

# Indirect methods of investigation for evaluating historic masonry

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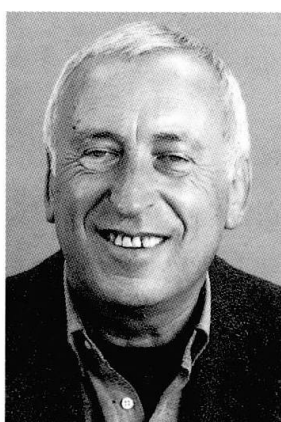
## Indirect Methods of Investigation for Evaluating Historic Masonry

Méthodes indirectes d'investigation des constructions anciennes en maçonnerie

Einsatzmöglichkeiten indirekter Erkundungsmethoden an historischem Mauerwerk

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### SUMMARY

In recent years, the applicability of indirect investigation methods to historic masonry has been assessed and further improved through research projects. On the basis of the experience gained from this research into radar, geoelectric, seismic and ultrasonic testing as well as from its first commercial exploitation, its use can now be recommended. This applies particularly to the evaluation of existing historic buildings and the assessment of their structural condition.

### RÉSUMÉ

L'utilisation de méthodes indirectes d'investigation des constructions anciennes en maçonnerie a été évaluée et améliorée ces dernières années. Les expériences réalisées avec les méthodes du radar, de la géoélectrique, de la sismique et des ultrasons ainsi que les premières applications commerciales permettent d'affirmer la fiabilité des investigations indirectes dans le cadre de l'inventaire et de l'analyse de l'état de conservation des constructions anciennes en maçonnerie.

### ZUSAMMENFASSUNG

Die Anwendbarkeit indirekter Untersuchungsmethoden an historischem Mauerwerk wurde in den letzten Jahren in Forschungsprojekten erprobt und verbessert. Aus den Erfahrungen bei diesen Untersuchungen mit Radar, Geoelektrik, Seismik oder dem Ultraschallverfahren sowie ersten kommerziellen Einsätzen kann die Empfehlung abgeleitet werden, indirekte Verfahren gezielt im Rahmen der Bestandserkundung und Zustandsanalyse historischen Mauerwerks anzuwenden.



## 1. INTRODUCTION

In recent years there has been an intensification of research to improve the range and scope for non-destructive and partially destructive methods of investigation and measurement in the field of historic masonry. This has come about by the modification and further development of certain methods, such as ultrasonic, seismic, geoelectric and radar, which are already well established in other areas of science and technology [1]. Interest by the building industry lead to the first commercial exploitation of these methods, and demonstrates their degree of success. Nevertheless, further research and development work is necessary in order to increase the capability of these techniques and thus widen their market potential.

Positive results in the laboratory and field work currently indicate that these techniques can be recommended for the evaluation of existing historic masonry. They allow determination of characteristics and material constants needed for the historic, static and physical analyses. This, in turn, presents important advantages for the architects and engineers involved, such as:

- reasons for existing damage can be detected more accurately, thus facilitating more reliable repair work;
- the stability of constructions can be assessed more precisely;
- measures for the securing, repair, strengthening or alteration of existing historic buildings can be planned earlier and on a reliable planning basis; and
- interventions in the construction can be reduced by the use of less invasive target-oriented methods.

However, these new methods should not be overestimated. They do not offer neat and convenient solutions for each and every problem. In particular, they are no substitute for the intense and indispensable in-situ work at the specific building.

These techniques do not provide stand-alone solutions; they must become part and parcel of systematic, well coordinated evaluations of the existing building. On the other hand, they do supply data needed by the architects and engineers for their analyses and facilitate correct conclusions. As difficulties may arise when the various disciplines have to work together, the paper recommends how to proceed in a sensible and methodical way.

'Non-destructive' is not a neutral term and so it gives rise to problems when it is used, particularly for those involved in the preservation of historic monuments who expect too much of these methods. A 'non-destructive investigation' in absolute terms will be the exception in the future, too, as damage to the construction finally occurs when drilling is carried out in order to countercheck and calibrate the results. Therefore, the advantage of these methods is not that interventions into the construction can be avoided in total, but that better results can be achieved, which in turn facilitates a sensible concept for the necessary repair work with lesser interventions.

Thus the term 'non-destructive', which is quite common in other areas, cannot be defined without difficulty in the sensitive area of investigations of historic buildings. Therefore, the term 'indirect methods' will be used herein as it describes the situation more accurately: physical measurements are being carried out, which only provide an "analogue" of the results and information searched for.

## 2. EVALUATION OF HISTORIC BUILDINGS, GENERAL APPROACH

Leaving apart the subsoil conditions and urban environment, when planning new buildings, the condition on the site is of lesser importance. The planning can be done in an office. But dealing with historic masonry necessitates intensive in-situ work; the geometry, the load bearing system, the materials and their characteristics are not to be freely chosen by the planner. They are simply given without being obvious in all details; they have to be determined, taken into consideration and should be altered only partially.

Therefore, the basic planning facts are of great importance when dealing with historic buildings. The survey and evaluation of existing buildings are areas which not only need enough time to be dealt with but also adequate financial funds to be made available. "... you will pay to have good investigation, whether you have it or NOT!" (Karl Terzaghi). If this is not taken into account, unpleasant surprises can occur during the work, causing unavoidable changes and alterations, which in turn lead to additional costs, time delays and further destruction of the historic building. Experience from unsuccessful conservation measures have demonstrated quite clearly the importance of detailed surveys and evaluations of existing structures.

