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Control and Detecting System related to the construction of the underground railway line in Rome

Système de contrôle et de détection établi pour la construction du métro de Rome

Für den Bau der Römer Untergrundbahn aufgestelltes Überwachungs- und Entdeckungssystem

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SUMMARY
The paper presents, in connection with an application to some old masonry buildings in Rome, the criteria for the control of the behaviour of a structure affected by external works (excavations, back fill, near constructions, etc.). The control involves the use of an instrumentation and monitoring network and has a double function. It is in a sense an «insurance policy»; it can represent, in fact, a warning bell that intervenes only in case or unfavourable of dangerous events. It can provide a knowledge of the actual response of a new or old structure to imposed foundation settlements.

RESUME
Cet article présente les critères à la base du contrôle du comportement d'une structure affectée par des travaux extérieurs (excavations, remblayages, constructions voisines, etc.) ainsi que leur application à quelques anciennes constructions en maçonnerie à Rome. Le contrôle comporte l'utilisation d'un réseau d'instruments et d'une chaîne de surveillance ayant une double fonction: il s'agit dans un certain sens d'une «police d'assurance» et consiste en fait en un signal d'alarme intervenant seulement en cas d'évènements défavourables ou dangereux. Le systèmes en question permet de relever la réponse effective d'une nouvelle ou ancienne construction à des tassements imposés.

ZUSAMMENFASSUNG
Dieser Artikel stell die, für die Überwachung von äusseren Arbeiten (Ausgrabungen, Aufschütten, benachbarte Arbeite, u.s.w.) beeinflussten Bauwerken, gründsätzliche Kriterien vor, sowie deren Anwendung für einige ältere Mauerwerkbauten in Rom. Die Kontrolle erfasst das Verwenden von Messgerät- und Überwachungsnetze und hat eine zweifache Tätigkeit: es handelt sich in einer Sinn um einer «Versicherungsvertrag», und kann eigentlich eine Alarmhupe darstellen, welche nur im Falle von ungüstigen oder gefährlichen Ereignissen eintrifft.
Dieses System ermöglicht die wirliche Antwort von neuen oder älteren Bauwerken zu gedrängte Grundstützensekungen zu ermitteln.

1. INTRODUCTION

Disturbances connected with external works (such as excavations, filling, nearby construction etc.) can cause significant alterations to the pattern of stresses in the structural elements of buildings.

Such disturbances can be represented as deformations imposed on the foundations as a result of soil subsidence.

In the case of masonry buildings, these deformations may cause lesions or the aggravation of an existing pattern of cracks, according to the stresses induced in the bearing elements.

The present article examines some old masonry buildings in Rome in the area between Via Palestro, Via Vicenza and Via Villafranca (Figures 1-3), which have been affected by works to extend Underground Line B. Two tunnels, first one, then the other, for this extension were bored under these buildings at a depth of 20-25 metres below the road surface

The masonry structures examined (see para 2) were markedly cracked prior to the start of work on the tunnels. When the second of the two tunnels was built, it was decided, in conjunction with the Intermetro and La Girola companies, to adopt a system to check the structures concerned.

The check was based on the use of an instrument network to provide data on deformations and therefore stresses in the materials, the width of cracks, lesions, joints, temperatures, movements of foundations, and water levels. These data were acquired automatically and in real time.

In both this specific case and also generally, the control system has a dual role. On the one hand it is a sort of insurance policy, money spent to ensure that people can use the buildings without incurring risks, at the same time keeping preventive measures to the minimum, since each and every alarm signal is transmitted promptly and allows any necessary measures to be taken in time (such as evacuation, buttressing, reinforcement, etc.).

It also makes it possible to know the real response of the structure to the deformations imposed at the base of the foundations. This may be very useful, both in correctly analysing the development of the crack picture and in rational definition of the consolidation works necessary, and also as a test for use in developing methods for use in similar buildings to which the results may be extrapolated.

2. DESCRIPTION OF THE WORKS AND PRE-EXISTING CRACK PATTERN

The buildings to which the recording system described in this paper was applied comprise the end part of a block, situated between Via Palestro, Via Vicenza and Via Villafranca and arranged in the form of a "U".

The three buildings recorded are situated one against the other and separated by joints in the construction (see Figures 4-7). The characteristics of the three buildings are very similar and can be summarised as follows.

The buildings comprise a basement part-floor, a ground floor mostly used as shops, and 5 or 6 floors over. The roofs are flat, terrace-type.

The buildings were constructed in the early 1900s, and entirely of masonry. The thickness of the vertical structures is 80-90 cm at ground floor level, decreasing to 50-60 cm at the top floor.

The external width of the window openings is about 100-120 cm on all floors except the ground floor, where the windows are about 2 m wide. The height of the windows, however, varies according to the floor. The foundations are of hardcore-filled "wells" connected by masonry arches on which the wall rest. The stairs are mostly "Roman" type (resting on masonry half-arches) with steel beams and slabs introduced later in some cases. In general the horizontal structures are small arches resting on steel beams at about 85 cm spacing.

