city segment seems to coincide with a bedding fault, is very close to Via Garibaldi in the section included between Via Madonna del Prato and Corso Italia.

- NW of the creek and of the bedding fault, Via Garibaldi encloses the oldest nucleus of the historic center, otherwise defined by the Medicean city walls. The topographic conformation of this zone of the city is on a steep slope with acclivity included between 5% and 25%. The geological map indicates stony rocks of the Tuscan Series ("Macigno del Mugello"), made up of sandstones alternated with marls and shales; over this rock formation are present, for a thickness varying between 4 and 6 meters, heterogeneous soils of a silty-clayey character containing elements of gravel, pebbles and organic sediment, heavily anthropized, fill materials and remains of ancient pre-existences.

- SW of the creek and of the bedding fault and more in general of Via Garibaldi, the topographic conformation of the city is almost flat. The geological map indicates alluvial-fluvial deposits of clay, sand and pebbles. Due to the more recent building development of the zone, the foundation soils are less anthropized.

1. THE LAYOUT AND EXCAVATION TECHNIQUES

The layout of the sewer line to the right of the Castro is indicated in figure 2. It is developed in line with Via Garibaldi, and does not pass under any building although, due to the small covering and the narrowness and curving of the street, in several points, it is dangerously close to the foundations of the buildings located on the sides. In fact, Via Garibaldi has a variable width, average 8 m, but in some sections it narrows to 4.5 m.

The sewer line was designed with the thought in mind of making an open-cast excavation, by previous construction of reinforced concrete retaining diaphragms; but for the historic center, the solution of the mini tunnel, to be made with the following excavation technique, was afterwards preferred:

1) Construction of a main thrust pit in Piazza del Popolo: 4.75 m deep, the shape of which would permit the housing of the thrust machinery in two directions. The structure was made with bored concrete piles, diameters 80 and 40 cm, connected by a slab at the base of the excavation and by reinforced concrete walls in the upper part.

2) Construction of intermediate jacking stations for the recovery of the thrust by means of a series of hydraulic jacks set along the perimeter of the lining.

3) Making of a circular hole, diameter 1.90 m, by means of the sinking of a shield and subsequent removal and carrying away of the soil from the cavity. As the shield advanced, the cavity was lined with precast reinforced concrete cylindrical pipes, 22 cm thick and 3 m long. Since the thrust was exerted by means of hydraulic jacks, which operated in the thrust pits (main and intermediate), the section of tunnel lining already realized, was made to shift ahead, as the excavation proceeded.

The excavation was carried out by means of milling cutter mounted on a trolley and manoeuvered by a workman on the face of excavation. The material loosened by the bits was removed on a conveyor belt, deposited in a container at the main pit then picked up and carried away completely from the workyard.

The excavation technique and installation of the tunnel involved a remolding and prolonged in time re-arrangement of the soil in contact with the lining, as well as the creation of voids where rocky elements of considerable dimensions were encountered along the contours.

After the first disorders were manifested in the masonry buildings underpassed by tunnel, the excavation technique was perfected: a mixture of fine sand, bentonite and cement was systematically and radially injected, to fill up the void left by the cutting edge. This device, at time combined with protective or underpinning works for the buildings underpassed or located very closely to the tunnel, avoided further damages to the masonry structures.

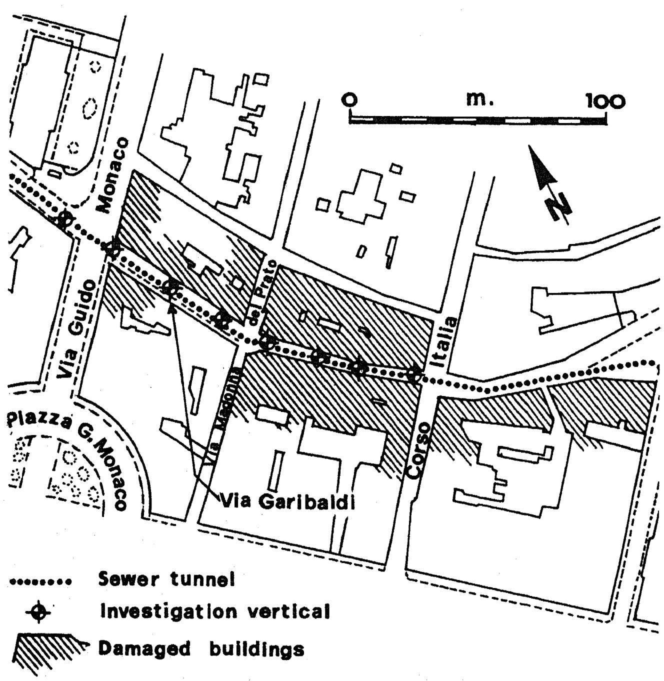

Fig. 2: Close-up to damaged area

2. GEOTECHNICAL DESCRIPTION

The stratigraphy of the soil involved in the sewer line in the historic center of Arezzo can be briefly described as follows:

- from street level to a depth of 4.0 ÷ 6.0 m:
  sandy and silty clays, from soft to medium consistency, at times with pebbles and fragments of bricks, often with organic sediments;

- below a depth of 4.0 ÷ 6.0 m:
  marls alterated and/or silty shales, sometimes in the high part, in the form of layer portions in a silty and clayey matrix.

The bottom of the tunnel is located at a level of 4.2 ÷ 5.5 m from street level. Since the finished work has an outside diameter of 1.9 m and thickness of 22 cm, a large part of the excavation took place in the silty and sandy clay surface formation (figure 3).

The origin of the surface layer must be related to three distinct and partly connected phenomena:

- the deposit of Castro creek;
- the accumulation of surface erosion debris of materials constituting the hill on which the historic center of Arezzo rises; and
- the backfill due to organization.

At present the Castro flows in a contact foot hill zone between the fluvial deposits of the plain and stony rocks which constitute the principal relief of Aretine urban territory. This location does seem, moreover, to be the original one (Fatucchi, 1969), and it can be hypothesized that the Castro, canalized into new foot hill bed, has eroded not yet completely consolidated materials,

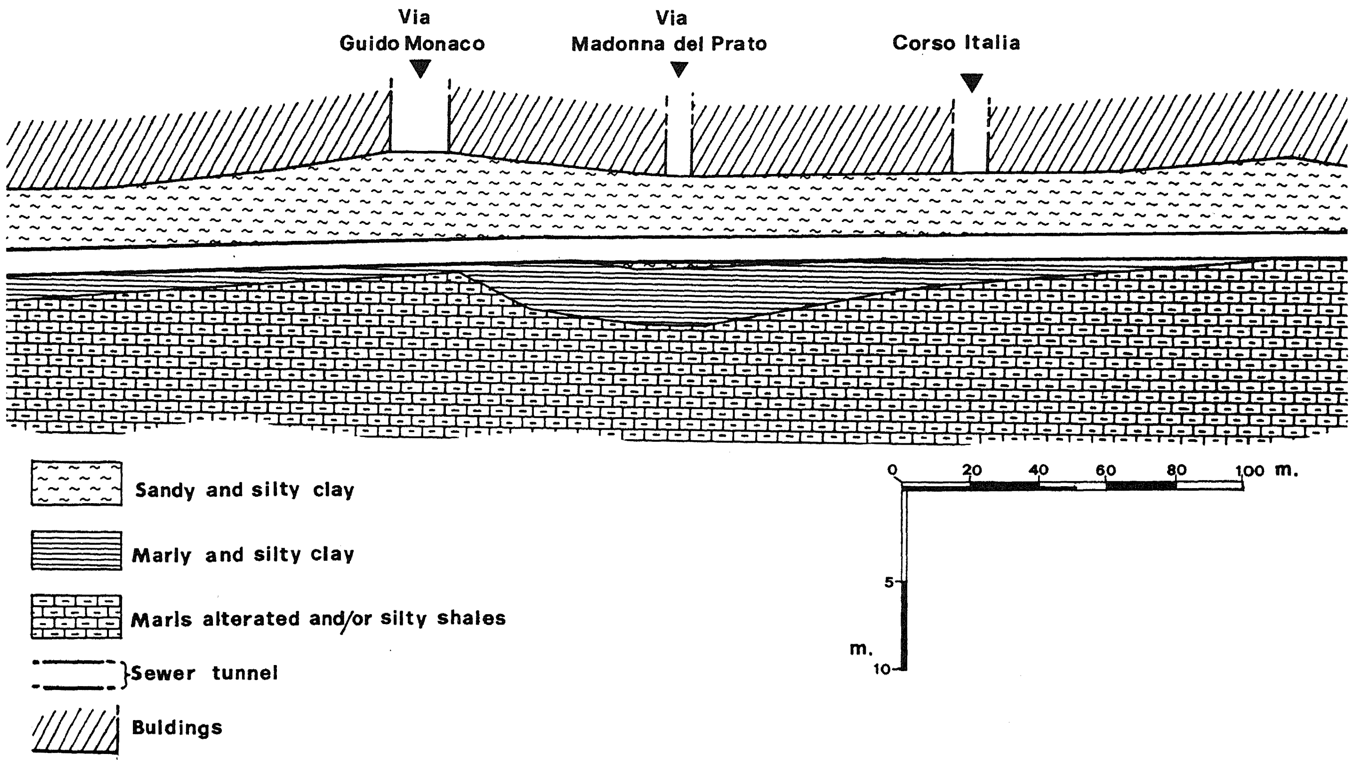

Fig. 3: Geotechnical section of the tunnel in the damaged area

subsequently causing the caving in of the surface rubble overhead.

The geotechnical properties of the surface layer vary gradually, passing from the foot hill zone to the hill zone of the city. In the plasticity chart (figure 4), the representative points of the surface soils in the hill zone, marlish in origin, fall within the highest part of the chart, while the representative points of the surface soils in the foot hill zone, fluvial in origin fall within the lower part of the chart: they have a larger silt/sand component and, therefore, lesser plasticity.

In the zone involved with the sewer tunnel construction, where the most serious damages to the buildings on the sides occurred, the geotechnical properties of the surface layer, taken from the documentary material which it has been possible to gather from geotechnical surveys made at different time and with different aim, are the following:

- Liquid limit — $W_l = 29\div37\%$
- Plastic limit — $W_p = 17\div19\%$
- Plasticity index — $I_p = 12\div18\%$
- Activity — $A = 0.3\div0.6$
- U.S.C.S. classification — CL

- Unit weight — $\tau = 1.92\div1.95$ gr/cmc
- Moisture content — $W = 24\div26\%$
- Degree of saturation — $S_r = 88\div93\%$
- Relative consistency — $I_c = 0.3\div0.6$

- Specific gravity — $G_s = 2.68\div2.72$ gr/cmc
- Void ratio — $e = 0.73\div0.76$
- Compression index — $C_c = 0.15\div0.20$
- Confined compression modulus — $E' = 30\div80$ Kg/cm^2
  (in the pressure interval, $p = 1.5\text{-}3.0$ Kg/cm^2)

- Cohesion — $C_{cu} = 0.0$ Kg/cm^2
- Angle of internal friction — $\Phi_{cu} = 26°\div29°$

- N. of blows in S.P.T. — $N_{spt} = 7\div9$

The granulometric zone of the upper soil in the section considered is represented in figure 5.

Unfortunately, it must be reported that an adequate number of laboratory tests does not correspond to the number of verticals examined (30 stratigraphic columns of depths of between 8.0 m and 23.0 m from street level; 8 static penetrometric tests; 6 dynamic penetrometric tests).

A typical CPT profile, in which the general stratigraphic outline is recognizable, is represented in figure 6.

The more superficial water table has been measured at depths varying between 4.0÷5.0 m from street level.

During the excavation of the tunnel, rocky blocks of even considerable dimensions were encountered, as well as the remains of ancient masonry, walls with 4.0 m interaxis, on which perhaps in part the foundations of existing buildings rested.

3. DAMAGES TO BUILDINGS

The buildings damaged in consequence of the excavation of the sewer tunnel in the historic center of Arezzo rise on both sides of Via Garibaldi, in a section of about 250 m. between Via Guido Monaco and Via Margaritone (figure 2).

The supporting structures are of brick and/or stones masonry; the floors are of wood or of iron and shelves of brickwork; the foundations are superficial and continuous. The period of construction differ greatly. Several