When dealing with complex buildings, the appraisal and the assessment of their structural condition should be done step-by-step in a well coordinated way (fig. 1). The indirect investigation methods must be integrated into the overall concept, since the necessary documentation should be available for their use. Also, the investigation aims must be determined beforehand.

In the ideal situation the evaluation of the existing building starts with the historical investigation, which means collecting documents, plans, drawings, photographs, etc. from archives and other sources. In-situ, the building researcher depicts the findings which can be derived from the surfaces in writing or by means of drawings or photographs. In the following step, investigations from the field of restoration and building archaeology may be necessary, supported by specific techniques (for example dendrochronology). The acquired data gives information about the historic and technical composition of the construction. With this knowledge the historical value of the building can be deduced.

The survey of the structure supports the historical investigation as well as all other investigations and analyses. It provides the means to define the geometry of the building and draw the corresponding plans. Measurement by hand, geodetic methods, computer-aided processes and photogrammetry supply different degrees of accuracy. Additional information is included in the plans or documented by photographs.

The survey of damage includes the mapping of visible damage to the structure, for example deformations, cracks, disintegrated areas as well as specific surface characteristics, for example the detachment of flakes, sanding, discoloration and efflorescence. Need may arise to trace the development of the damages in the course of time by continuous or periodic monitoring.

Structural investigations are directed at the composition and structure of the parts. Very often the visual inspection of the surface informs about the materials used and the binding. In order to gain information about the interior, i. e. possible voids, multiple leaves or discontinuities, interventions into the building are necessary, e. g. drillings. In this context, indirect methods offer a non-destructive or only partially destructive way to gain data covering huge areas.

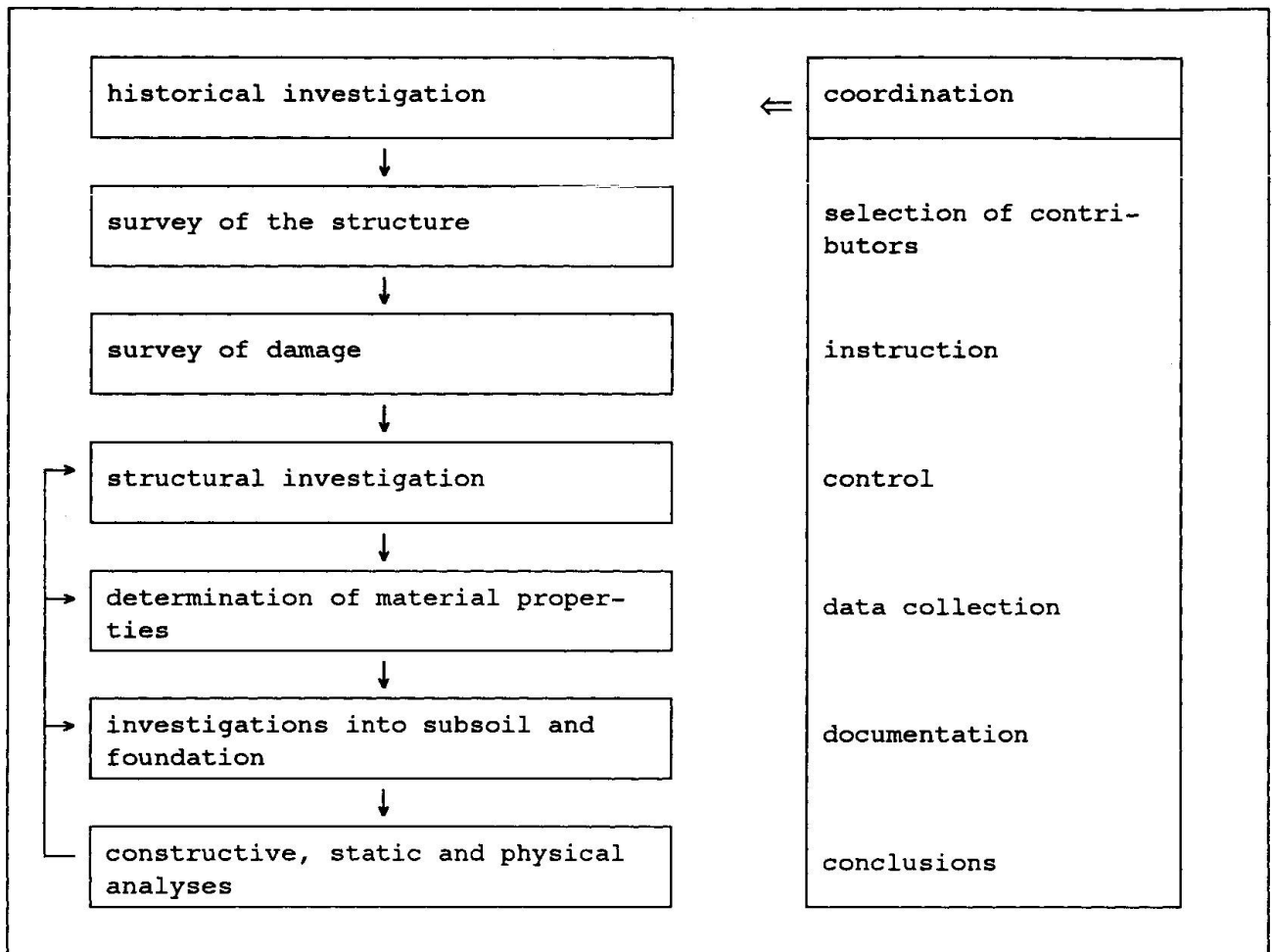


Fig. 1: Survey and evaluation of historic buildings

In order to determine material constants, e. g. strength and deformation parameters, it is necessary to take samples, usually by drilling, from the surface or the interior of the component. In addition to the mineralogy, it may be necessary to determine the concentrations of detrimental salts, and also the hygrical characteristics, e. g. equilibrium and saturation moisture, as well as physical and mechanical constants.

