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Assessing the concrete of Nuclear Power Plants containment by NDT

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ABSTRACT

The aging of prestressed concrete containments wall of nuclear power plants is experimentally modelled by a 1/3 scale mock-up of 15 m in diameter and 20 m in high carried out by EDF within the VeRCoRs project. This aging leads to the modification of the concrete properties as well as to possible mechanical damage during a pressurization cycle at 4.2 bars of the containment. This pressurisation carried out annually on the mock up, represents the conditions of the ten-year inspections imposed by the French regulations for Nuclear Power Plants (NPP).

On the basis of several previous projects having developed Non Destructive Techniques (NDT) for civil engineering in laboratory and structured their transfer on site, a consortium made up of 9 partners participated in the monitoring of this double-walled containment within the framework of the ENDE project (Non Destructive Evaluation of the NNP containment walls). NDTs have been implemented with two objectives: assessing the physical (water content, porosity) and mechanical (strength, modulus of elasticity) properties of concrete over time and monitoring structure damage (depth and opening closing of cracks) more specifically when the containment vessel is under pressure. The techniques used for characterization are: ultrasonic waves (linear, diffuse and nonlinear acoustics), electromagnetic and electric fields and permeability. A statistical selection of the most efficient measured parameters is associated with a fusion of multi-technical data to assess the concrete properties.

To monitor the damage, the NDTs are implemented on an area with cracks. They are surface ultrasounds for deep auscultation, acoustic emission, and diffuse waves.

A third approach is developed with a global analysis of the structure by follow of modal analysis and vibration.

The article presents the auscultation strategies and measurement methodologies for the three objectives, the proposed innovations, and the results. We focus on the evolution of the water content that we can quantify as well as on the control of cracks length and opening.

We intend to propose a strategy of Structural Health Monitoring of the containment walls with a global-local approach based on the modal analysis of the enclosure.

Keywords: NDT, Cracks Control, Concrete Characterization, Containment Walls, Data fusion

1. INTRODUCTION

The containments of the power plants constitute the last barrier in the event of an accident such as the rupture of the primary pipeline or during a major external mechanical event. It is important that their tightness and mechanical resistance be assessed during operation or during ten-year inspections of nuclear power plants. In the event of a rupture of the primary pipe, the pressure rises to 4.2 bar and the temperature to 180°C in 20 s, which generates the opening of existing cracks or the creation of new ones, especially since the mechanical properties of the concrete have evolved.

The ENDE project (Non Destructive Evaluation of Nuclear Power Plant Containment Walls 2014-2022) aims to characterize the concrete as well as the cracks. It follows several projects [1-2]. It is based on a 1/3 scale mock up (VerCoRs) of a containment building. The dimensional homothety of the thickness (0.4 m for 1 m) and therefore of the saturation conditions of the walls makes it possible to simulate the Integrated Leak Rate Test (ILRT), scheduled each Ten Years in France, by a test each year. The project is built on 4 stages from laboratory measurement to on-site measurement:

The first stage consisted in the laboratory of studying the sensitivity of the parameters resulting from the non-destructive testing (NDT) regarding the properties of the concrete: saturation, thermal damage and stress applied. The objective is to select the NDT measurements most capable of characterizing the concrete.

The second time allowed in the laboratory to follow the diffused damage in the concrete then the generation of cracks in different cases of loading by acoustic and imaging techniques. Some tests have been realized to follow the opening and the closing of cracks.

The third phase enabled laboratory techniques to be transferred to on site. This change of the structure dimensions was implemented through the VerCoRs mock up measurements.

The fourth step led during the extension of the project to make NDT techniques operational for industrial measurements. It also made it possible to structure part of the links between the END measurements and the thermo-hydromechanical modeling (THM).

After a reminder on the laboratory tests and the general principles of the transfer, we target here the on-site tests and their applicability on a real structure.

2. LABORATORY TESTS

2.1. Characterization of the concrete

To follow the evolutions of the parameters which can evolve during the ILRT or a primary accident, NDTs were carried out, on a type of concrete of NPP, under press to take into account the evolution of the potential stress from 0 to 12 MPa, with specimens at different states of thermal damage (heating at 80, 150 and 200°C) and different states of saturation (30, 60, 100%). Conversion models were determined between the observables (NDT measures) and the targeted reliability indicators (Strength, Modulus of elasticity, Saturation, Damage, Porosity, Stress)

10 NDT techniques were implemented following an approach described in [3] (linear and non-linear acoustics, radar, capacitive, electrical, permeability). 62 observables deduced from these tests were correlated to the changes of the indicators (Strength, Modulus of elasticity, Saturation, Damage, Porosity, Stress).

