Displacement monitoring in the church of Sint-Jacob in Leuven[1]

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1. Monitoring in the process of monument conservation

Fundamentally, the persons in charge of monument conservation have to **take decisions** among which “do we have to intervene?” is one of the more frequent. Taking them leads to verifying criteria which, if we limit ourselves to structural problems, usually concentrate on resistance, stability and rigidity. Very often stability will be the determining criterion.

In order to verify these criteria, one needs to study the structural behaviour of the building, and hence has to know the structure as well as the boundary conditions to which it is subjected. But, what is true for any building is even truer for historical buildings: the **data is uncertain**. One only has a discrete set of mean information available. Geometry is frequently complex, deformed. Surveys are more often executed for reasons other than stability studies. They are always spoilt by mistakes, rarely estimated. Materials have variable characteristics, the techniques used for construction are not known with certainty. Also the boundary conditions have to be known. The initial stresses are a function among other things of the construction technique, of the history of the structure, of its construction, of its transformations and of its solicitation history (extreme winds, earthquakes, etc.). The structure also rests on soil whose characteristics are just as uncertain.

The data is uncertain, which influences the results and so which decisions to take. Even if some factors have less influence than others, one easily understands that to try to search for the actual behaviour of a structure is illusory. To study it, the engineer is forced to use simplified reproductions, the models. To study according to the principle of limit analysis, a model structure which is “certainly” less strong (or regarded as such)is subjected to “certainly” more harmful solicitations (or regarded as such) in order to fix reliability domains. We will call this model structure the ***mathematical model***.

It is this model which, ultimately, will allow the decision criteria to be verified. The quality of this model will lie as much in the good knowledge of its limits as in its capacity to supply results. Because the structure already exists, **other types of information** can also be used in order to define these limits better. Other models can be built (they have to be models because the information is never direct and complete). In this hazy context, one understands how interesting it is to try to gather all the available information to build as sound a base as possible, on which the decisions will be taken. We can name, without being exhaustive, the *geometrical model* (survey), the *existing deformation model* (cracks and existing deformations), the *historical model* (construction phases) and the *deformation model* (monitoring).

The ***deformation model***, built with the results from the monitoring, plays a special role. In relation to stability, it is clear that geometrical aspects are fundamental. The more direct and reliable source of information on the geometry changes, is the monitoring of displacements.

If nothing were to change, stability studies would be unnecessary. The *deformation model* allows us to see how the structure deforms (every structure moves) and the *mathematical model* allows us to see how worrying these deformations are, so these models must be taken together. Generally speaking, bidirectional exchanges of information between all the models of the building and the modalities of these exchanges have to be designed.

The potential contribution of the monitoring to stability studies can be clarified in accordance with the nature of the causes of the movements, the *events*.

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For **steady or periodic events**, the monitoring system can give a direct answer. The existing deformations of the historical monuments are often important. However, most of the time, these deformations happened in the past, even if the awareness of their existence is recent. The monitoring permits us to see if the movements are only linked to variations (daily, seasonal, etc.) of the external factors (temperature, water table, etc.) or if a continuous trend exists. Thus we can also understand better the behaviour of the structure and so choose models closer to reality and determine the more sensitive zones to external actions. It helps to delimit the boundary value variations. For **controlled exceptional events**, such as restoration works or construction works in the vicinity, the monitoring system can be used to verify the good progress of the works and the effectiveness of measures. For **uncontrolled exceptional events** (extreme winds, earthquakes, etc.) the monitoring system usually brings no direct answer. Afterwards, it can, however, produce information about the behaviour of the structure during the event.

To finish and to qualify a vision of conservation of monuments, which could appear too pragmatic, one should maybe return to the prime aim of conservation. If man wants to preserve historical buildings it is because they are part of the human heritage and, as such, are bearers of **messages**. As a message implies reading, the actions on monuments should not be limited to the necessary protection measures but also include parallel studies aiming for a better understanding of them. If the artistic and historical dimension of this message is well recognised, it is not always the case for the structural dimension. And, in the end, a better understanding leads to the adoption of more sensitive solutions.