The investigations into subsoil and foundation are used to establish the nature, geometry, structure and condition of the total foundation system, including the ground water regime, together with the relevant properties.

The data obtained serve as the basis for constructive, static or physical analyses. They aim to determine the reasons for damage, describe the bearing system, assess the structural strength as well as to investigate into the moisture and heat balance of the building. In addition, the repercussions of the planned measures, which might bring about alterations in the structure, applied loads or environmental influences, have to be checked. When the required data are not available, further in-situ investigations of a more precise and more extensive nature have to be carried out.

The coordination of the investigations should be done at a central place. It is also there that the conclusions are drawn from the evaluation of the building, in order to formulate a rational concept for the securing, repair, strengthening or alteration of the historic building.

### 3. UTILISATION OF INDIRECT METHODS OF INVESTIGATION

#### 3.1 Preconditions

Indirect methods can be used for investigations into the building structure, the determination of material constants as well as for historical surveys and probe the subsoil and foundation. When applying them, exact surveys of the parts should be available as they are needed for the preparation, execution, evaluation and documentation of the investigation. In addition, it should be distinctively clear what the aims of the investigation are, i. e. investigation purpose and measurement area must be defined exactly. Taking into account the sequence of surveys, this may only be possible at a later stage, indeed, it may be after the constructive, static and physical analyses have shown, that it was not possible to obtain the necessary data by conventional methods.

A further precondition for the utilisation of indirect methods must be that free access to the area concerned be granted and that impediments due to other investigations or construction work be avoided. In addition, the weather conditions have to be taken into account; in particular the radar investigations are improved by dry weather conditions, as the quality of the data increases with reduced absorption.

#### 3.2 Users of indirect methods

In general, indirect methods will be applied by specialized technical firms or institutions. One reason for this is the necessary equipment, involving high investment, another is the know-how which is necessary for the operation of the equipment and the evaluation of the data collected.

This has led to a situation in which one more specialism enters the field of investigations into historic buildings while at the same time the other parties involved in the evaluation of the construction are unfamiliar with its possibilities and limits. Those who apply the indirect methods mostly come from other backgrounds (e. g. geophysics) and thus some difficulties of communication are almost inevitable.

The success of investigations carried out by means of indirect methods mainly depends on the equipment available to the operators, but also on their experience with the equipment in the context of historic buildings. These are the criteria that should be considered foremost when comparing alternative offers with possible price differences of a lesser importance.

#### 3.3 The investigation concept

The expectations from the use of indirect methods have to be clearly defined, i. e. the engineer or architect responsible has to state exactly which information he needs at a specific point.

The user has to evaluate whether the data in fact can be obtained, which conventional or indirect method should be employed and estimate the cost of the investigation. Experience has shown that it is quite difficult to describe the problems and the surrounding aspects by verbal means or through plans or photographs. It is always recommended to make an on-the-spot inspection of the building.

The specialist operator and the engineer or architect respectively need to cooperate in formulating a concept for the investigation, which has to be agreed to by those responsible for the coordination of the project.



In many cases it will be possible to limit investigations to smaller areas thus also limiting the investigation costs. Here considerations are necessary as to what extent any findings can be transferred to other areas. If investigations into larger areas are necessary, a two-step approach is being recommended. A typical sample area is chosen in order to test the applicability of the procedure, to optimize the measuring programme, to calibrate the data and to check the results. The parameters derived serve the investigation into larger areas in an efficient way.

#### 3.4 Preparation of the measurements

After the order has been received, the operator converts the investigation concept into a measurement programme which determines the most important parameters, i. e. the measurement arrangement, the direction of profiling or the measurement grid. In addition, it has to be decided whether the investigation will be carried out using a scaffold, a ladder or a lifting platform and what might be a suitable point in time for the measurements.

#### 3.5 Performance of the investigation

Additional measurement parameters are being determined at the building itself. The first data acquired should be examined thoroughly and a preliminary evaluation of their reliability should be carried out on the spot in order to alter the measurement arrangement when necessary. These checks should be carried out in between the measurements in order to detect changes in the measurement conditions in an early state.

The measurement points or profiles must be related to a system of coordinates, generally, with one axis horizontal and one vertical. They in turn must be referenced to geodetic fix points or distinctive points of the building noted in the plans, as this is the only way, that the information can be reconstructed by anybody concerned.

Very often supplementary work is necessary for the data evaluation. It is important to note down characteristics that can be directly detected from the surface of the parts, so as to correlate them with possible measurement anomalies. If the existing plans are not accurate enough, it may be necessary to measure the width of certain parts in order to calculate the velocity of mechanic or electromagnetic waves.