Fig. 1 Facade looking on
Via Palestro

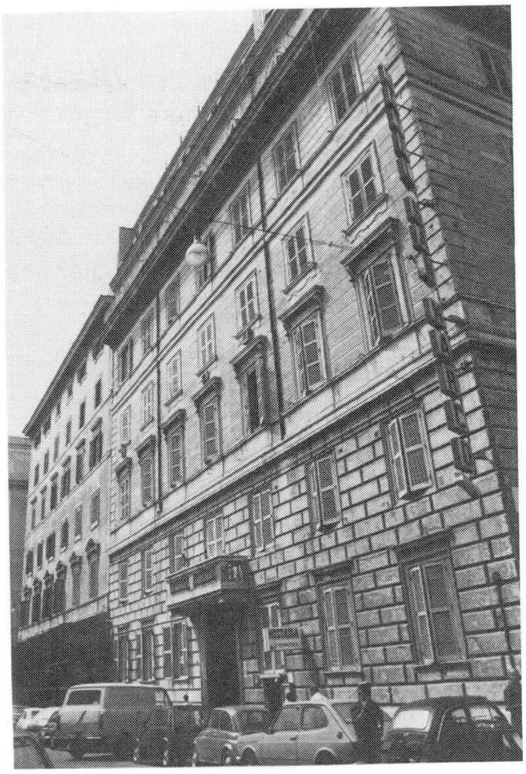


Fig. 2 Facade looking on
Via Vicenza

Fig. 3 Facade looking on Via Villafranca

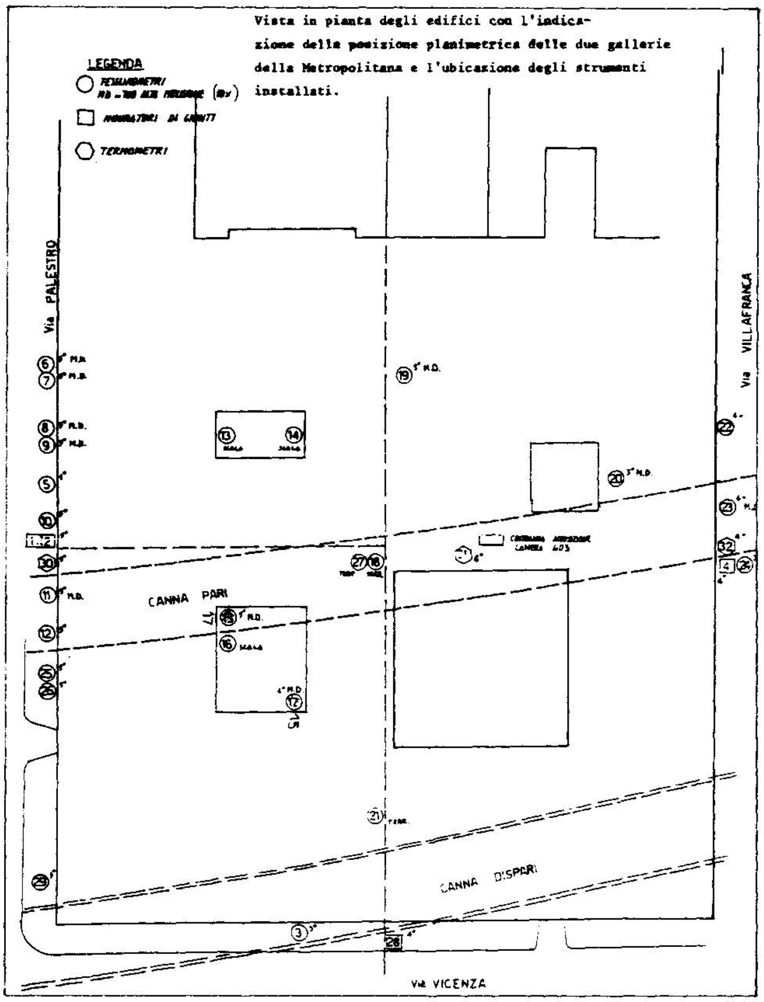


Fig. 4 Plan view of the buildings with the indication of the two underground tunnels position and of the instrument location.

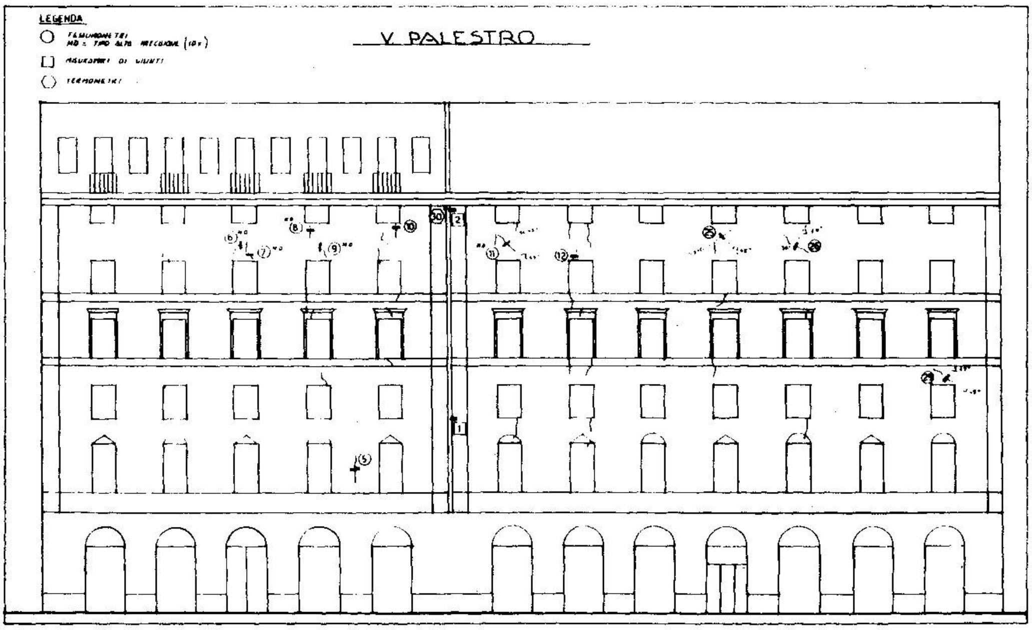


Fig. 5 Facade looking on Via Palestro
The crack pattern and the installed instruments are visible.

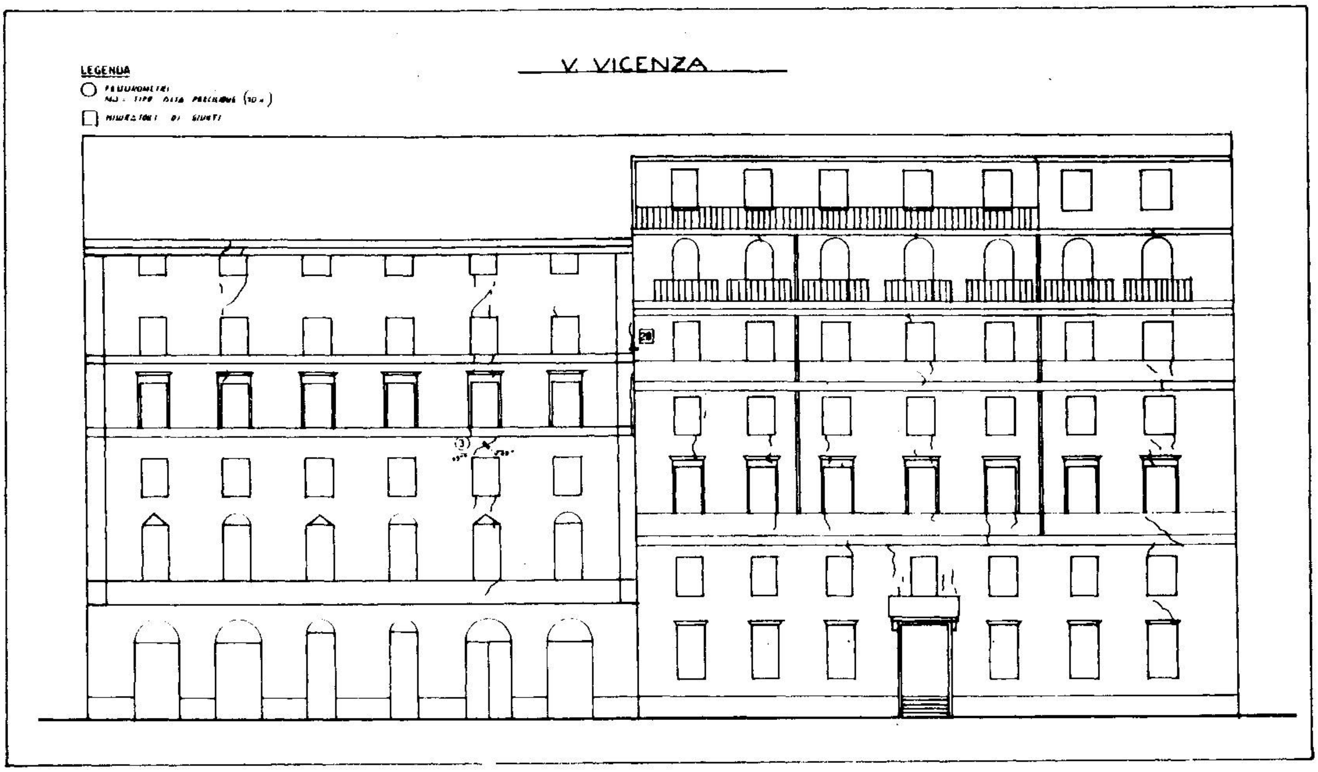


Fig. 6 Facade looking on Via Vicenza.
The crack pattern and the installed instruments are visible