Figure 1 shows 3 examples of the capability of measuring stress and thermal damage and saturation with very different coefficients of variation from 1 to 500%. The observables sensitivities are very different regarding the indicators. Especially the stress evolutions are difficult to measure.

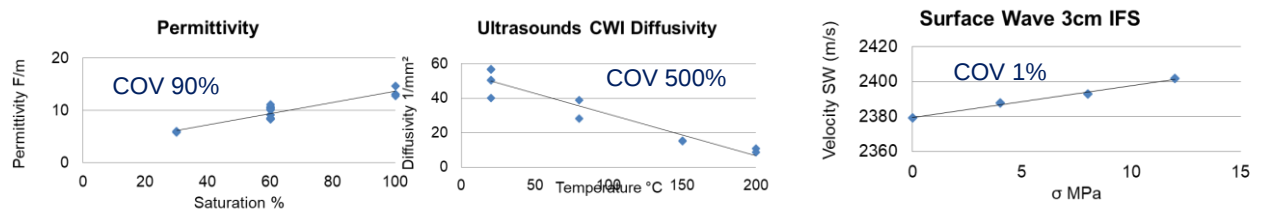


Figure 1. Examples of evolution for 3 observables according to 3 indicators

A statistical selection process made it possible to retain the most efficient observables that will be transferred to on-site measurements. Table 1 shows the sensitivities identified by technique. We can note that the first 4 techniques (*italics*), usually used in Civil Engineering, make it possible to mainly evaluate the saturation and that the last 3 (**bold**) which are techniques in the making complete the previous ones by improving the capability of measuring the stress and thermal damage.

Technics	Saturation	Stress	Thermal Damage
<i>Capacity</i>	+++	+	+
<i>Radar</i>	+++	<i>O</i>	<i>O</i>
<i>Resistivity</i>	+++	<i>O</i>	++
<i>Ultrasounds</i>	++	+	++
Permeability	+++	+	++
Ultrasound Multi Diffusion	++	++	+++
Non Linéaire Acoustique	+	+++	+++

Tabel 1. Sensitivity of NDT to Saturation, Stress, Thermal Damage indicators

Figure 2 shows the evaluations resulting from the inversion of the ENDS of the saturation and the damage temperature of the concrete for the ENDE specimens tested in the laboratory. The inversion consists in data fusion process integrating the readjustment of the conversion models [4]. The quality of the evaluation is good in both cases.

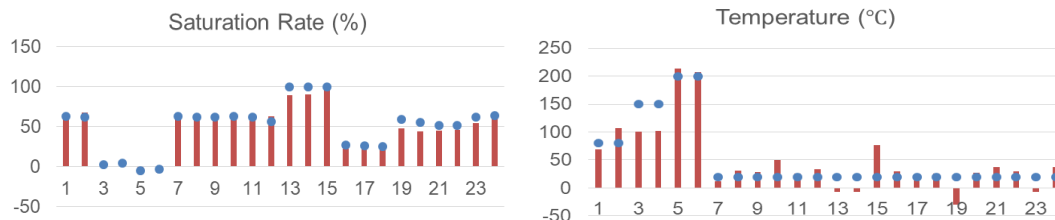


Figure 2. Evaluation of saturation and damage temperature of concrete by inversion and data fusion ENDS (merged red – measured blue)

2.2. Control of the cracks

Ultrasonic tests by diffuse waves, acoustic emission, linear and non-linear acoustics, and image correlation, were carried out in press during bending tests of two types of specimens. NDTs made it possible to follow the formation of diffuse mechanical damage in the form of microcracks then their coalescence in macro-cracks [5].