#### 3.6 Evaluation of the data obtained

In general, the evaluation of the data obtained is carried out in the office and takes two or three times the time necessary for the measurements themselves. It comprises the data processing, the presentation of the data in diagrams or tables, the data evaluation and the interpretation of the results.

An investigation report should be drawn up containing the most important basic findings. Such a report comprises a short description of the methods used, a list of the measurement and evaluation parameters, a presentation of the measurement data (preferably in the annexes) as well as a verbal and graphic presentation of the overall results. It should be clearly stated on what basis the interpretation of the data was carried out and to what extent the statements made in the report are reliable. The most important results and conclusions should then be summed up in a clear and understandable form for all those concerned, particularly the non-specialists.

### 3.7 Significance of the results

By definition, indirect methods do not bring about the results needed directly, but only physical data that can be related to the parameters sought. However, in most cases there is a dependency between the measurement data obtained and several parameters, and this is the reason that unmistakable statements are rarely possible. The situation can be improved by using several indirect methods in parallel and/or by drilling to control and calibrate the results.

If the user of indirect methods have broad experience with the investigations of historic masonry, they will base their work on a sensible investigation concept and carry it out with the necessary care. In this case, the results will be reliable. But first of all, the concept has to be agreed to, i. e. the necessary funds have to be allocated, the investigation should be carried out without constraints and the necessary samples have to be taken.

## 4. INDIRECT METHODS FOR EVALUATING HISTORIC MASONRY

### 4.1 Preliminary remarks

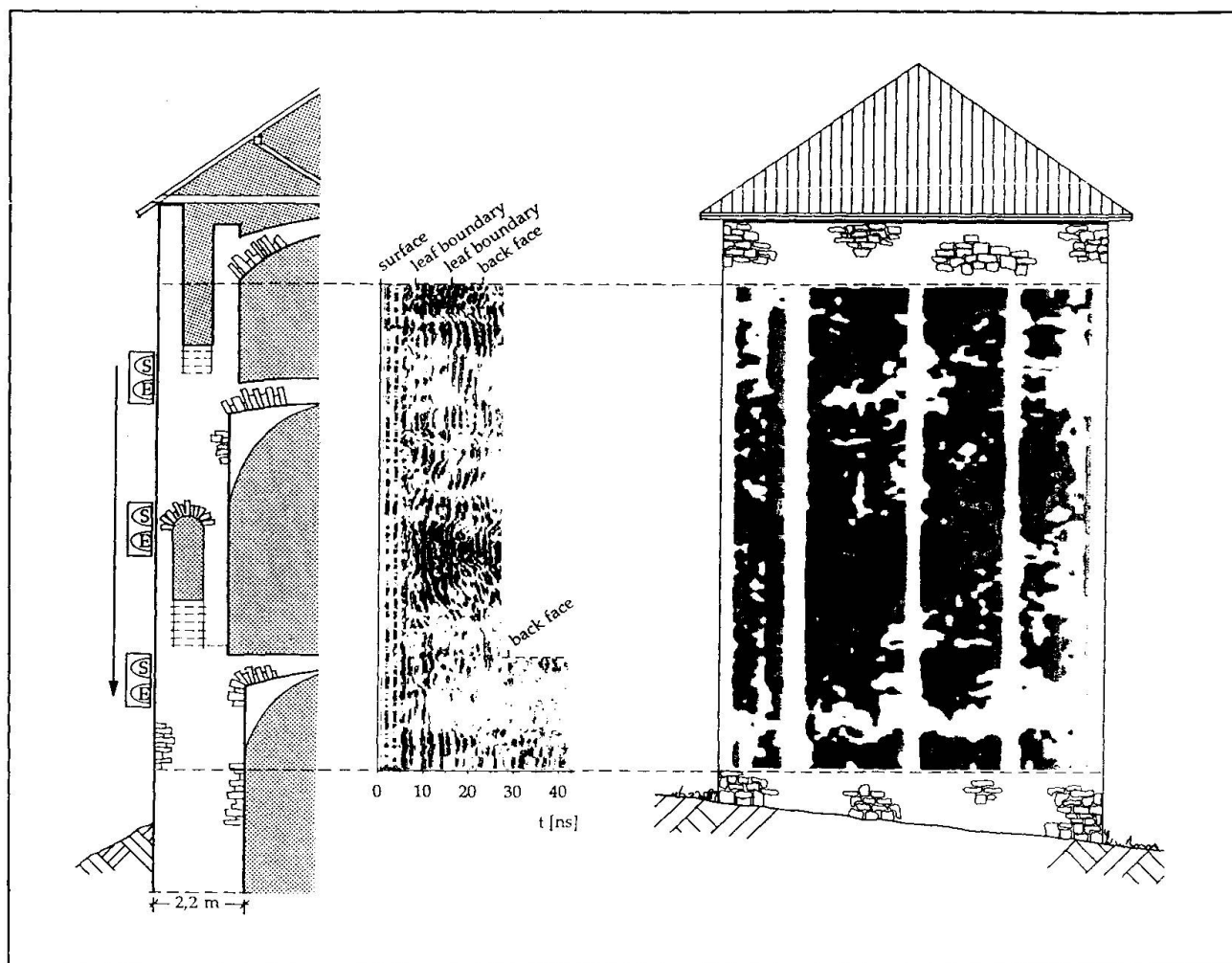
Radar, geoelectric, magnetic, ultrasonic and seismic testing methods along with infrared thermography and various moisture meters are among the available tools for which there is a stack of experimental as well as practical experience in the field of historic masonry. However, further research work is necessary in order to solve still existing problems and develop equipment and methods. Therefore, the following findings and statements are not conclusive.