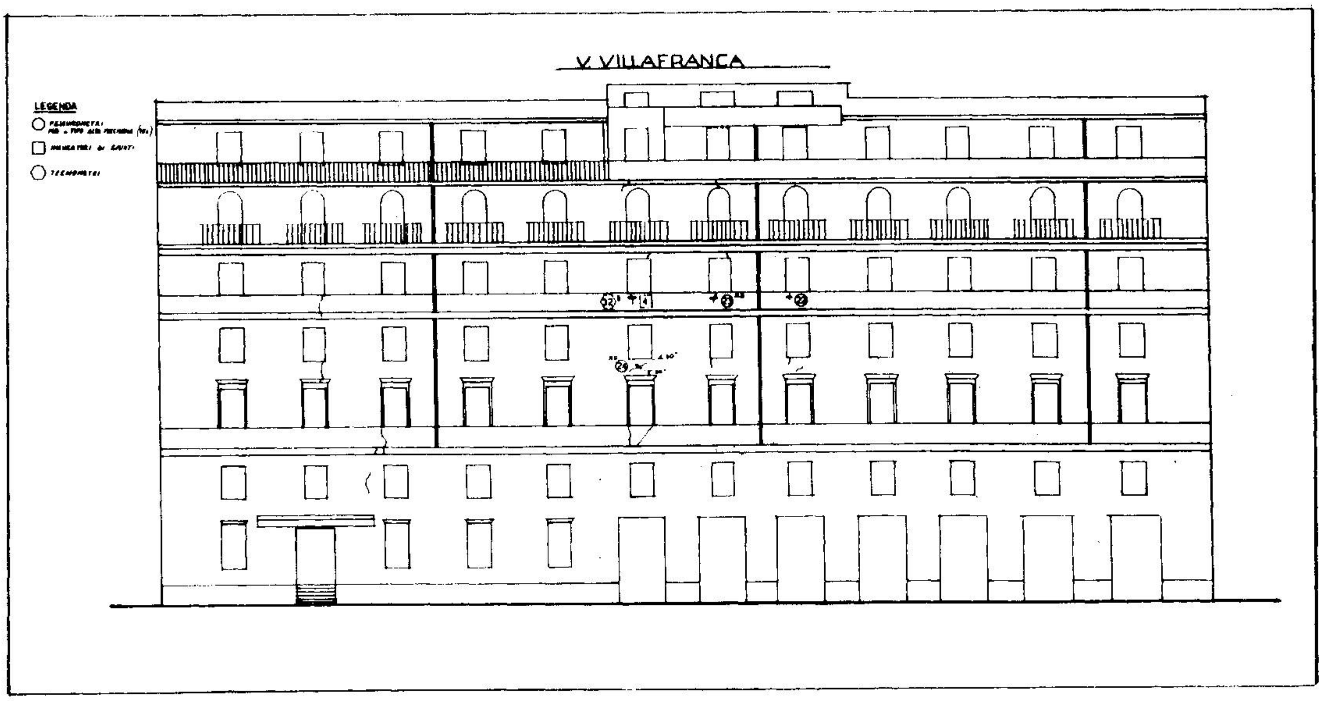


Fig. 7 Facade looking on Via Villafranca
The crack pattern and the installed instruments are visible

Some structures in the buildings in question have been modified at various times. Both the outsides and the internal structural elements show pronounced craking. The lesions present on the outsides are shown in Figures 5-7, while Figures 8-11 show the most significant lesions encountered inside the buildings.

This pattern of craking, which existed prior to construction of the second tunnel for the Underground and to the installation of the measurement system described in this article, is attributable to a series of causes and phenomena occurring during the time since the buildings were constructed. Two of these seem to be largely responsible for the present static condition of the buildings.

The first is settling of the foundations due to rises and falls in the groundwater level. This is a characteristic of the whole zone and has, over time, produced a well-defined pattern of cracks in all the buildings examined. Such effects have been aggravated by a deterioration (sometimes directly observable) in the construction materials used, not all of which were of the best quality.

The second factor is the series of minor earthquakes occurring during the century, which have contributed to and accentuated the process of deterioration.

3. DESIGN CRITERIA FOR THE INSTRUMENTATION NETWORK

The instrumentation network was designed to check the most significant lesions on both the insides and outsides of the buildings studied: on the faces looking into Via Palestro, Via Vicenza and Via Villafranca, on the terrace roofs, and on the walls facing the courtyards.

Knowledge of the change in the width of these lesions over time as excavation of the second tunnel proceeded was considered necessary for two reasons. First, to provide a continually updated picture of the static conditions of the buldings, thus providing a complex of interrelated pre-alarm signals whenever the buildings might behave in any way abnormally. Second, interpretation of the signals received from the measuring instruments, together with other data, would make possible a theoretical analysis of the behaviour of the structures studied and correlation between the results of these analyses and the experimental measurements (see para 5). The author was also given access to the data recorded by a ground engineering instrument network (set up by others) covering the whole zone and composed of subsidence meters, inclinometers and piezometers.

Figures 4-7 show the positioning of the instruments on the structures and some details are visible in Figures 12-15.

The instrumentation network installed included two thermometers positioned on the outside walls, facing Via Palestro and Via Villafranca respectively and a third located within the operations room. These made it possible to correct the other measurements for the effect of temperature variations.

4. INSTRUMENTS AND DATA ACQUISITION SYSTEM

The instruments used were as follows.

14 Crack width measuring devices (fissurometers) made by the SIS (Società Italiana per la Strumentazione Geotecnica) company and consisting of a potentiometric transducer. The field of measurement is ± 10 mm and the resolution 0.1 mm.

11 Deformation measurement deivces, SIS Mod. D312, consisting of a potentiometric sensor. The field of measurement is 0-25 mm and the resolution is 0.01 mm.

4 Monodirectional joint measurers, SIS Mod. D311, consisting of a potentiometric transducer with a plastic conductor. The field of measurement is