In what follows we are going to describe an experience. It will not be, unfortunately, the perfect illustration of definite theory. The importance of studying and designing the interactions between the models in order to better answer the various questions provoked by the monument will be emphasised.

2. Sint-Jacob church

Sint-Jacob church (fig.1) is situated in Leuven. It has Romanesque, Gothic and neoclassical parts. Owing to stability problems, it was closed in 1963. In 1994, the *Flemish Community*, in order to study the possibility of a restoration, ordered a stability study from the *R.Lemaire Centre for Conservation*.

The church has a western tower, a four-row nave, side-aisles, a prominent transept, a choir and two chapels on the western side of the northern and southern parts of the transept. From the structural point of view, the construction of the church in many phases and the bad quality of the ground have led to important differential settlements. At the turn of the 15th and the 16th centuries, the **nave was heightened and covered with brick vaults** whereas the original nave must have had a wooden roofing. A heavy increase of the loads on the columns and important deformations resulted from that.

Figure 1

The analysis of the existing deformations and of the cracks shows very well that the main problems of the church are the consequence of the differential settlements of its various parts. So, priority was given to following through their evolution. We also decided to follow the deformations of the springing of the vaults.

- The vaults, causing horizontal thrust, are destabilizing elements; the knowledge of their behaviour is important when the time comes to check the general stability.
- The two first rows of the nave have their thrust held by a tie-rod and the two last by flying buttresses. The study of the movements of the springing of the vaults gives an opportunity to look for the influence of these systems.

The temperature was also measured at various points. A system to measure the variations of the water table was installed but, unfortunately, it did not work properly.

Of course, other measures could have been taken but setting up a monitoring project always means that an optimal solution not exceeding a given budget should be sought.

3. Altimetrical survey

The disorders found in the structure of the church have, most certainly, the **differential settlements** as their main cause. Two types of measurements were carried out: geometrical measurements with a precision level and continuous measurements with hydrostatic levelling. These measurements are important because it is quite possible that the differential settlements took place mainly just after the nave was heightened. Against that hypothesis, the constant concerns throughout history, ending with the closing of the church, seem to indicate that the situation was not stabilised. But there is another problem. In the year 1970 an important metallic structure was installed in the nave to help the columns to carry their charge. This structure could have invalidated the results. Even if the movements are small it does not mean they would remain unimportant if the metallic structure was dismantled.

Levelling

On each column and, more generally, on each “structural node”, a levelling reference mark in stainless steel and ending with a sphere, was fixed. In total, 63 marks were placed, every one of them at about 50cm from the ground. Five measuring campaigns were planned, at three-monthly periods (08/04/1994, 03/08/1994, 28/10/1994, 13/01/1995 and 20/04/1995). During these campaigns the heights of all the marks were measured again and the difference with the original measurements and with the previous campaign computed. The measurements were taken with a Wild/Leica N3 bubble level. This high precision device, equipped with a parallel plate micrometer, allows, if used with an invar rod, a reading to the nearest 1/100mm. Considering the path measured, we estimate a standard deviation of 0.1mm for the measurements. Since we are interested in differential settlements and not in absolute settlements, one point, point number 30 situated in the choir, was considered steady and its height conventionally fixed at 10m.

The height differences range from 0 to 1.6mm. For every campaign pair, the maximum differences are (N^{2-1} : 0.9 mm, N^{3-1} : 1.1 mm, N^{4-1} : 1.3 mm N^{5-1} : 0.8 mm). The lower differences between the two campaigns are separated by one year. The seasonal deformations are therefore important in relation to the possible continuous movements. To determine the existence of such a trend with certainty, new measurements should be taken.