### 4.2 Radar method

Radar is a powerful and versatile method of evaluating existing masonry in an efficient and comprehensive way [2, 3, 4, 5]. Pulses of electromagnetic waves in the frequency range of 100 to 1000 MHz are being directed into the structural part via a transmitter which is located at the surface of the part. The waves propagate through the part with a specific velocity which is determined by the material. At interfaces of different electrical properties, some waves are reflected and the remainder is transmitted. The signals are picked up by a receiver, amplified depending on the delay time, transmitted to the microcomputer and finally displayed in radargrams on the screen. The reflection arrangement is used in order to investigate the structure of a part (fig. 2). Multiple leaf masonry or facing walls are being detected either by the reflections due to leaf boundaries or by the different reflection patterns of the leafs. The reflections from leaf boundaries, which have separated, are characterized by significantly higher amplitudes. Voids can be detected as long as their dimensions are of structural importance. In case of discontinuities due to enclosed metals the resolution of radar is even higher, but often not sufficient to detect modern metal ties in the middle of a wall. Disintegrated, porous or sagged zones can be detected because of their increased reflectivity.

The moisture content of masonry materials is determined on the basis of their relative permittivity which in turn is calculated from the velocity of the electromagnetic waves when penetrating the part. In general, these calculations necessitate a transmission arrangement consisting of transmitter and receiver, which means that both surfaces of the structural part must be accessible. Because of the high measurement volume, smooth lateral moisture profiles do result that present the lateral moisture distribution in a realistic way.





**Fig. 2:** Radar investigation on the wall of a medieval tower; left: cross section and radargram, right: view of the wall with radar data

#### 4.3 Geoelectric method

In the geoelectric investigation method, an electrical direct-current field is induced in the test zone by means of two or more electrodes. The current within the circuit of the equipment, the voltage between the two probes (which pick up the potential difference at the surface) and a specific factor, which is derived from the configuration used, are the parameters from which the specific electrical resistivity of the material is calculated. The value depends mainly on the two parameters 'moisture content' and 'concentration of dissolved salts' [4, 6, 7, 8].

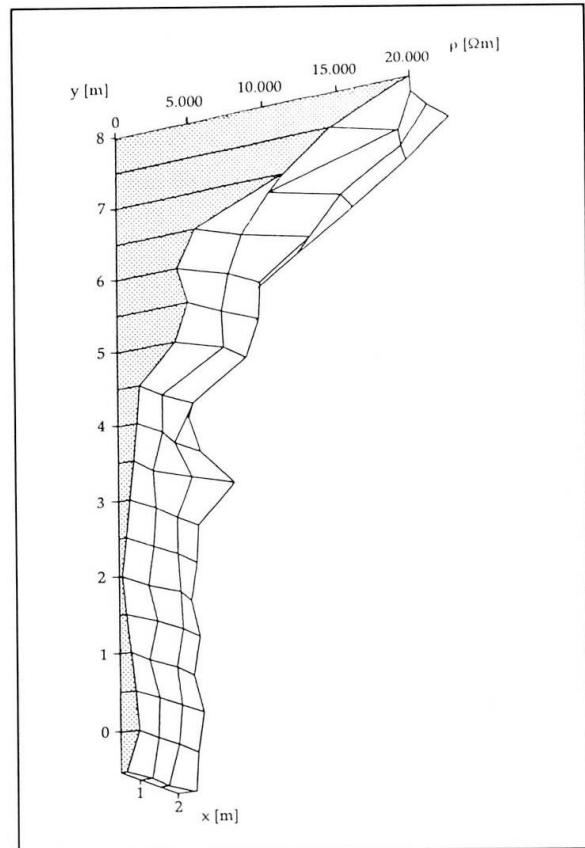
Therefore, it is not acceptable to state quantitative moisture contents directly, even if this is done in the case of moisture meters (see 4.8). However, it is possible to detect moist zones by mapping the specific electric resistivities, e. g. by using the Wenner arrangement as shown in figures 3 and 4.

With the geoelectric method it is also possible to investigate into the structure of a building, above all with regard to multiple leaves and voids. However, the resolution is quite low compared to radar.

A special variant of the geoelectric technique, the self-potential method, is based on the principle that iron corrosion generates an electric field that is picked up by two probes [9]. This method is very suitable for the detection of active corrosion processes. However, precondition is that the location of enclosed metals is known and that one of the probes is placed directly at it.



**Fig. 3:** Investigation with the geoelectric method



**Fig. 4:** The distribution of the electric resistivity  $\rho$

#### 4.4 Magnetic method

Magnetic methods in various forms can also be applied to historic masonry in order to detect the presence of enclosed metals. A simpler equipment used to detect the location and diameters of steel bars in reinforced concrete structures work on the basis of permanent magnetic or inductive methods. The pulse induction method is used for the detection of metals enclosed in greater depth. With this method, a pulsed electromagnetic field induces an electric current in metals and the mutual induction caused by this current is picked up by a receiving coil.