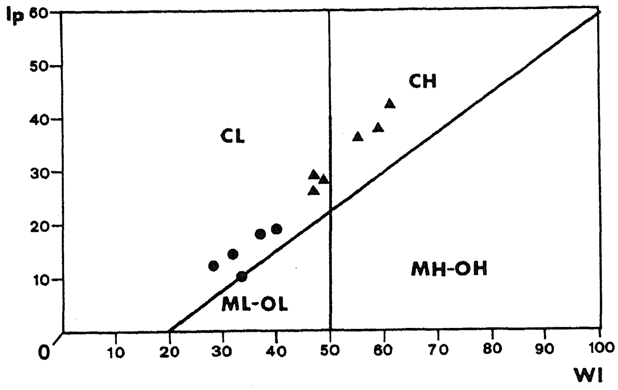

Fig. 4: Plasticity chart

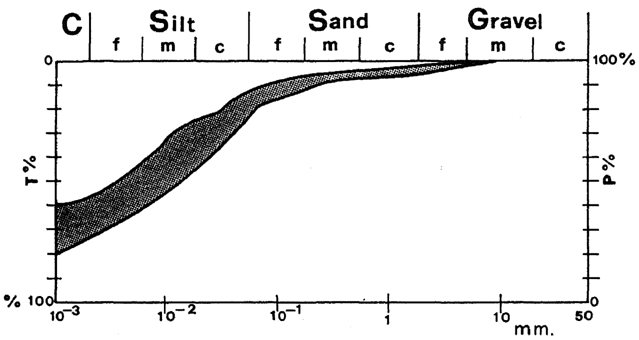

Fig. 5: Granulometric zone of the upper soil

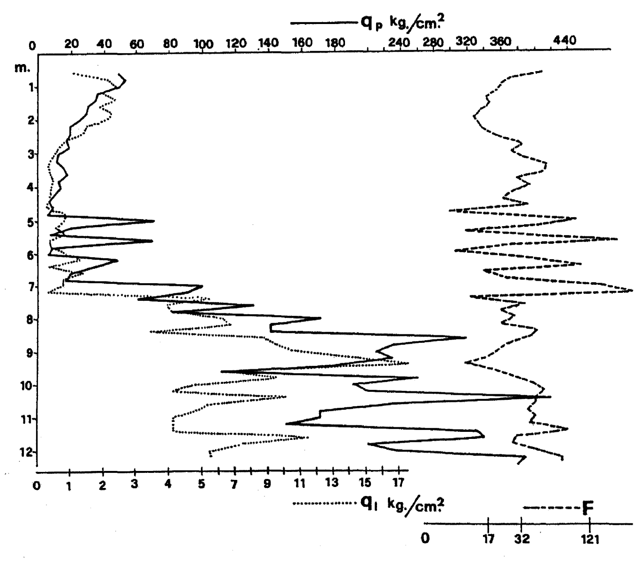

Fig. 6: Tipical CPT profile

buildings have suffered in time successive modifications and even structural remakes: some recent and documented; others, older and difficult to identify. The design drawings of the structures in elevation and in foundation were not available. In particular, the depth of foundation plan was not known.

It was not possible to establish exactly the evolution in time of the disturbance phenomena and their correlation with the progress of the excavation front, since the instrumentation of the buildings was planned only after evident and serious cracks on the masonries appeared togheter with the impossibility of opening and closing doors and windows. Nevertheless, there is reason to believe that such damages manifested themselves, for every building, during and immediately after the passing of the excavation front.

In fact, for example, from the workyard daybook containing the description and chronology of the work carried out, it can be gathered that on 22nd November 1983 the excavation front was at the crossroad with Corso Italia.

The notification of serious damages to one of the buildings on the corner between Via Garibaldi and Corso Italia is dated 4 December 1983.

Since the measurement instruments, installed on 14th March 1984, and consisting of extensometers and inclinometers only reported very small and not monotonic movements, it must be considered that the phenomenon lasted for a brief period and wore itself out in a short time.

4. Stability of the excavation front and calculation of the settlements.

The stability conditions of the excavation front of a circular tunnel in cohesive soil can be evaluated through the stability ratio, defined in the following manner:

$$N = [(\sigma s - \sigma t + \tau \cdot (C + D/2)]/Cu$$

where:

- C is the cover
- D is the diameter of the tunnel
- Cu is the undrained shear strength of soil, constant with depth
- σt is the fluid pressure in the tunnel
- σs is the uniform pressure applied to the ground surface
- τ is the soil unit weigth

In the case in point, approximately, taking into account the uncertainty of several data, N results between 4 ÷ 3, to which corresponds the safety factor SF = 0.55 ÷ 0.75 (Davis et al., 1980). The excavation front was therefore stable, although with a not very high safety margin.