In order to try to interpret the results spatially, plans were drawn up. Their study allows us to draw some temporary conclusions. The deformations are quite complex and their interpretation questionable. The church does not have a symmetrical behaviour around its longitudinal axis. The two metallic reinforcing structures, the one on the northern side of the church and the one on the southern, have in particular, a different behaviour. Some independence of behaviour between the various parts of the church can be noted. The points in the transept seem to indicate quite important differential movements between the nave and the transept. It is also in that transition zone that the crack pattern is more extensive. The tower has roughly an alternating movement around a northwest-southeast rotation axis. In the present situation the nave is one of the more stable parts of the church. Again, it would be beneficial to have new measurements at our disposal to confirm the hypothesis.

Hydrostatic levelling

Hydrostatic levelling is based on the principle of communicating vessels. The instrument used is the HLS, developed by the French company *Fogale nanotech* in collaboration with the *ESRF* (European Synchrotron Radiation Facility). The instrument is composed of vessels (fig.2) linked to a double circuit: one to let the measuring liquid circulate and another one, an air circuit, to set an identical pressure in all the vessels. The liquid used is water (normal water, non-distilled so that it can conduct electricity) with a colouring (to be able to control the presence of bubbles). In each vessel, the height is measured with a capacitive sensor (which measures the distance between the water level and the sensor). The readings range from 5000µm to 10000µm. Measurements are taken with the system frequency (about 33Hz) and the results visible on the computer screen. They are stored with an adjustable frequency (we chose every 15min.). The measurements stored are the means of 100 values taken in 3s. Normally, every day, one file is created to store the temperatures and another one for the displacements. Various precautionary measures were adopted to improve the accuracy of the system. The temperature is measured in every vessel and the rough displacement measurement is directly corrected according to it. The tubes of the water circuit are placed as horizontally as possible in order to remove the effects of a temperature gradient. The tubes of the air circuit lead upwards from the vessels to prevent the condensation water from staying in the air circuit. The analogical response of the sensor is digitalised and linearised by a 12Bit card.

Figure 2

Eight vessels were installed inside the church: four in the tower and four in the nave. The measurements were made from the 8th of July 1994 to the 13th of November 1995, namely 139 days. In the tower, the vessels were placed in every corner. In the nave, they were placed at the bottom of four columns, corresponding to the two central rows. Again, as no vessel can be considered steady, it is impossible to know the absolute values of the settlements. In practice, all the displacements are recalculated in relation to the mean level of the water in the circuit.

To study the daily variations, three sample weeks were chosen (the weeks 30, 37 and 46 of 1994). To eliminate the long-term variation, the variations were recalculated for every week around the regression line. Temperatures in the vessels are, at any given moment, relatively equal. In the tower, the minimum temperature is reached at about 7.00 hours and the maximum at about 18.00 hours. There is a phase difference of about 2 hours between the nave and the tower. The maximum daily variations range, for the temperature, from 0.5℃ to 2.5℃ and for the displacements, from 0 to 30µm. There is no marked difference between the nave and the tower and not even between the vessels. There is a good correlation between the mean level of the water in the vessels and the mean temperature. An increase of the phase difference between the mean level and the temperature maximises this correlation coefficient.

As measurements were taken every 15min, the amount of data was quite enormous. After having studied the higher frequency phenomena, we concentrated the data. For every vessel, three values a day: a maximum, a minimum and a mean value were computed. Looking at the graphics (see example on fig.3), we can try simplifying the situation by saying that all the curves have a general trend and transient variations. The general tendency is generally linear and sometimes (vessels 4,6,7 and 8) slightly curved indicating perhaps a first manifestation of the seasonal influence. During the 5-month period the displacements were of the order of 0.1mm, from 30µm (vessel 1) to 120µm (vessel 4). The transient variations around the general trend are of the order of 10µm. If the trend were constant (200µm/5 months), it would mean a 4mm move in 10 years which is not very worrying, also because the seasonal variations most probably produce a slowing down of the movements.

In our particular case, the knowledge of the order of magnitude of the displacements justifies the choices made for the optical levelling. The high frequency variations with a magnitude ten times lower than the levelling precision are imperceptible and do not influence the results. The results given by the two levelling systems show that a precision of 1/10mm is just sufficient to follow the seasonal variations.