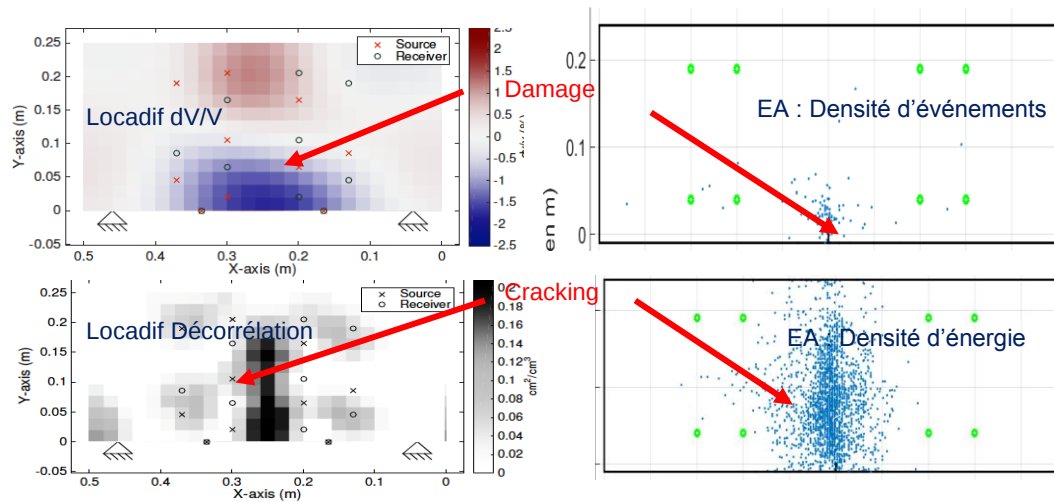


Figure 3. Suivi de l'endommagement mécanique puis de la propagation d'une fissure

Figure 3 shows the parallel between 2 techniques, by diffuse waves and by acoustic emission (AE). The relative ultrasonic velocity variations of the diffuse waves (Locadiff) and the density of events in acoustic emission make it possible to detect and position the damage which appears before the initiation of the crack. The decorrelation of the diffuse waves for Locadiff and the energy density for AE make it possible to identify the position of the crack in the space of the specimen. A test on a beam with a prestressing cable showed that it is also possible to follow the opening and closing of a crack.

These data can be associated by fusion with logical operators to identify the length of a crack.

3. ON SITE TRANSFER

3.1. Characterization of the concrete

The transfer is made on the VerCoRs mockup developed by EDF. It is 1/3 scale in terms of dimensions and 1/10 in terms of saturation evolution. It therefore undergoes each year the equivalent of a ten-year inspection ILRT which consists of carrying out a pressurization cycle of the containment walls up to 4.2 bar and then decompression over a week (figure 4).

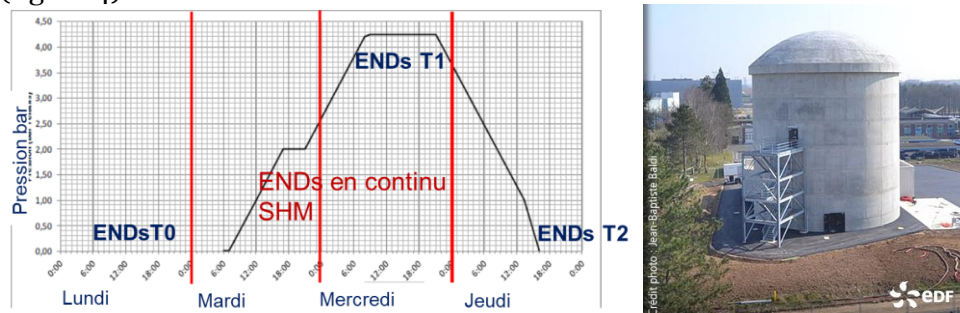


Figure 4. Pressurization cycle and VerCoRs mockup

The first objectives are to characterize the concrete on the structure and to follow the evolution of the cracks. Initially, the measurements were carried out in June 2016, December 2016, and March 2017 outside the pressurization cycle, then during the pressurization cycle in March 2017. Due to the measurement times and the time available to make them, they are performed only on 2 points.



Figure 5. Location of measurement points for characterization.

The NDTs techniques transferred on site are Surface ultrasonic waves, UPE, Capacity, Radar, Permeability, Non-Linear Acoustics. These techniques are not very automated in these testing campaigns. They had to be optimized for rapid implementation. They made it possible to estimate the evolution of the observables and to follow the properties of the concrete.