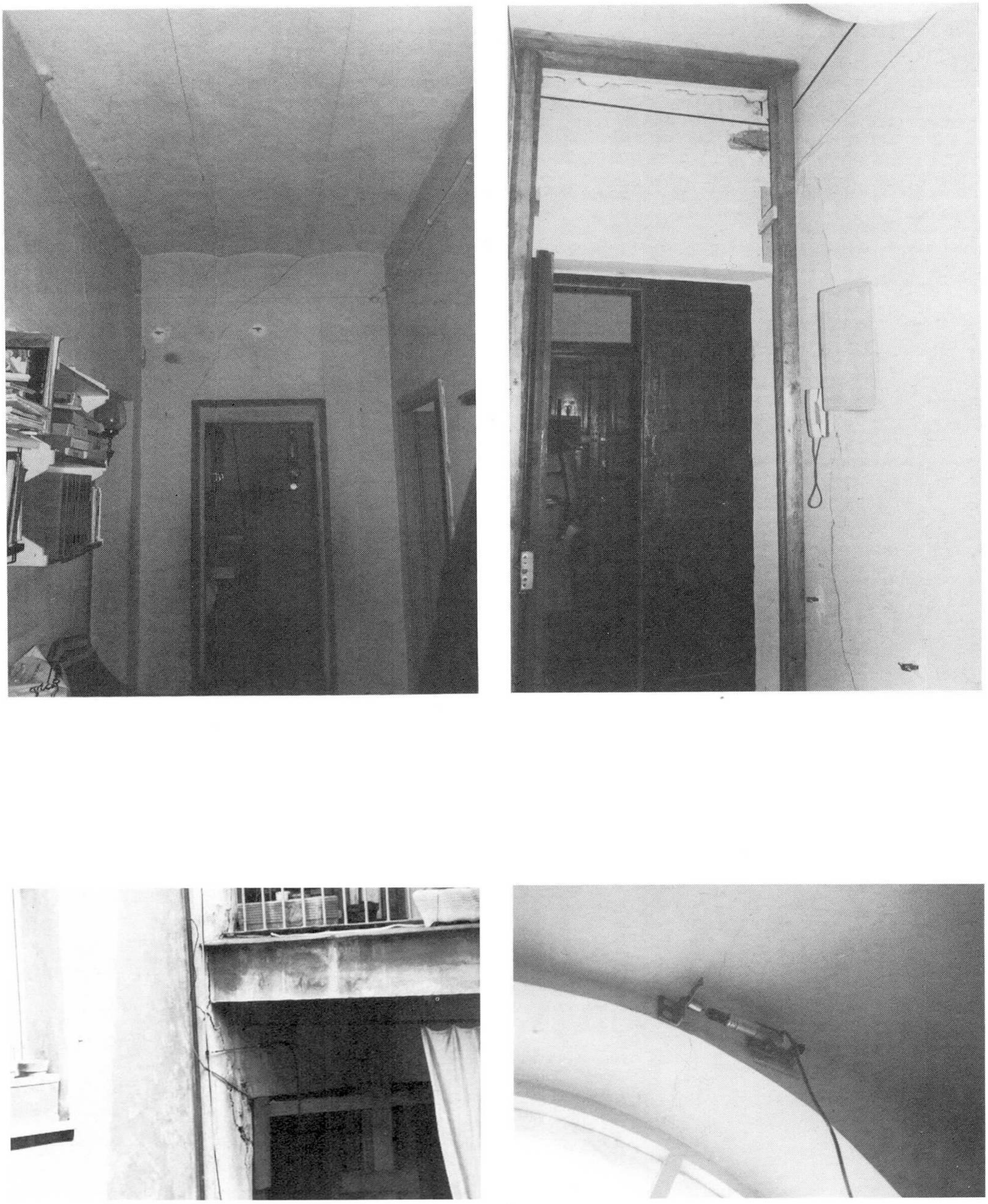


Fig. 8-11 Some of the most significative cracks on the masonry structures

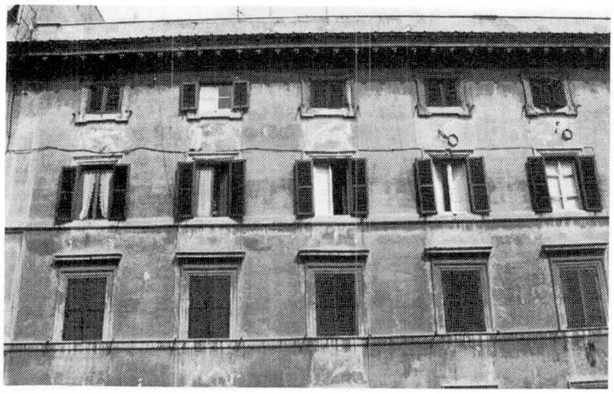


Fig. 12 Facade on Via Palestro with some of the installed instruments

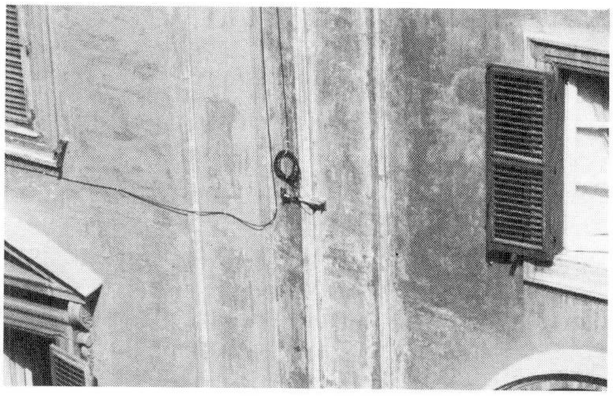


Fig. 13 The instrument n° 1

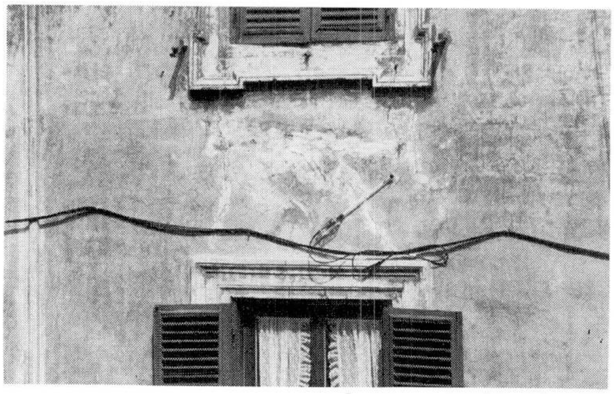


Fig. 14 The instrument n° 11

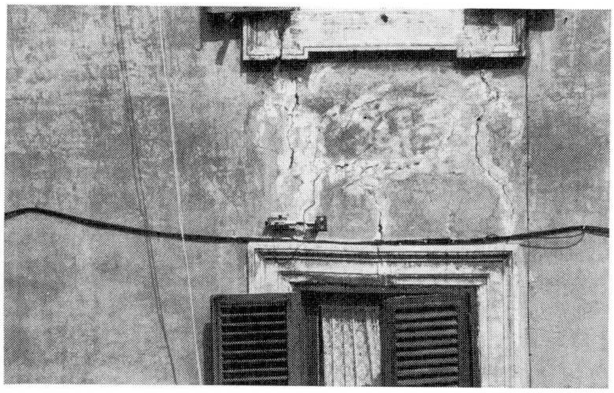


Fig. 15 The instrument n° 12

Table 1

graphics	channels	cables	instruments
1	18 19	12 25	FIUSSUROMETER
2	22 23	13 14	FIUSSUROMETER
3	1 5	16 21	FIUSSUROMETER
4	2 3	17 19	DEF. MEASUR
5	4 17	20 11	DEF. MEASUR
6	20 21	26 29	FIUSSUROMETER
7	6 7	30 31	TEMP. SENSOR
8	24	15	DEF. MEASUR
9	8	32	TEMP. SENSOR

Table 2

graphics	channels	cables	instruments
1	22 23	23 24	DEF. MEASUR.
2	17 24	27 4	FIUSSUROMETER
3	18 19	18 28	JOINT MEASUR.
4	20 21	3 22	FIUSSUROMETER
5	7 8	1 2	JOINT MEASUR
6	1 2	6 7	DEF. MEASUR
7	3 4	8 9	DEF. MEASUR
8	5 6	5 10	FIUSSUROMETER

± 25 mm and the resolution 0.1 mm.
3 Temperature sensors, SIS Mod. T111, semiconductor type, field of measurement - 10°C to + 60°C, accuracy better than 1°C.

These 32 instruments were connected to two electronic control units with 16 channels each for automatic recording of the data measured. The acquisition interval for these two units can be varied and in the period in which the checks described were carried out was varied between 4 minutes and 1 hour.

Tables 1 and 2 show the control units and channels to which the sensors were connected. The same tables show the coupling of the instruments in the graphs discussed in para 5.1.

The control units, wiring panels, computer and printer were sited in a room in the Hotel Villafranca, in one of the buildings checked.

5. INTERPRETATION AND FORECASTING OF STRUCTURAL BEHAVIOUR

5.1 Processing of data supplied by the instruments

The supplied data by the instruments were acquired and memorized by the (remote) control units. The polling interval for these units can be programmed at the start of each recording period and can also be varied at any time. The intervals used in this case varied between 4 minutes (which is the minimum and can be considered as effectively real time) and 1 hour.

The data were processed by converting the measurement units to technical units and plotting these against time. The resulting graphs could be displayed immediately on the screen of a personal computer and subsequently printed on a portable printer connected to the same computer. Figures 16 and 17 are examples of the graphs produced. The processed data were recorded on diskettes.

Later development of the data acquisition system makes it possible to present the data recorded by the instruments in graphs produced in real time, using a subsequent generation of remote control unit, special software and a personal computer permanently connected to the acquisition equipment, which is given the name of "scanner".