Hydrostatic levelling is a powerful technique. Its high precision and the automatic recording of the measurements allow the almost continuous monitoring of the various phenomena affecting a building. Its cost however will restrict its use to very delicate situations, for important monuments or for scientific reasons (to understand better the behaviour of historical structures, especially faced with transient events). However, geometric levelling cannot be totally replaced by hydrostatic levelling. What is won in precision and *continuity in time* is, because of its high cost, lost in *continuity in space* (number of measured points).

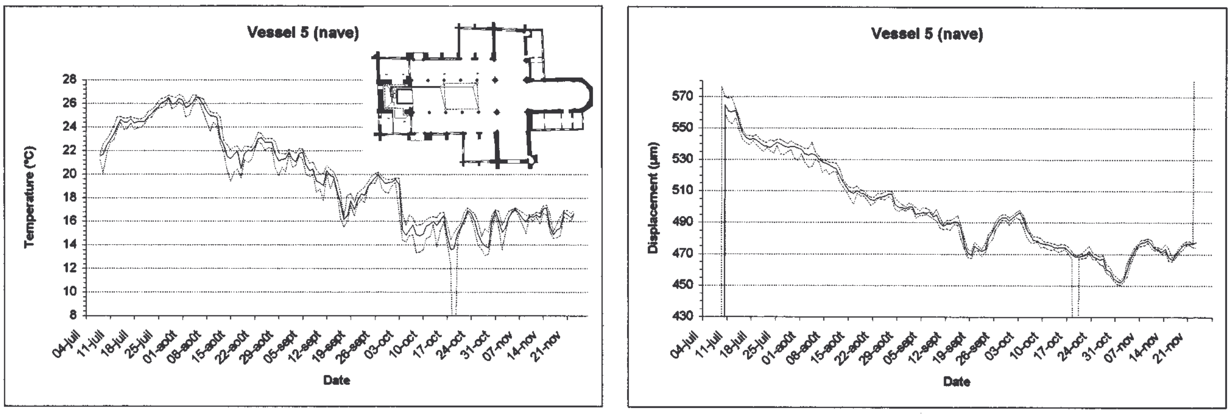

Figure 3

4. Planimetry, measurements of variations of distance

In order to control the deformations of the vaults, the variations of distance between reference marks placed on the structure at the level of the springing of the vaults were measured. The instrument used was the Distinvar marketed by the Swiss company J.Baechler+Fils in collaboration with the CERN and which allows high precision distance measurements (0.03mm/50m). The system is composed of three elements: invar wires, the measuring instrument (fig.4) and a fixed point. The points to be measured are made by reference cylinders fixed on L-shaped brackets anchored in the walls of the structure. At the moment of the measurement, the instrument and the fixed point are each placed on a cylinder by a male piece allowing a precise centring, with the invar wire linking the instrument and the fixed point. The distance between the two cylinders is computed adding to the known length of the wire a positive or negative value given by the measuring instrument. The reading is made in 1/100mm.

Ten reference marks were chosen (1001,1002,…,1010), at the level of the four rows of the nave. With three calibrated wires; for the transverse, the longitudinal and the diagonal measurements, the network could be measured by trilateration with overabundant measurements. Five campaigns (1,2,…,5) were planned (01/06/1994, 07/09/1994, 09/12/1994 and 15/06/1995).