As an example, figure 5 shows the evolutions of the dynamic modulus of elasticity and of the saturation from June 2016 to March 2017 for the points in blue and during the pressure cycle in red.

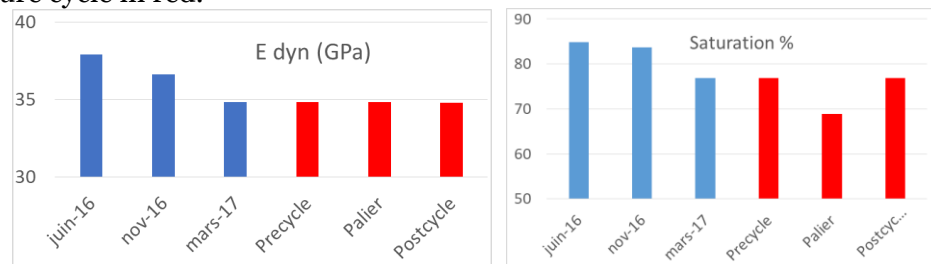


Figure 5. Evolution of the elasticity modulus and saturation with time (blue) and then with pressure (red)

The mock-up is maintained approximately at 33° C to approximate concrete aging conditions in service. During pressurization, for reasons of accessibility, the temperature is not regulated. This results in a drop of around 15°C which generates a bias. We took it into account [6] to correct the raw NDT measurements.

We note that we can follow the saturation and elasticity modulus that decreases over time. Then we observe during the pressurization that the modification of the stress generates a bias that must be integrated into the inversion for the saturation assess.

A more general mapping of ENDS data has been built on the entire containment with 114 points examined by 6 techniques: Surface ultrasound, UPE, Impact Echo, capacity and more partially resistivity and permeability. The points are distributed over 3 verticals and 2 circular horizontals and are subsequently merged to go up for each point to a value of the properties of the concrete. For example, we can see on the cartography below the saturation and the modulus of elasticity of the concrete after interpolation of the data..

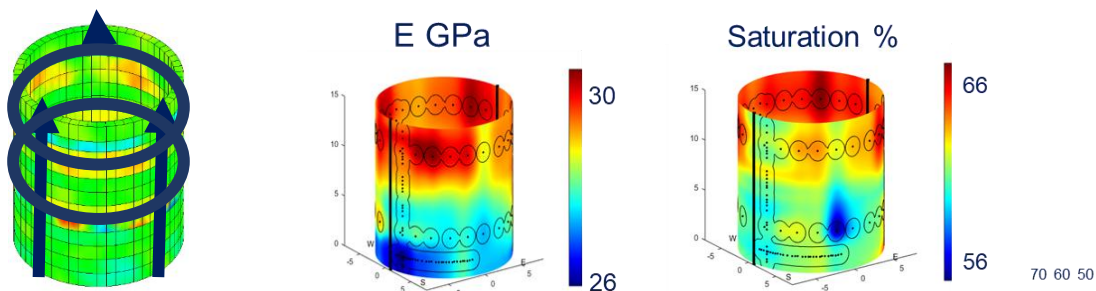


Figure 6. Mapping of the modulus of elasticity and saturation without pressurization of the VeRCoRs containment

It appears that these 2 indicators vary according to the height and the angular position therefore the variations in temperature and associated partial vaporization pressures as well as according to the polar orientation. It should be noted that these parameters can introduce biases in the context of the natural aging of the concrete or during stress on the containment, but also during its construction, which lasted 6 months with highly variable water and thermal conditions.

The points to remember in the context of these on-site concrete characterization tests are:

- All the indicators sought can be assessed by NDTs. Data fusion is an important element for converging all the measurements towards quantitative values by separating the cross effects of the different indicators on the observables. The absolute stress value is not accessible by NDT on site.
- To achieve quantitative measurements, it is not possible to readjust the inversion processes on destructive tests on concrete samples from the structure because these are prohibited. It is necessary to adjust the inversion process on hypothesis, embedded probes or/and modeling results.
- Saturation can be measured using surface or bulk ultrasonic velocity techniques, the diffusivity of ultrasonic waves as well as resistivity and capacitive techniques.
- The monitoring of the stress is possible by the ultrasonic waves in velocity and diffusivity as well as by the permeability. The low variation of the observables with the stress don't allow to assess absolute stress.
- The 2 points that have been monitored are 5 m apart and come from 2 different lifts. The two materials are different with the more porous for C3 point.
- Saturation depth gradients are highlighted by calculations or measurements by implemented probes. A difference of 20% between the core and the surface is observed. This bias must be also integrated into the inversion.