5.2 Analysis of structure behaviour using theoretical models

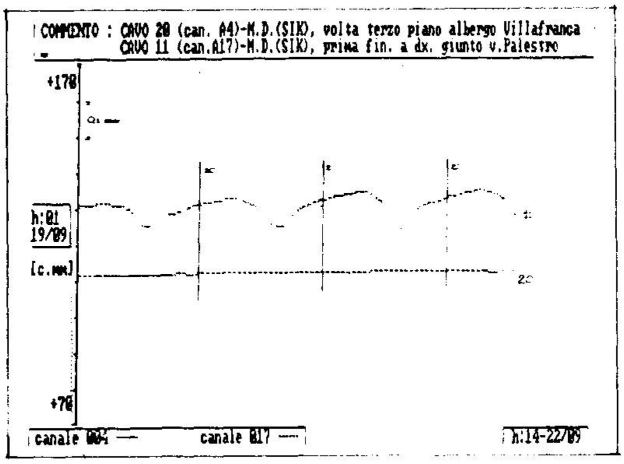
5.2.1 Modelling the structures

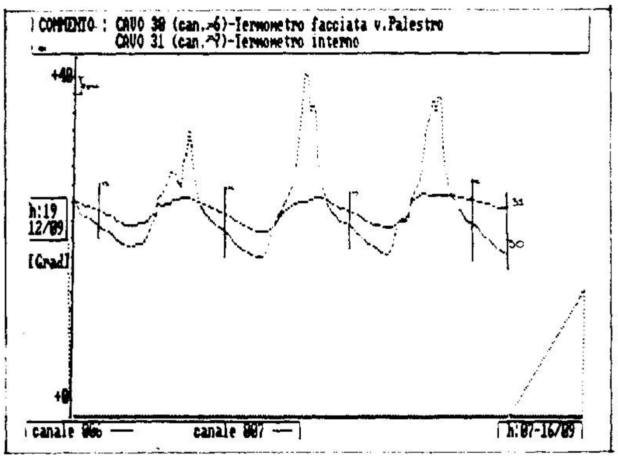
To analyse the stresses and the responses in the buildings studied, and especially in the areas where a well defined crack pattern existed and where the instruments were installed, finite element models were developed for the structures.

These were plane models for the faces of the buildings looking onto Via Palestro and Via Villafranca. The modelling was done using finite elements of the plate type. Rigidities corresponding to the thickness of the outside walls concerned were introduced into the models.

The voids (windows, doors, etc.) in the walls and structural discontinuities (joints and lesions) in the walls were also introduced into the models. Pairs of reference nodes were positioned at these discontinuities and their relative movement made it possible to measure opening and closing of the openings over the course of the structure's response to the disturbances induced by the tunnelling.

The structural models analysed extend below the road surface level, at which point finite elements were inserted whose rigidities simulate the behaviour of the foundation wells and of the surrounding ground. Figure 18 shows the mesh design for one of the models.





Figures 16 and 17 Two examples of the graphs produced

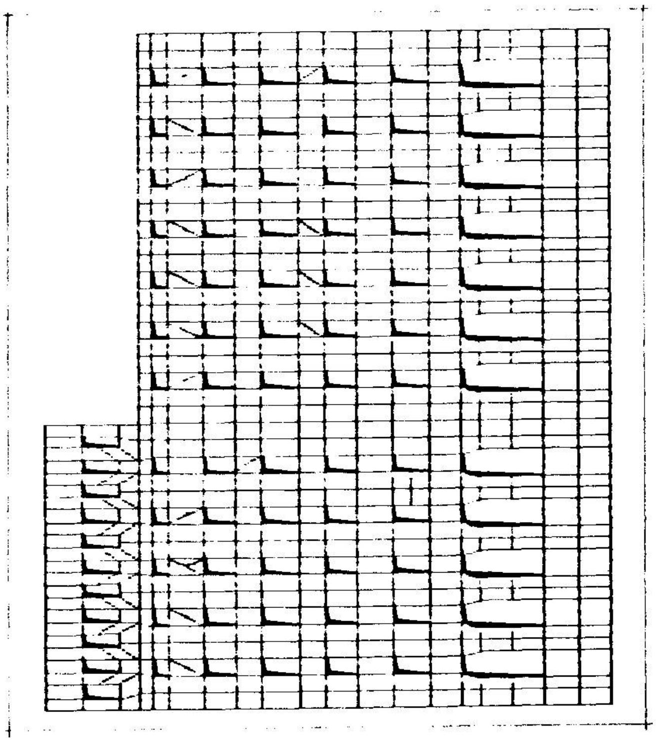
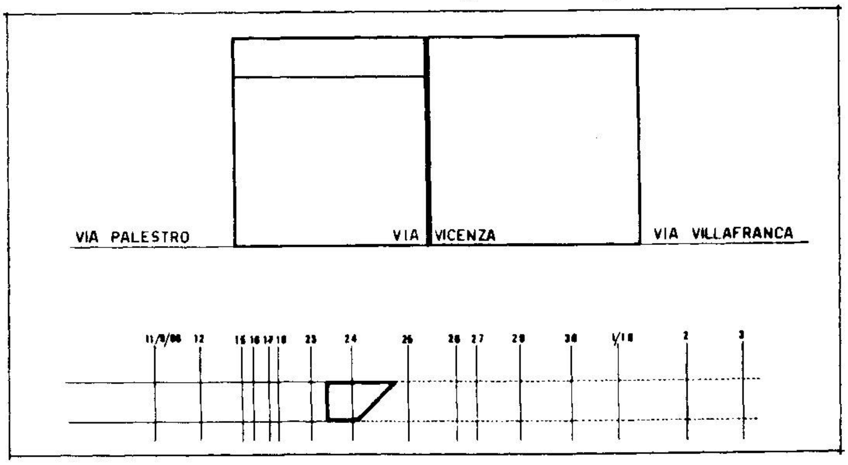


Fig. 18 Plot of mesh for one of the finite element models

Fig. 19 Progress of excavations



5.2.2 Analysis of the structural models

A series of static analyses in a linear elastic field was carried out on the models described above, applying imposed deformations to the base of the structures which corresponded to the values for subsidence recorded by level measurements during excavation.

Figures 20 and 21 show the subsidence diagrams measured at the base of the buildings on the Via Palestro and Via Villafranca faces respectively. These diagrams were drawn during the course of the excavations, the progress of which is shown in Figure 19 .

The analyses were carried out at different times, on each occasion using the subsidence values recorded in a generic time t_i as input values, and with different values for the mechanical characteristics of the materials making up the masonry structures and ground.

This made it possible to calculate the theoretical response of the structures over time and compare it with the data recorded by the instruments. It also made it possible to carry out sensitivity analyses on structural behaviour in relation to both uncertainties affecting the mechanical characteristics of the materials and deterioration of these which might locally alter the behaviour of the structural elements. The results of these analyses are discussed below.

5.3 Correspondence between theoretical analysis and data measured - Interpretation and forecasting of structural behaviour

5.3.1 Ground deformation and behaviour of lesions and joints. Evolution of the phenomena over time

In general the results of the analyses carried out on the theoretical models show good agreement with the measured data (see Figures 22-24). The comparison was made at different times during the course of excavation and showed that it was possible to obtain a clear correlation between the real behaviour of the structure and theoretical predictions.

Figures 25-29 show the extent and variation over time of the subsidence together with the measurement at the base of the buildings, movements of the lesions and of the joints. Figures 25 and 26 are for the Via Palestro face and show changes in subsidence over time with the corresponding changes in the opening of the joint between the two buildings examined and of the lesion measured with crack meter No. 12 (see Fig. 22).

The same Figures 25 and 26 show that most (about 60%) of the rotation about the joint occurred in the period between 12th and 17th September 1986, the day on which the shield reached the left hand building for about a quarter of its length. The remaining 40% of the rotation took place in the period from 18th September ti 1st October at an almost constant rate, if one excepts a slight temporary increase on the 25th and 26th.