The building of a tunnel always produces strains in the surrounding soil, which fact is reflected in settlement of the ground level. As is well known (Peck, 1969), the surface subsidence has a normal or Gaussian error curve profile:

$$S = Smax \exp(-X/2i)$$

where

- X is the current abscissa measured by the center-line of error curve profile: that is, the distance from the tunnel´s vertical axis;
- Smax is the maximum ground settlement over the tunnel center-line;
- S is the ground settlement in correspondence with the current abscissa X;
- i is the X abscissa of the inversion point of the curve.

Because of movements of the ground, both radial and normal at the excavation front, as well as subsidences in the lining, the volume of soil removed is always larger than the final volume occupied by the tunnel: the difference between these two volumes is called ground loss per unit length of tunnel, Vs. In undrained conditions the cohesive saturated soils strain in costant volume, and therefore the ground loss per unit length of tunnel is equal to the area of the settlement trough.

If the latter is described by an error curve profile, we have

$$Vs = 2.5 \cdot i \cdot Smax$$

Although there is uncertainty and variability in several data, in the case in point we can reasonably estimate i = 2.5 m (Peck, 1969) and Vs = 6.5% (Mair et al. 1981). With reference to the more critical geometric conditions, the maximum settlement of the street level can be computed as follows:

$$Smax = 1.04 \text{ cm}$$

At the depth of the foundation level, which for several damaged buildings has been ascertained between 1.5 m and 2.7 m from street level, i = 1.10 ÷ 1.70 m and Smax = 1.5 ÷ 2.4 cm.

The angular distorsion is, therefore:

$$[Smax - S(i)]/i = 0.009 \div 0.008$$

values not allowable with the structural integrity of multi storey buildings of masonry. By way of orientation, the U.S.S.R. building code adjudges (Mikhejev & al., 1961; and Poslhin & Tokar, 1957) as acceptable for multi storey buildings of masonry and settlements which wear themselves out rapidly in time, distortion values of 0.003, three times lower than those which were presumably verified for the buildings on the sides of Via Garibaldi in the most critical section. Bjerrum (1963) considers that, for angular distorsion greater than 1/150 = 0.007, considerable cracks are foreseeable in courtain and bearing walls of brickwork, as well as structural damages to the buildings.

5. MEASURES ADOPTED IN ORDER TO AVOID FURTHER DAMAGES

Because of the damage suffered by the buildings in the vicinity of the sewer tunnel in the period November 1983 January 1984, excavation work of tunnel was suspended until March 1986.

For completion of the tunnel, the following measures, which have avoided, or at least greatly limited, the damages to the structures, were adopted:

- behind the cutting edge of the shield and to fill in the void left by it, injections of plastic mixture of bentonite, fine sand and cement were made

- the foundations of the buildings nearest to the tunnel were protected by a discontinuous bulkhead of drilled micropiles 8÷10 m long, reinforced with a steel pipe and connected at the top by a reinforced concrete beam. In order to realize a structure of considerable stiffness, the micropiles were bored fan-shaped with different inclinations; and to avoid the creation of grout curtains (watertight diaphragms), they were sherted with a geotextile braiding (figure 7).

CONCLUSIONS

In the planning of civil engineering works, we often resort to structural and geotechnical idealizations which do not always correspond adequately to actual local conditions. This is especially true when one is operating in an environment which, for historical as well as natural reasons, is very complex and difficult to become acquainted in advance. At times the consequences can be very "unpleasant": the realization of the sewer tunnel in the historical center of Arezzo is an example of this.

The objective and "unbiased" analysis of the causes of unsuccess and of the efficacy of the remedies adopted can furnish very useful informations for future design. Unfortunately, and this is understandable, only very rarely the failures are made public. In planning geotechnical investigations for the realization of a civil engineering work, one must take into consideration both a costs benefit analysis and an evaluation of the potential (not only economic) damage in the case of failure.

It is essential to provide controls in the course of the work in order to verify the suitability of the design hypothesis for the actual local conditions, and to use realization techniques which can, in part and without excessive burdens, be possibly modified during the work so as to adapt themselves to local conditions which are different from the ones considered most probable during the primary planning stage.

In the case of sewer line in Arezzo, where the geotechnical conditions were particularly difficult and not completely foreseeable on the basis of the investigations made before starting the work (in others not very distant zones in the city, the foundation soils in fact were found to be more consistent), the damage would have been more limited if an efficient control system both of the soils encountered during excavation and of surface movement, had been planned in advance. Furthermore, these same measures for avoiding or limiting damages, which were adopted with success after more than two years of interrupted work, could have been adopted immediately after the manifestation of the first serious disturbances.