3.2. Control of the cracks

Important advances made during these tests on VeRCoRs concern the monitoring of cracks.

Three types of measurements were implemented with a fully monitored process (figure 7). The area studied is $3 \times 2 \text{ m}^2$ located at the bottom of the barrel and making the link with the gusset. Cracks have already been identified in this area. The techniques are Acoustic Emission, Locadiff (diffused waves), Surface wave robot.



Figure 7. Instrumentation for acoustic emission, diffuse waves (Locadiff) and surface wave robot set up to monitor to follow the cracks: Inspected zone with in red vertical cracks.

During the pressurization of the containment and despite the initial prestressing, the opening and even the generation and growth of the cracks are monitored in real time.

Acoustic Emission and the Lodadiff technique, which is based on the multi-scattering of ultrasonic waves, make it possible to report in situ on the activity of crack opening and

closing. The links with the dimension and the opening of the cracks are not identifiable at this level of information. Locadiff also makes it possible to follow the distribution and the evolution of the stresses in the structure as well as to identify the damage by the decorrelation of the signals.

During these same pressure cycles, the implementation of a robot using surface waves that can inspect the entire wall over a depth of 40 cm works on the basis of the attenuation of the propagated surface waves [6].

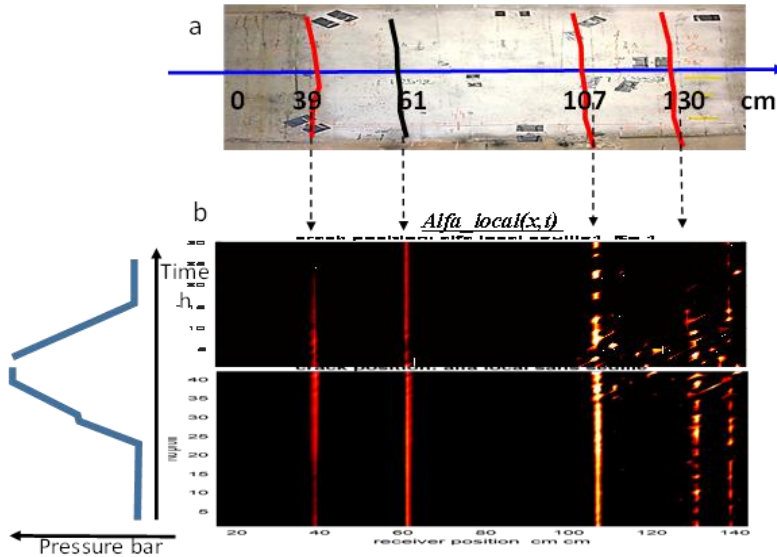


Figure 8. Evolution of the cracks opening during the pressure cycle.

This set allowed access in figure 8 to the opening of the cracks visible on the surface (red) for which the attenuation of the waves increases with their opening. This was correlated with fiber optic measurements. A subsurface crack was also identified (black) and its opening monitored. It is also possible to assess the cracks depth considering the length waves evolution.

The points to remember in the context of these on-site cracking monitoring tests are:

- Acoustic emission and diffuse waves (Locadif) are to be implemented as part of monitoring in a large, localized area. They make it possible to identify the existence of an activity either of modification of the constraints, or of opening and closing of cracks. It is not possible to evaluate the depth of the cracks.
- The surface wave inspection robot, developed as part of this project, can inspect a smaller localized area but in greater detail. It makes it possible to follow the opening and closing of even non-visible cracks and to position them in depth.
- These techniques can be covered in the following timeline. First, EA and/or Locadif to detect the existence of cracks then second, the surface waves to characterize them. This chronology can be done on a single pressurization cycle because the cracks detection can be obtained during the increase of the pressure and the cracks characterization during the decrease of the pressure.

3.2. Global approach

Finally, a third global approach has been implemented to highlight the possibilities offered by the vibration and modal analysis of the containment.