The geomagnetic methods used in geophysics measure the earth's magnetic field which is locally distorted by masses that can be magnetized. This is a possibility to detect enclosures that are near to the surface but not for detecting longitudinal ties in the middle of thick rubble walls (fig. 6).



#### 4.5 Infrared thermography

With the infrared thermography, the heat radiation emitted by the surface of the building - the intensity of which is dependent on the temperature - is being registered. Thus anomalies with regard to the temperature can be detected and presented fast and without even touching the masonry, i. e. without the need of a scaffold etc. A precondition is, that there is a heat flow through the part. This method has been successful in those cases where there are differences in material obscured by plaster, e. g. closed openings, joints, carcassing timber. In addition, humid areas can be located [10, 11].

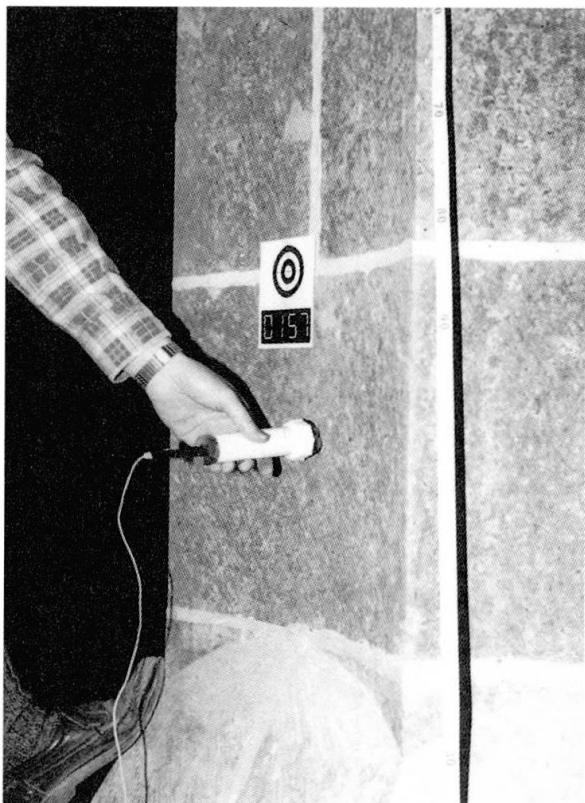


Fig. 5: Investigation with the self-potential method

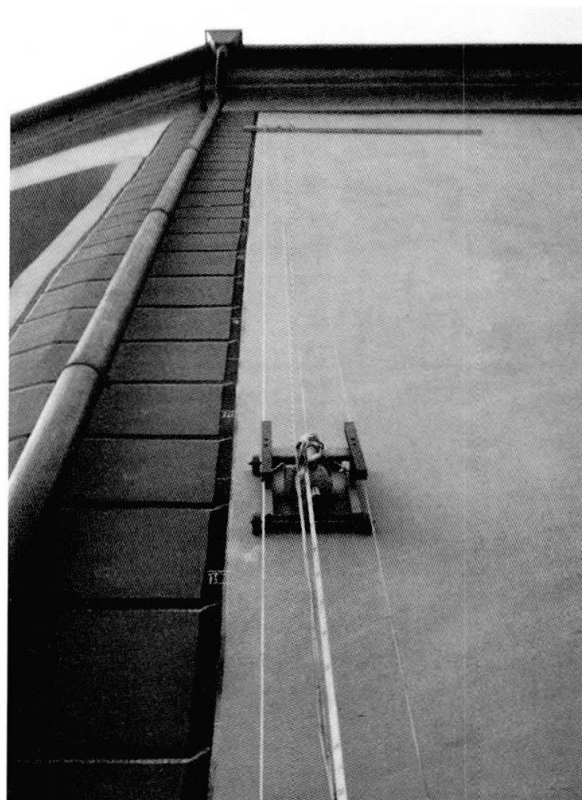


Fig. 6: Investigation with the geomagnetic method

#### 4.6 Ultrasonic method

With the ultrasonic method, mechanic waves with frequencies higher than 20 kHz are generated by means of piezoelectric or magneto-strictive transducers, and picked up after passing through the part that is to be measured. However, only masonry up to a thickness of 1 m can be inspected with this method, limiting structural investigations to thin or monolithic parts [6] (fig.7). In all other cases, the seismic method is used as the pulses propagate far enough because of the higher signal intensity and the lower frequencies, causing less absorption.

Further research work is necessary to increase the knowledge as to whether measuring the velocity of ultrasonic waves allows statements about the strength of stones or masonry (fig. 8). While the relation between the velocity of elastic waves and material properties has been proven physically for homogenous materials, the transformation into a measurement method that can be used under real conditions has not yet taken place [12, 13, 14, 15, 16].

#### 4.7 Seismic method

With the seismic method, mechanic waves in the frequency range between 300 Hz and 3 kHz are generated at the surface of the structural part, preferably with a hammer. They propagate through the part and are picked up by one or more receivers. The development of reflection methods is still being worked on, therefore only the transmission arrangement will be discussed here. With this arrangement, the propagation time of the longitudinal wave, which is the fastest of the various kinds of waves, is measured between the transmitter and the receiver(s). The wave velocity calculated from this value depends on the one hand on the material properties, on the other hand also on voids, for example open or unfilled cross joints. Such anomalies cause deviations of the wave propagation and therefore a seemingly lower velocity. The seismic method permits a differentiation between areas of different materials or structures, e. g. multiple leaf masonry, filled openings, joints. As the measurement results are related to the mechanic properties, this method is often of great help. In addition, large voids can also be detected [6, 17]. The seismic has also been used for checking the effectiveness of injections aimed at the improvement of damaged masonry [18].