Immediately after the beginning of October, when the subsidence had stopped, (as had the changes in the instrument readings), level recording on Via Palestro was terminated. At this time the shield was crossing Via Villafranca at the opposite side of the block.

The behaviour of the joint over time seems to be in good agreement with the changes in subsidence over time and also with the behaviour of the lesion measured with crack meter No. 12.

Figures 27 and 28 show the relationships between the changes over time in the subsidence measured at the data points on the Via Vicenza face and the bahaviour of the joint between the two buildings on the same face. The following points deserve specific mention. First, the slightness of the subsidence and joint movements recorded up to 17th September (when the shield was entering below the building to the left of the joint) and, second, the

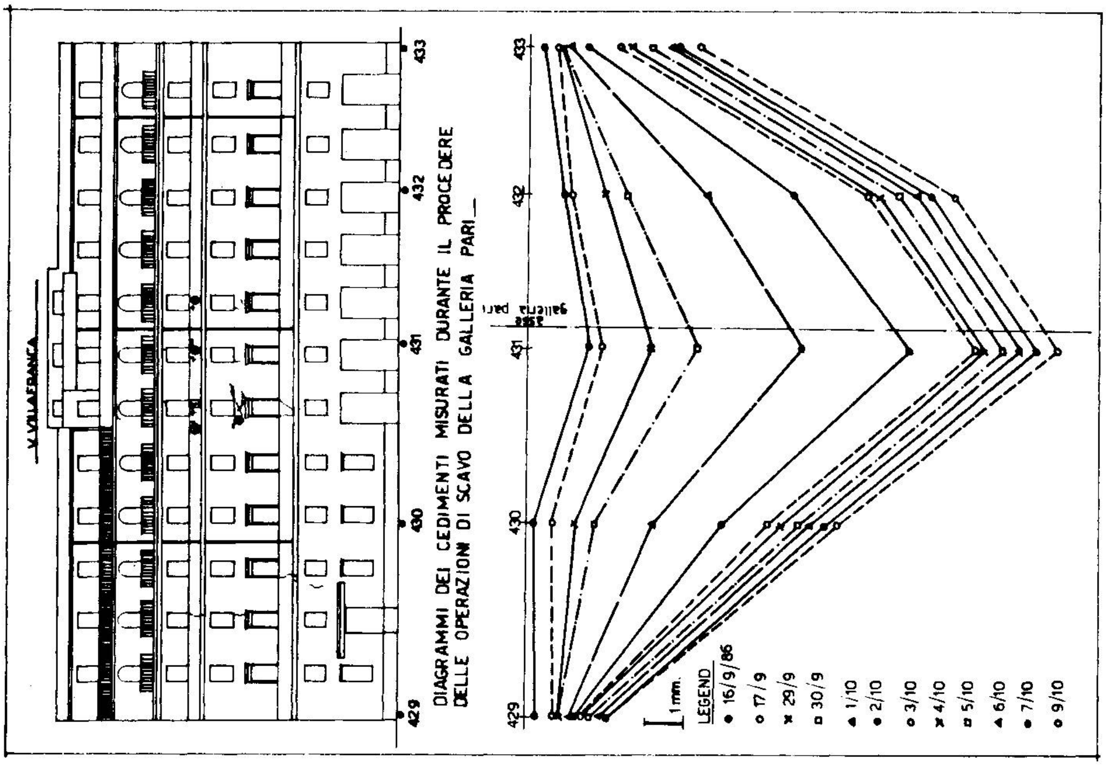


Fig. 20 Settlements diagram measured at the base of the building on Via Palestro

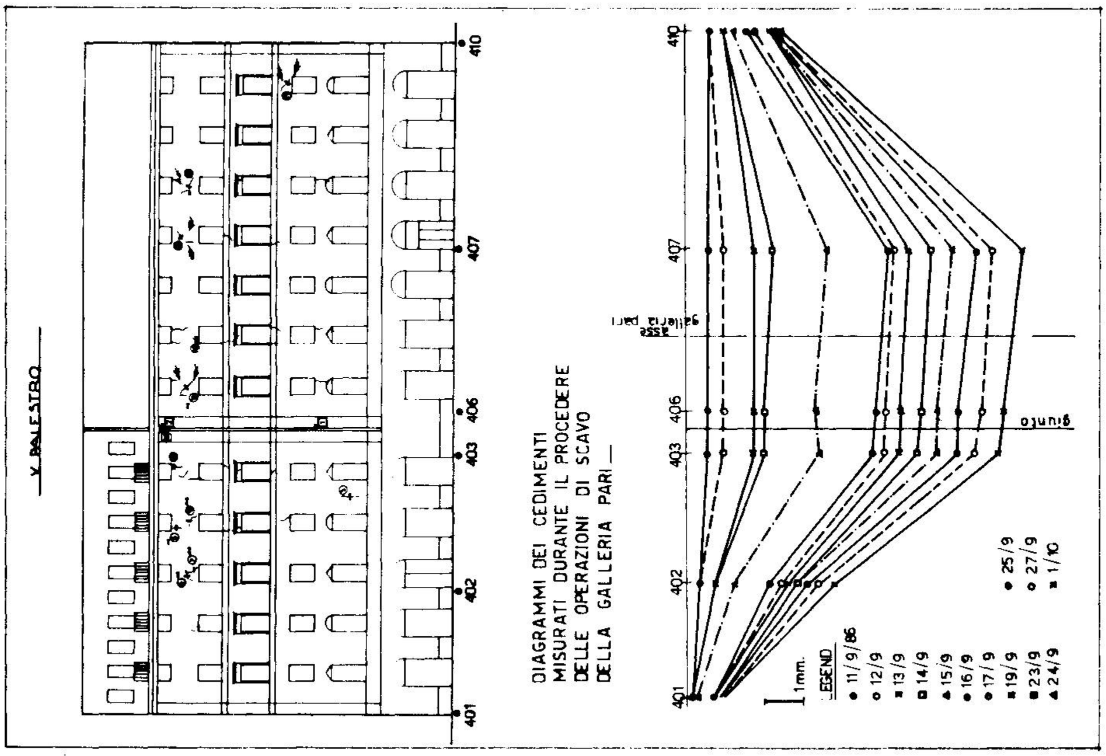


Fig. 21 Settlements diagram measured at the base of the building on Via Villafranca