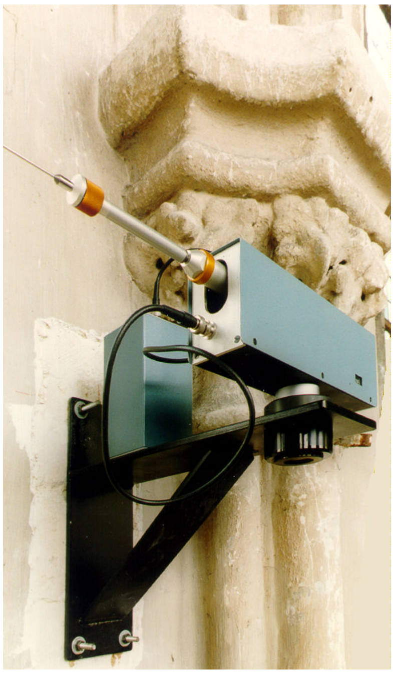

Figure 4

The measured length variations range from 0 to 1mm. This order of magnitude is the same as the one linked to the variations of temperature. The deformation between summer and winter is greater than the annual deformation. The time span was not long enough to strictly divide the trends from the seasonal variations. The low number of measurements makes any conclusion uncertain. In order to understand better the deformations, interpretation drawings were prepared (fig.5). Thanks to the knowledge of the distances between the points, changing from one campaign to another, it is possible to draw the structure after deformation. That shape is determined minimising the error between the measurements taken on the building and the ones taken on the model. The general movement of that shape is unknown. To allow a comparison between two campaigns, the general movement is considered non-existent and the shapes are superposed as closely as possible, that is, in such a way as to minimise the mean quadratic distance between the corresponding points of the shapes. The variations of distances are then calculated, multiplied by 5000 to be visible, and added to the shape of the first campaign.

The eastern part of the nave has a completely different behaviour from that of the western part. This difference is probably the consequence of the presence of flying buttresses in the east and of tie-rods in the west. During the winter the tie-rod could contract, bringing the nave walls closer whilst the flying buttresses could impress a contrary movement on the walls, and conversely during the summer.