Fig. 7: Investigation of a sandstone pillar with the ultrasonic method

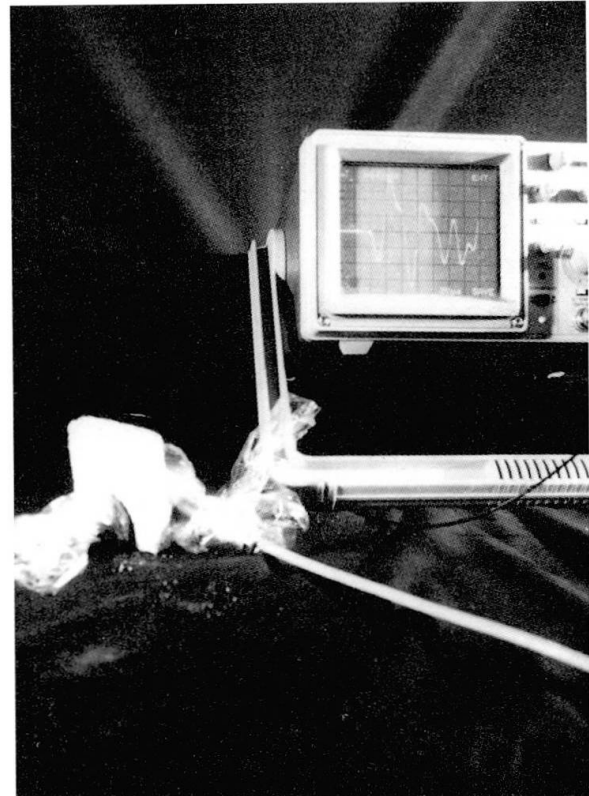


Fig. 8: Ultrasonic measurement to determine the mechanic properties of mortar

#### 4.8 Moisture meters

Various non-destructive methods for measuring from the surface of masonry the moisture contents of materials are offered on the market and being used.

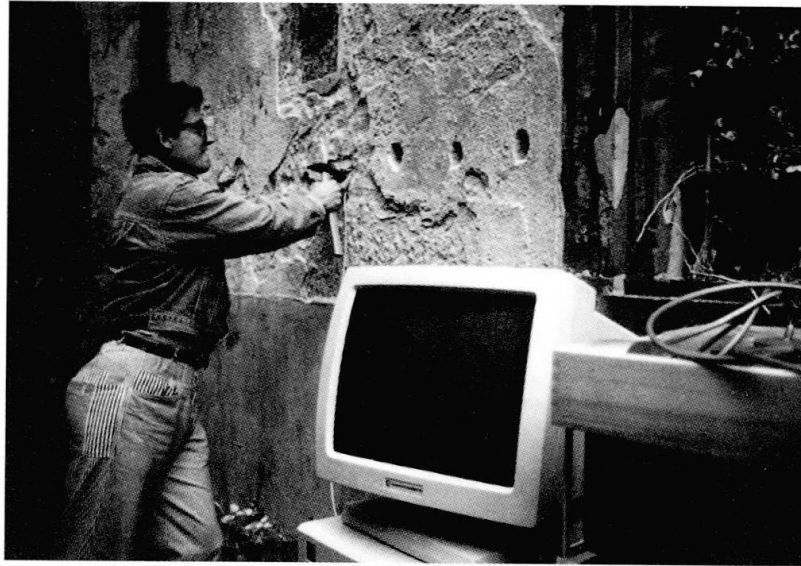


Fig. 9: Investigation of a wall with the seismic method

In contrast to the geoelectric method with four probes, the conductivity meters comprise only two electrodes which generate an electric field within the part and also pick up the potential difference. Therefore, there are two reasons why this equipment is not suitable for historic masonry: on the one hand, the high transition resistances between the electrode and the part itself falsify the measurement values to quite an extent; on the other hand, the specific electric resistivity does not only depend on the moisture content, but also on the concentration of dissolved salts [4].

With the capacitive technique, the relative permittivity of the material is determined using stray field capacitors. If the measurement frequencies are sufficiently high, the permittivity mainly depends on the moisture content. However, the units on the market only offer a penetration depth of a few centimeters, which is too shallow. In addition, the electrodes must be placed on the surface with very high precision in order to avoid measurement mistakes.

Neutron meters emit fast neutrons which are slowed down mainly by collisions with hydrogen atoms. The slow (thermic) neutrons are counted with counter tubes and the detection rate serves to derive the moisture content [19, 20]. Up to now, the applicability of neutron meters to masonry has not been investigated in a systematic way but experience indicates that it can be used. Disadvantages are the use of a radioactive radiation source (which has to meet legal requirements), the influence of chemically bound water on the measuring results and the relatively shallow penetration depth of approximately 10 cm.

#### 4.9 Combinations of indirect methods

In many cases, it will be reasonable to combine indirect methods in order to get more reliable results. When doing so, the additional expense is not very high and can well be justified, if significantly better results are expected.