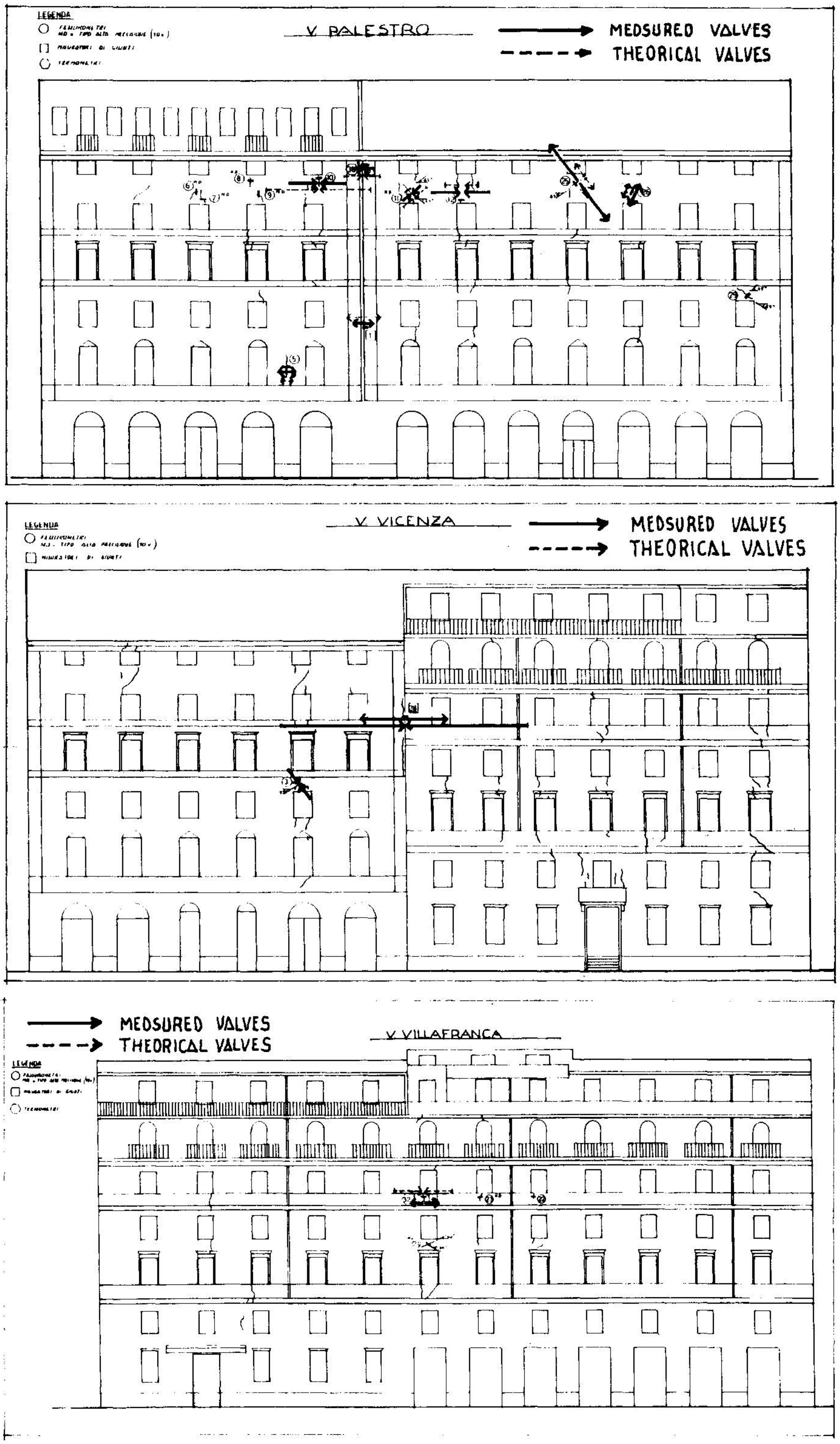


Fig. 22, 23 and 24 Corrispondence between theoretical analysis and data measured

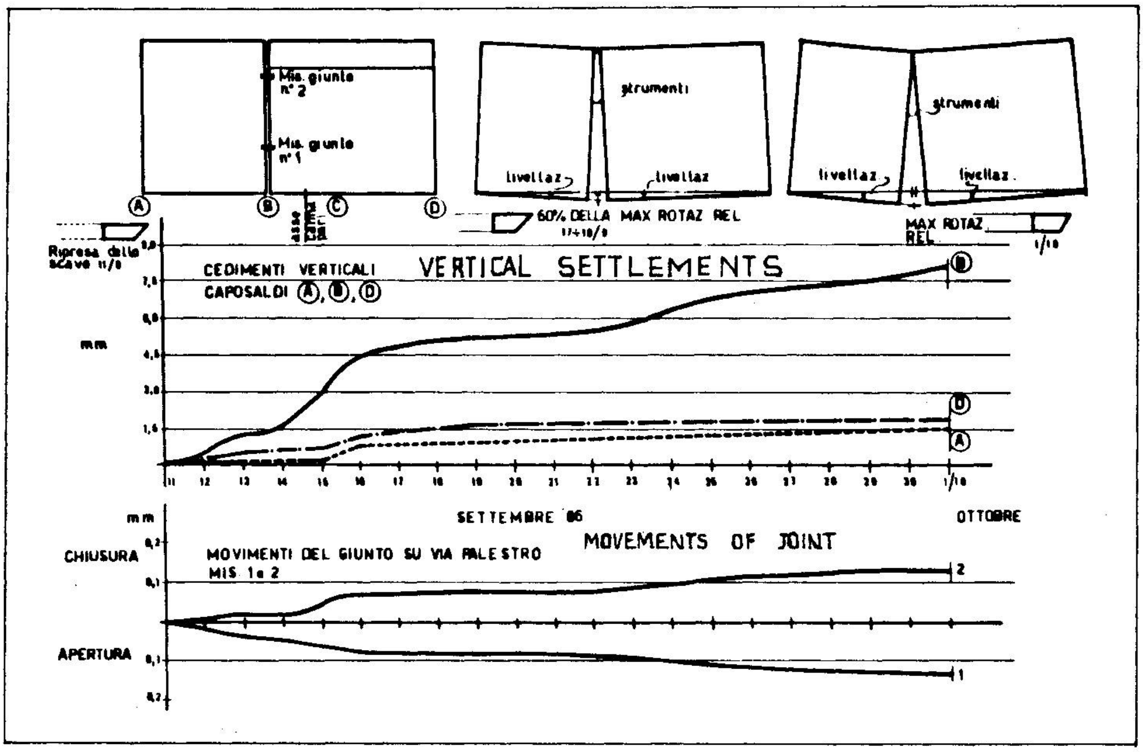


Fig. 25 Comparison between the measured settlements at the base of the building on Via Palestro and the movement of the joint.

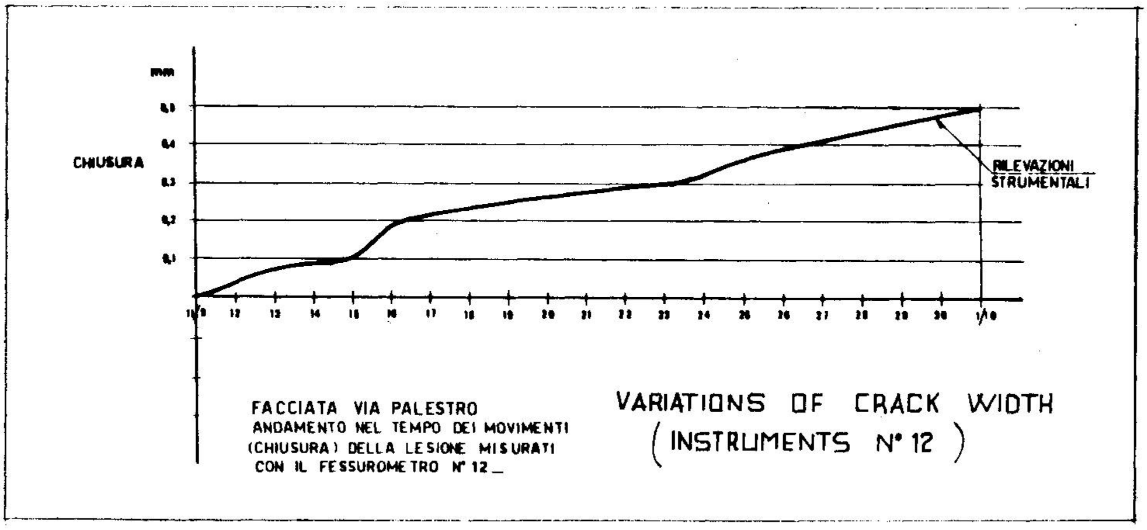


Fig. 26 Facade looking on Via Palestro
The variation over the time of the movements of the lesion on which was installed the fissurometer n° 12

