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STRUCTURAL MONITORING OF PRE STRESSED CONCRETE CONTAINMENTS OF NUCLEAR POWER PLANTS FOR AGEING MANAGEMENT

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ABSTRACT

The containments of Pressurised Water Reactors (PWR) of the fleet currently operated by EDF are built of pre stressed, reinforced concrete. Pre stressing is used to balance the forces that containments would be subjected in the event of internal accident (LOCA).

During the construction of EDF's PWR fleet in the 1970s, it was decided to fit concrete containment structures with VWSGs to monitor concrete strain during pressure testing and operation. The use of VWSG to measure strain into concrete has been widespread in dams' construction since the middle of the previous century, as shown in Coyne (1938) or Bellier (1956). Today these sensors are used by EDF to monitor any changes in concrete pre stressing during operation and to check the mechanical response of the containment during periodic pressure tests. Compliance with design requirements is assessed by comparing the measurement and the theoretical containment behaviour based on design assumptions.

Pre stressing must be monitored regularly to ensure that it remains sufficient and efficient throughout its operating life. Phenomena, such as concrete creep, shrinkage and tendon relaxation contribute to pre stressing losses and can quantified thanks to this monitoring. Thanks to frequent measurements, high level of confidence in the measurement uncertainties, and maintenance including metrological control of the various devices (when feasible), it is possible to predict the losses at end of operation. These measurements can be used as input data to verify the design hypotheses and justify a potential operation extension.

INTRODUCTION

The use of unbonded tendons (US practice for example) provides the opportunity for direct in-service inspection of the tendons. Furthermore unbonded tendons can be replaced if found defective or degraded.

In France, the choice has been made to coat the pre stressing tendons with cement grout. This option offers advantages by preventing the strands from corroding. Furthermore, in the event of a strand failing, the bonds between the tendon and the grout enable some of the post-tensioning forces to continue to be transmitted to the structure. On the other hand, this option prohibits all future inspection or maintenance operations, which would have been possible for pre stressing injected with grease. This decision therefore led to the setting up of a monitoring system consisting of periodic tests (every ten years) at design basis accident pressure and monitoring the behavior of a containment throughout its life.

Consequently, monitoring pre stressing losses in the concrete of pre stressed nuclear containments is of primary importance for safety and industrial purposes.

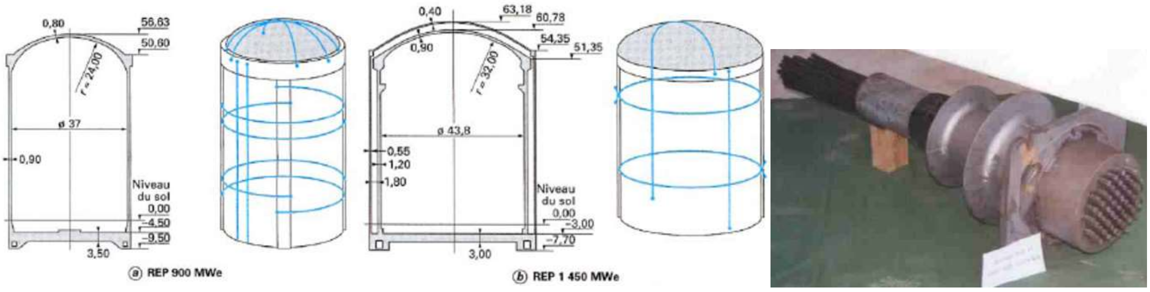


Figure 1. Main dimensions of French 900 MW and 1300MW-1450 MW Pre stressed containments (left) - photo of pre stressing cables and anchorage head (right)

OBJECTIVES OF CONTAINMENT MONITORING – DESCRIPTION OF THE MONITORING SYSTEMS

For cement grouted containment design, direct monitoring of the bonded post-tensioning system is not possible, proven reliable indirect methods can be used to ensure continuous integrity of the post-tensioning system over the service life of the plant. A dedicated monitoring device is used to measure continuously the delayed concrete strains/displacements (creep/shrinkage) and strength relaxation in the cables.

Periodic leak tightness tests (Integrated Leakage Rate Test “ILRT”) and resistance tests (Structural Integrity Tests “SIT”) are carried out at design pressure (~0,5 Mpa abs.) each 10 years. These test aim to verifying:

- the leak tightness of the building, by comparison with the criteria imposed by the regulations,
- that the mechanical behavior of the containment, when submitted to internal pressure equivalent or greater than design pressure, is consistent to the design. This acceptance test requires the measurement of structural mechanical response using a wide range of instruments (displacement, strains and temperature sensors).