The combination of radar with other methods can be recommended in many cases. Radar is used for the complete area as it is very versatile, fast in picking up data and of high resolution. For checking and improving the interpretation of the data, an additional method, possibly with only few measurement points, can be used. The following gives three examples for such a combination.



The radar method is well suited for the detection of leaf boundaries, but it offers no statement concerning the characteristics of an inner core in the case of multiple leaf masonry. This can be achieved in the following way: By means of the seismic method, the propagation velocity of the elastic waves in the masonry is measured, while the velocity in the stone is measured at the surface or on drill cores using the ultrasonic technique. If the two values differ significantly, this serves as a clear indicator for the existence of a rubble infill.

Quite often, anomalies that were detected with radar cannot be classified. Magnetic methods, in some cases also the geoelectric method, can be used for checking as to whether there are enclosed metals. In addition, the self-potential method can be used to detect active corrosion.

If radar is applied for the determination of the moisture contents, the geoelectric method can be used to measure the specific electric resistivities, thus allowing statements about the concentration and distribution of dissolved salts. However, the use of two indirect methods influences the accuracy of the results, which should then be checked by sampling.

#### 4.10 Taking samples

In general, samples have to be taken in order to control and calibrate the results obtained via indirect methods. If necessary, they must be inspected and further examined. The extraction procedure is dependent on the required form and dimensions of the sample, the necessary depth of the intervention and other factors. In most cases the taking of drill cores will be chosen, but for the determination of the moisture content of masonry it may be sufficient to take drilling debris gained with a spiral drill. In very few cases individual stones or mortar taken from the masonry serve as samples.

The samples are visually inspected and, if necessary, tested in the laboratory in order to determine ultrasonic velocities, mechanical properties, natural or saturation moisture content, hygroscopic moisture, salt concentrations, etc.

In addition, the drilling holes can be inspected with an endoscope, in particular, if the information required cannot be gained from the cores.

## 5. THE USE OF INDIRECT METHODS - COSTS AND BENEFITS

### 5.1. Costs

The time required for the measurements depends on several factors. Roughly estimated, an area of approximately 50 sqm can be covered with one method in the course of one day; with radar it can be twice the size. The evaluation and documentation of the investigation, which in general are carried out in an office, take two to four times the time needed for the measurements.

The prime costs of the investigation derive from the time needed for the preparation, performance, evaluation and documentation of the measurements. Additional costs arise from travelling, accommodation, scaffolds or lifting platforms, as well as from additional sample taking and examination. Costs for investigations that necessitate one day of measurements amount to DM 3,000 to DM 6,000. In many cases, this will be enough to clarify questions, but it can be well above this sum.



### 5.2. Benefits

A great advantage of the indirect methods is the possibility of non-destructive measurements. However, interventions into the masonry will be necessary in the future, too, in order to check and calibrate the results. On the other hand, fewer samples are necessary under these circumstances and they can be taken in a very target-oriented way.

The decisive advantage of indirect methods is due to the fact, that relevant information on an extensive area of the building is gained and no important features are missed. This has the following advantages:

- The reasons for existing damage can be determined in a reliable way. Once they have been dealt with, the damaged areas can be repaired. The reoccurrence of damage can be avoided.
- Risks due to structural failure or disintegrating ornamental parts can be assessed. Necessary measures can be initiated.
- The structural strength of existing buildings can be assessed in a more reliable way. Strengthening can be limited to the parts where it is unavoidable.
- Construction measures can be initiated early and on a sound planning basis. Thus, the necessary decisions can be taken and mistakes be avoided.
- New target-oriented and less invasive repair methods, for which the knowledge of certain characteristics is needed, can be implemented.
- The success of measures can be checked by later investigations.

The advantages mentioned above are in parallel with reduced interventions into the historic masonry and savings during the works as well as lower follow-up costs due to the employment of inappropriate measures.

### 5.3 Decision making

In many cases, the costs of an investigation with indirect methods, plus an additional sampling, will be much lower than other savings, achieved due to the elaboration of an optimized working concept for the securing or repair of the historic building. However, very often it is difficult to convey this to the client and others concerned. The reasons for this are, that on the one hand a new thinking must prevail with regard to the necessity of an extensive evaluation, and on the other hand, clients do hesitate less to spent sums of this order of magnitude for apparently necessary construction work than for an investigation, the necessity of which in their understanding is not so obvious.

However, apart from the cost-benefit analysis, there are also other criteria for a decision in favour of the use of indirect methods:

- specifications or requirements imposed by the Monument Protection Authority with regard to interventions into the masonry in the course of the investigation or the carrying out of construction work;
- requirements expressed by architects, structural or proof engineers who need detailed information when evaluating the masonry and planning construction work;
- requirements imposed by official bodies in case of risks due to structural failure or disintegrating ornamental parts.

## 6. CONCLUSIONS

Indirect investigation methods have proved their applicability to historic masonry in the laboratory as well as in the field. However, further research is necessary. When evaluating existing historic buildings, these methods bring about important results which allow a reliable assessment of structure and condition of the building. Thus, it is possible to determine the cause of existing damage, and sensible concepts for the securing and repair of historic masonry can be developed. The planning of these measures can be initiated early and on a more reliable basis. Fewer interventions into the masonry are necessary. Costs can be cut through sound planning and reduced target-oriented measures, so that the use of indirect measures becomes an economic option.

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