Acknowledgements

We wish to thank the Municipal Administration of Arezzo, Department of Technical Services, for the documentary material and for having given the permission to publish the present paper.

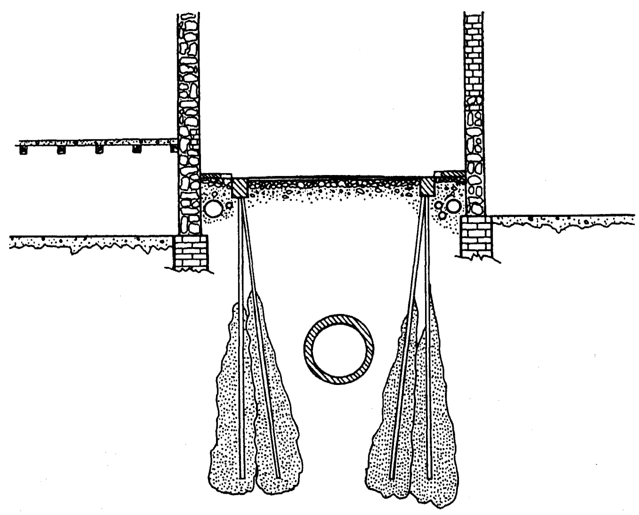

Fig. 7: Sketch of buildings' protection

REFERENCES

BJERRUM, L. (1963), "Allowable settlement of structures", Proc. European Conference on Soil Mechanics and Foundation Engineering, Weisbaden, Germany, Vol. III: 135 - 137.

BOSELLI, L.; FRANCINI, G. & SBRAGI, E. (1985), "Suolo e Ambiente - Quaderni di Arezzo 3", Revisione del Piano Regolatore Generale, Arezzo.

COMUNE DI AREZZO (1972-1986), materiale documentario relativo al progetto ed alla realizzazione del IV° Stralcio Esecutivo del Collettore in Destra Castro.

COMUNE DI AREZZO (1987), "Variante Generale del Piano Regolatore 1987 - Cartografia Geologica. Relazione Generale" Arezzo.

DAVIS, E.H.; GUNN, M.J.; MAIR, R.J. & SENEVIRANE, H.N. (1980), "The stability of shallow tunnels and underground openings in cohesive materials", Geotechnique, 30, 397-416.

FATUCCHI, A. (1969), "I primi mille anni della vicanda urbanistica di Arezzo", Atti e Memorie dell´ Accademia Petrarca, Vol.XXXIX, Nuova Serie, Anni 1968-69, Arezzo, 284-321.

GHINELLI, A. & VANNUCCHI, G. (1980), "L´ attraversamento in sotterraneo del centro storico di Firenze: previsione dei cedimenti", Atti del 14° Convegno Nazionale di Geotecnica, Firenze, Vol. I, 205-214.

MAIR, R.J.; GUNN, M.J. & O´REILLY, M.P. (1981), "Ground movements around shallow tunnels in soft clay", Proc. 11th. International Conference on Soil Machanics, Stockholm, Vol. I, 323-328.

MERLA, G. & ABBATE, E. (1967), "Note illustrative della Carta Geologica d´ Italia, Fogio 114, Arezzo", Servizio Geologico d´ Italia, Ministero dell Industria, del Commercio e dell´ Artigianato.

MIKHEJEV, V.V. & al. (1961), "Foundation Design in the USSR", Proc. 5th. International Conference on Soil Mechanics, Paris, Vol. I, 753-757.

PECK, R.B. (1969), "Deep excavations and tunnelling in soft ground", Proc. 7th. International Conference on Soil Mechanics, Mexico City, State of the Art Volume, 225-290.

POLSHIN, D.E. & TOKAR, R.A. (1957), "Maximum allowable non-uniform settlement of structures", Proc. 4th. International Conference on Soil Mechanics, London, Vol. I, 402-405.

RISTORI, G.B. (1871), "Nuova guida della Citta´ di Arezzo", Firenze.

ROSSI, F. (1985), "Il piano regolatore del 1867", Notiziario Turistico, Anno X, nn. 103-104-107, Arezzo.

TAFI, A. (1978), "Immagine di Arezzo. Guida storico artistica", Arezzo, Banca Popolare dell´ Etruria.