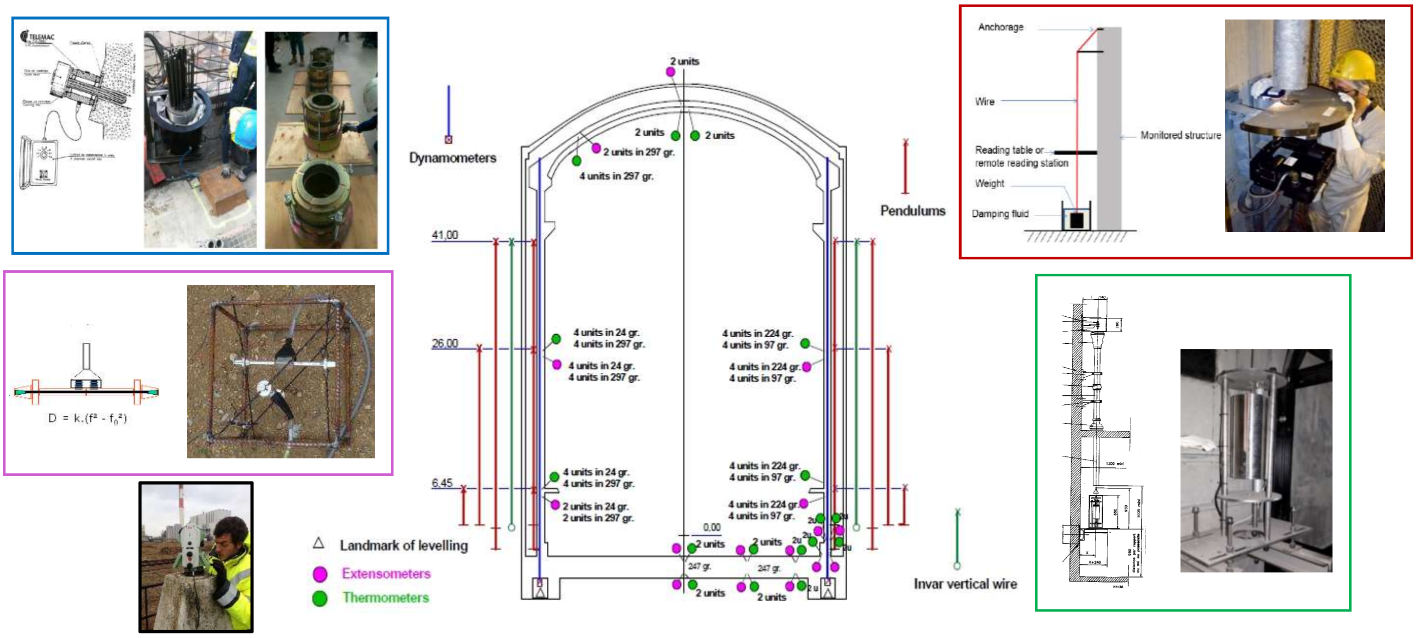


Figure 2: Example of a typical monitoring system used by EDF (sensors installed around penetrations are not represented)

In French Practice, embedded and concrete surface mounted instrumentation are used to monitor the response of the concrete containment structure. The systems are described in detail in (Alexandre Simon, Elise Oukhemanou, and Alexis Courtois 2013).

The main phenomena which are monitored are the following:

- Leak tightness during the pressure tests,
- Settlement and Tilt, corresponding to the global displacements of the building and monitored by topographical measurements. The objective is to check that the behaviour is compatible with design hypotheses, in particular for Soil Structure Interaction "SSI" purpose and design of mechanical connexions between civil buildings,
- Containment relative displacements measured by pendulums and invar wires, respectively for diameter and height variation and Concrete strains measured by VWSG (vibrating wires strains sensors)
  - ⇨ The objective is to verify the design hypotheses, in particular the amplitudes at end of operation due to pre stressing losses, the linearity and reversibility of the behaviour during the pressure tests.
- Raft displacements under pressure, generally measured by hydraulic levelling plots,
- Residual force in 4 wax injected tendons (generally thanks to vibrating wire loaded cell). The objective is to measure the total force in the cable and assess the strength relaxation phenomenon for these 4 tendons,
- Temperatures in the concrete thanks to temperature probes, which are used during operation for thermal correction of concrete strains/displacements

The ageing surveillance is also completed with periodic visual inspections (cracks and corrosion, for potential maintenance purpose), if needed, with additional non-destructive techniques.

MONITORING DURING THE WHOLE OPERATION LIFETIME OF THE BUILDING

Monitoring during construction

During the construction phase, monitoring some phenomena is important for the future ageing management program of the plant.