The recording of the noise generated by the air circulating in the pipes during the pressurization of the containment made it possible to identify recurring frequencies throughout the test. These increase with the pressure and return to their initial value when the pressure drops with a slight hysteresis. By selecting several of these, a multivariate regression model was deduced from the evolution of their value as a function of the pressure

in the containment. This model makes it possible to estimate in real time the internal pressure during the pressure cycle [7] as shown in the following left figure 9.

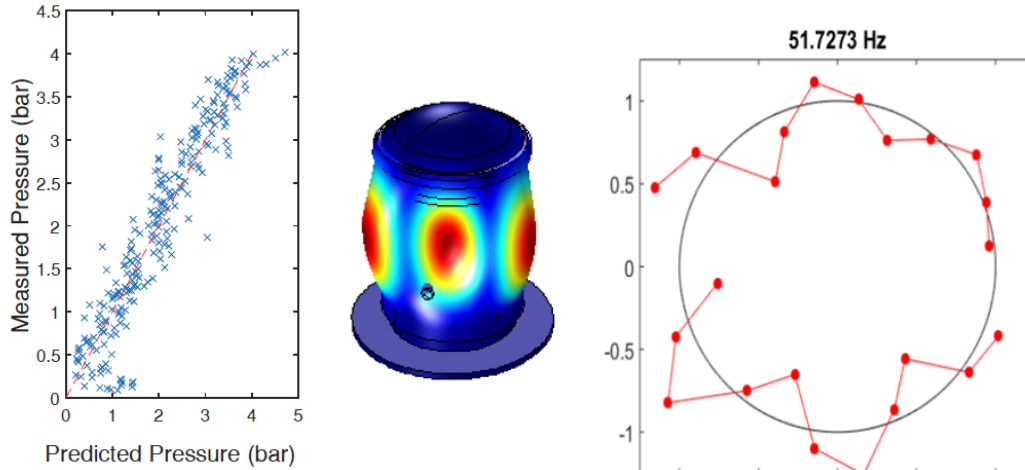


Figure 9. Comparison of numerical and experimental data : Predicted pressure (P_{pred}) vs. experimentally measured pressure (P_{exp}), Example of vibration mode

The modal analysis approach is more ambitious because it could be integrated into an SHN approach. It consisted of measuring, using simple instrumentation made up of 1 to 4 accelerometers depending on the tests carried out. The observables are the frequencies, shapes, and amplitudes of the vibration modes of the containment during pressurization, but also their evolution during the pressure cycle. An example of experimental numerical comparison is given by right figure 9.

It finally appears that modal analysis opens real potential. Up to date, it is difficult to work on exact descriptions of a complex and already partially damaged structure, real-time monitoring of these frequencies is possible à priori on the noise of air circulation within the framework of the ILRT of VeRCoRs. The evolutions of the modes and their amplitude could provide a significant alarm on an evolution of the local properties of the concrete or the structure. A numerical study of the sensitivity of this approach based on a Principal Analysis Component has been proposed on the data of VeRCoRs [8]. It shows the capability of the approach to provide statistical information on the modification of the modes linked to specific cases of concrete evolution.

4. CONCLUSIONS

The ENDE project has made it possible to apply NDTs to a nuclear civil engineering structure in the case of containment control during several phases of its life cycle. It is shown that NDTs are applicable for concrete characterization and crack control but also for structural monitoring. The developments have been made both on the technical aspects, operation, and link between the different scales. Versions of surface wave measurement robots and data fusion software have been proposed at a high level of TRL.

The ability of the different techniques to meet the expectations of the controls was studied in the laboratory, the on-site capability was shown as part of the measurements on the VeRCoRs mockup.

Parameters have been clearly identified as being able to integrate biases into the measures and inversion process. These are the temperature inside the containment wall, the temperature during the casting of the lifts as well as the gradients of properties such as saturation. Additional studies are necessary with an approach based on numerical studies such as the comparison between forecasts and capacitive measurements for saturation [9].

An auscultation approach can be developed around a multiscale approach. The SHN based on global auscultations either in service with the operating noise or in ILRT with the noise of the air flows can highlight a shift of the vibrations of the structure. The latter could be linked to positions of potential damage in the structure. A local measurement approach can then be associated with the detection by NDT of defects. The useful concrete characteristics can be assessed by NDT as well.

Such an approach could result of joint work between the owners and the measurers.

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