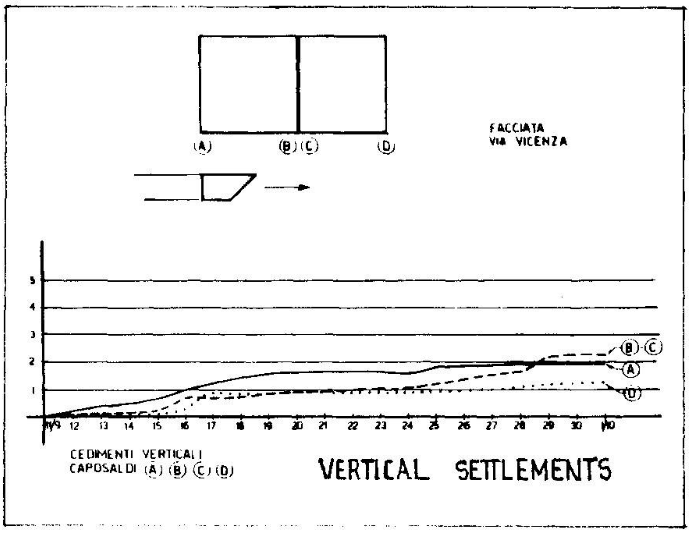


Fig. 27 Measured settlements on the base of the building on Via Vicenza

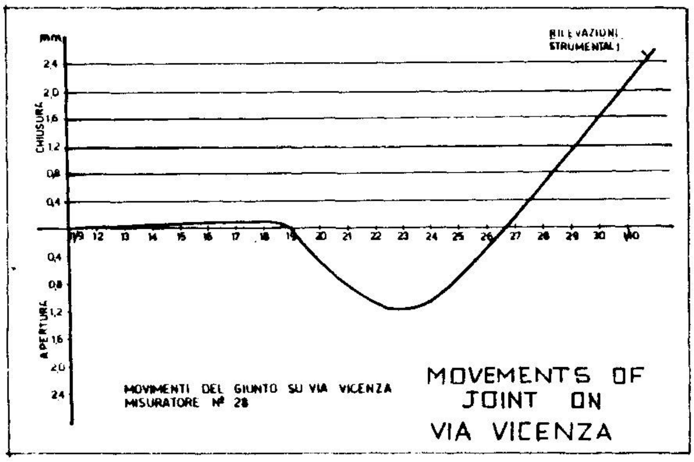


Fig. 28 Movements of the joint between the buildings on Via Vicenza

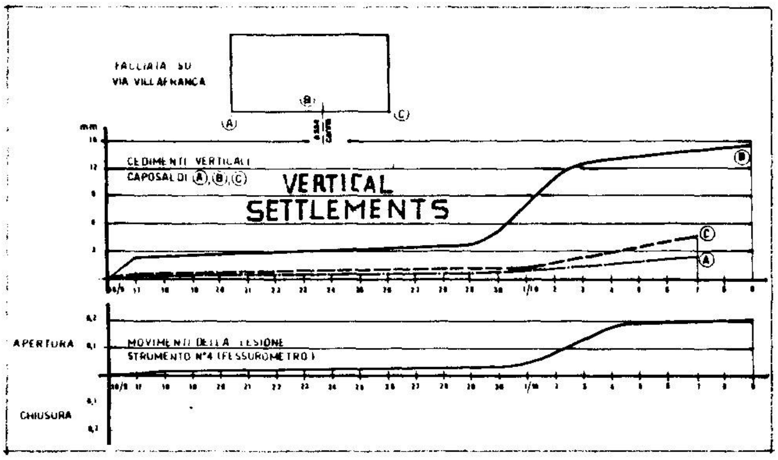


Fig. 29 Facade looking on Via Villafranca Comparison between measured settlements and movements of the joint

inversion of rotation about the joint on inversion of relative subsidence between the joint area and the opposite extremity of the building towards Via Villafranca. This inversion took place about 29th September when the shield was approaching Via Villafranca.

From Figure 27 one can obtain a final value for the relative subsidence between datum points A and B (corner with Via Palestro, joint) of about 0.4 mm, with a corresponding figure of about 0.1 mm between points C and D (joint, Via Villafranca corner).

The relative rotation of the joint (the sum of the rotations of the two buildings, 24 and 26 m long respectively, is:

$$\varphi_0 \text{ tot.} = \frac{0.0004}{24} + \frac{0.001}{26} = 5.513 \times 10^{-5}$$

To this rotation there corresponds a closing of the upper end of the joint, where the sensor is fixed, of

$$5.513 \times 10^{-5} \times 16.5 = 0.9 \text{ mm}$$

relative to the bottom end, the height being about 16.5 m. The value actually recorded by the instrument was 1.33 mm. The difference between these two correspond to the deformation of the structures.

Analysis of an elastic model based on F.E. of the two buildings for the above subsidence gives a value closing of the joint of about 0.12 mm. The total closing is therefore:

$$0.9 \times 0.12 = 1.02 \text{ mm}.$$

The higher value measured experimentally can be attributed to the greater deformability of the structures resulting from the crack pattern described previously.

Finally, Figure 29 shows the correlation between the subsidence of the datum points on the Via Villafranca face and the behaviour of the lesion instrumented with crack meter No. 4.

5.3.2 Ground deformations and stress induced in the structures

As already said, the analyses carried out on the theoretical models of the buildings provided the stresses induced in the masonry structures as external conditions varied, that is, as subsidence as the base resulted from excavation. In general, there are two principal features of the results.

The first is the good agreement between the distribution of the increased stresses induced by subsidence and the behaviour of the joints and lesions. The second is the low level of increased stresses induced in the materials (normal stresses of some Kg/cm^2 and tangential stresses below 0.5 Kg/cm^2).

This provides a theoretical counterpart for what was measured directly during the course of the excavation, that is, the absence of phenomena of significance in terms of the safety of the buildings.

6. CONCLUSIONS

The measurements made on the structures of the buildings in question were intended to make a contribution to the study of problems with the excavation of tunnels in urban areas, in particular the static safety of masonry structures on the surface.

The studies carried out showed that the instrument network developed functioned reliably and correctly and provided an accurate picture of the evolution of the deformations in the structures, though in the absence of phenomena of great significance.

The instrumentation installed also made it possible to continue with all the normal activities carried out in the buildings (hotels as well as dwellings), ensuring the safety of the occupants through real time observation of the behaviour of the buldings.

In the event of dangerous changes in the static picture, the instrumentation would have provided alarm signals in sufficient time for safety measures to be put into effect (shoring up, strngthening, evacuation etc.).

In the specific case examined, and thanks to the measures taken by the tunnelling contractor, prior to the start of excavation, to improve the mechanical characteristics of the ground concerned, the phenomena recorded by the instruments were well within safety limits. No critical situations occurred.

The instrument data were compared with the results of theoretical analyses of mathematical models of the structures. This made a full interpretation of the behaviour of the structures possible.

The results obtained show the particular importance of construction joints in masonry buildings subject to subsidence of the foundation soils. As has already been described, in the case of the buildings on Via Vicenza, thanks to the good functioning of the joint only about 30% of the deformation produced by the relative subsidence of the foundations went towards inducing a state of stress in the structures. The remainder of the deformation was transformed into rigid rotations of the two buildings around the joint.

This behaviour indicates the importance of the joint, which should not be rigid but allow for movement and rotation, with sufficient being left between adjacent buildings.

The main contractor for the extension to Rome Underground Line "B" is the "Intermetro S.p.A." company with Mr. Mario Cangiano as Director of Works.

The tunnelling contractor is "Girola". The instrumentation and checking of the buildings studied were supervised by Prof. Goirgio Croci, with the assistance of M. Biritognolo and S. De Vito.

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