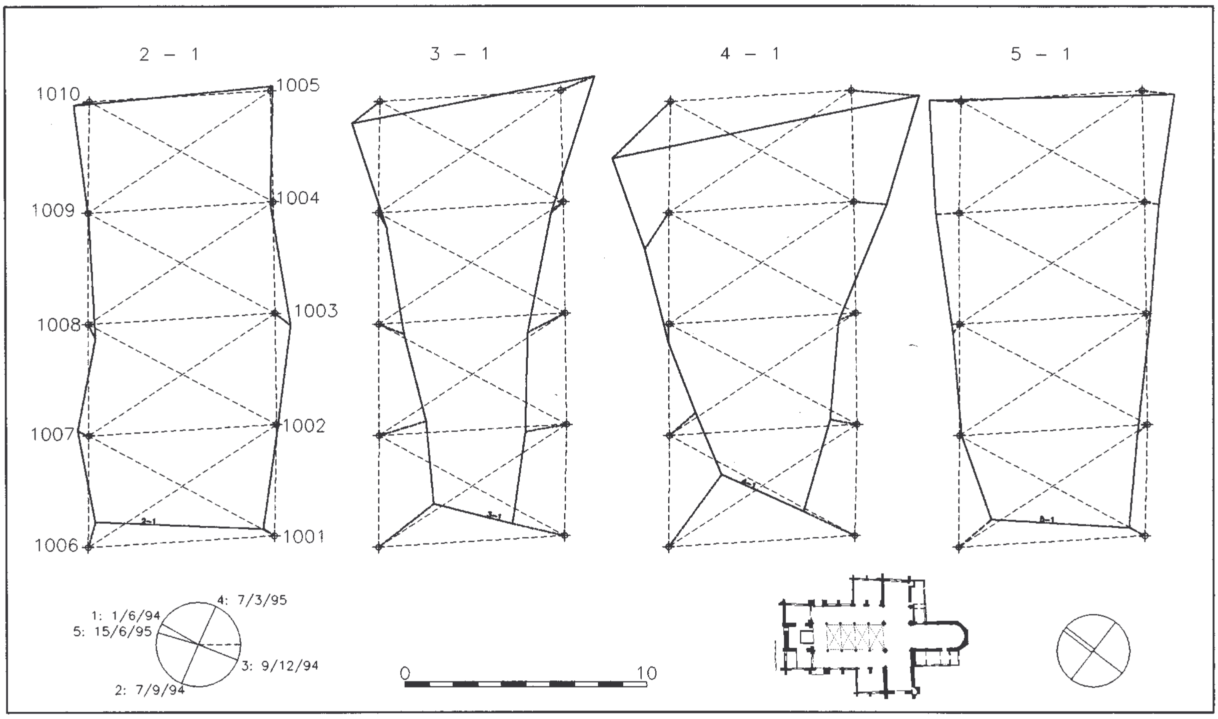

Figure 5

5. Conclusions

Displacement monitoring is an invaluable help to the conservation and knowledge of our historical heritage. In the planning of a project, considerations concerning number and type of instruments, precision, frequency, duration of the measurements and costs are deeply connected.

Measuring type

Without wishing to simplify too much, the stability and rigidity controls are mainly a matter of displacement and the resistance control a matter of deformation. If the stability problems are the dominating issue, the global measurements (invar wire, plumb line, etc.) are to be preferred to local measurements (extensometers, fissurometers, etc.) requiring integrations to provide information on displacements. Absolute measurements being difficult to obtain – demanding the presence of a fixed base - and not being compulsory – only the relative movements of building parts having an influence on the stability - the relative measurements are to be preferred.

Precision

The precision has to be adapted to the phenomenon one wants to follow. If we try to search for the movements liable to significantly increase the instability risk of a building, their order of magnitude changes from one case to the other, but it is more often closer to 10mm than to 0.1mm. The *mathematical model* assesses this. If we want to follow and understand the influence of the daily or seasonal variations of temperature or of the water table, the influence of a train passing or of a violent gust of wind, the precision will often have to be increased.

To ensure a long term maintenance of the precision, it is very interesting to place physical marks on the structure, with characteristics which are stable in time. Thus years later, even if the system was left without maintenance, it can be reinitiated so that the evolution of the phenomenon can be measured through the new results being compared with those from the past.

Frequency

The measurements will never be, strictly speaking, continuous; the instruments are only taking a discrete series of mean measurements. The frequency of the measurements has to be adapted to the rapidity of the evolution of the observable phenomenon one wants to follow. For the measurements to be **significant**, the measured value cannot vary too much during the measuring process nor between two measurements. The only way to verify this would be to dispose of continuous and instantaneous measurements and, as this is impossible*, “quietness” hypotheses* are always made. These hypotheses find a basis if one manages to link the movements to a discrete set of causes with a known character (other hypotheses). It is therefore sufficient to adapt, consequently, the frequency to the evolution velocity of the presumed cause (from a fraction of a second, if we study the influence of a lorry passing, to the year, if we are interested by the long-term settlement trends). To study slow effects, the frequency can progressively decrease as the influence of high frequency causes has been studied. For the measurements to be **economical**, the variations between two measurements must not be small in relation to the precision of the instrument. The frequency can also decrease if a point moves a little.

Placement

The problem of choosing the places to set the instruments is, in a certain manner, similar to the one of choosing the frequency. Here, the spatial dimension takes the place of the temporal dimension. What was said for the frequency remains valid. The *“quietness” hypotheses* are formalised by the *existing deformation model*. From the study of the *mathematical model* (critical points) and of *the existing deformation model* (critical movements), it is possible to determine as efficiently as possible the places for the instruments or for the reference marks. Moreover, the density of measured points should be sufficient to enable previous hypotheses made in other models to be questioned.

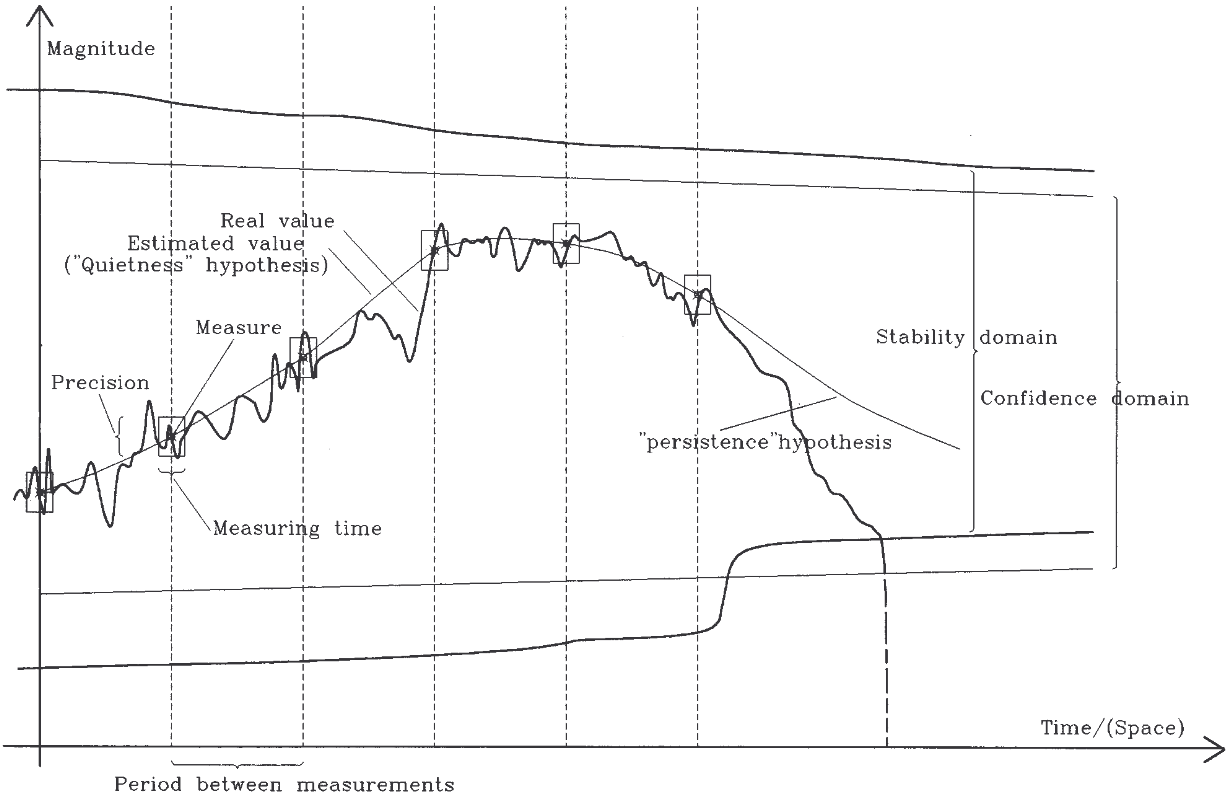

Figure 6

Duration of the measurements

The duration of the measurements should be sufficient to circumscribe the phenomenon. If, for instance, we want to study the influence of a lorry passing by, it could be of the order of a minute. If we want to detect a long-term trend, for diverse reasons, it is not possible to circumscribe the phenomenon anymore and we then need to introduce *"persistence" hypotheses*. Very often, the seasonal variations cause movements that, if persistent, would eventually become dangerous. To study the long-term trends, it is necessary to eliminate the influence of seasonal variations; so the absolute minimum for the duration of measurements must be one year. Experience shows, however, that it is very difficult to conclude after such a short time. If the movements were small and if there is a presumption of the dominant role of cyclic movements, non-dangerous for the stability, then we can imagine it would be sufficient to start the measurements only after a few years. In some cases it can be interesting to introduce some control measurements into the maintenance programme of the building.

Redundancy

To have a better control over the precision, it is important to have overabundant measurements. What we could call **internal redundancy** could even bring the idea of an **external redundancy** allowing for each model to control part of the information conveyed by the others. These controls are only possible if they are planned from the beginning. The *existing deformation and mathematical models* contribute, for instance, to the construction of the *deformation model* which in turn leads to the improvement of the former.

Cost

Monitoring is expensive, but contributing towards a better knowledge of the building and its problems brings the conservation costs down as low as possible. In the long-term, the costs can be lowered, confining the equipment to the most critical spots.

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