Monitoring the concrete strains at the early beginning of construction and concreting phase allows to check the functionality of the recently installed VWSG, by measuring thermal strains before concreting, instantaneous strains due to concreting and the early shrinkage period. This early monitoring period allows to identify the correct functioning of the VWSG, identify potential sensor losses due to construction, and verify the correct orientation of the sensors. This analysis is possible if automatic acquisition is installed very early during the construction, it was performed for example in EPR Flamanville 3. In such a case, it is useful to perform periodic analysis of the percentage of sensor losses during all the construction, in order to take a decision, if needed, to add some sensors in the following concrete batch in compensation to the ones which are not functioning in the previous one.

In the French practice, the concrete strains are monitored in particular during the tendon tensioning phase, because these measurements allow to calibrate the mechanical properties of the containment (structural modulus E), by the recording of instantaneous strains during tensioning.

Figure 3: Example of strain monitoring during construction

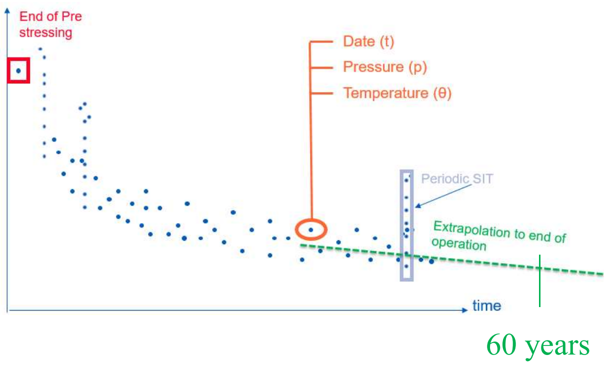
This calibration is then used before the Initial Structural Integrity Test "ISIT" in order to perform blind prediction of the containment behavior under pressure (displacements and strains). The comparison between the blind numerical modelling and the measurements during ISIT is very important for the validation of design hypotheses. In EPR context, such comparison is considered to be relevant when the difference between both is +/- 15%. This value considered as a reasonable one is recommended in RCC CW AFCEN 2021 and also considered in EPR HPC Project. This +/- 15% difference was correctly checked during EPR FA3 ISIT.

ISIT is a milestone for the building operation. Positioned at the end of inner containment construction phase, it allows to verify the design hypotheses on mechanical resistance, in particular linearity and reversibility of displacements and strains, and the limited crack opening during the test.

Another possibility related to early monitoring is the possibility to measure temperature during and just after concreting in order to check the maximum values in thick members like raft and gusset, giving an information for potential concrete pathology analysis afterwards (e.g. Internal Swelling Reactions, ISR).

Concrete strains during operation

After pre stressing phase, the delayed concrete strains due to creep/shrinkage are measured thanks to the VWSG, each 15 days when the monitoring system is automatically recorded (maximum 3 months when manual measurements are made). Except for some sensors on a limited number of units, almost the whole French feet is automatically recorded, maximizing the measurement frequency of strains and temperature and reducing the man induced measurement errors. Thanks to this big amount of data with a high level of confidence (the measurement uncertainty of VWSG is +/- 5% of the total measured strain, 95% confidence), a fine thermal correction of the raw data is possible, thanks to a physic statistics method. The pre stressing losses measurement since the end of pre stressing phase, allows to extrapolate the concrete strains to end of operation.



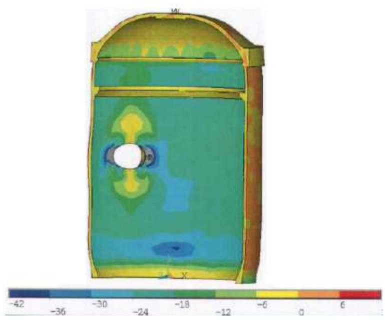


Figure 4: Example of strain monitoring during operation

It is then possible to justify a sufficient level of pre stressing at the end of operation, for all the pre stressed containments, by verifying the residual compression strength in accidental conditions. Numerical modelling calibrated thanks to these measurements are used for such justification.

Tendon relaxation

The pre stressing losses ΔT measured by the dynamometer loading cells, on the 4 vertical tendons injected with wax or grease, are composed of a delayed loss related to strength relaxation in the cable and a second related to the shrinkage/creep of concrete :

$$\Delta T = (\Delta\sigma_{relaxation} + \Delta\sigma_{creep/shrinkage})*A_p \qquad (1)$$

Where A_p is the tendon section and $\Delta\sigma_{creep/shrinkage}$ is measured with the VWSG.

Even if the representativeness of the instrumented wax injected tendon, compared to cement grouted tendons, can be discussed, the dynamometers allow to estimate the order of magnitude of tendon relaxation and compare the obtained value to the one calculated with the civil code. Is it then possible to estimate the ρ1000 coefficient, corresponding to the value of the relaxation loss (in %), 1,000 hours after tensioning, at an average temperature of 20°C.

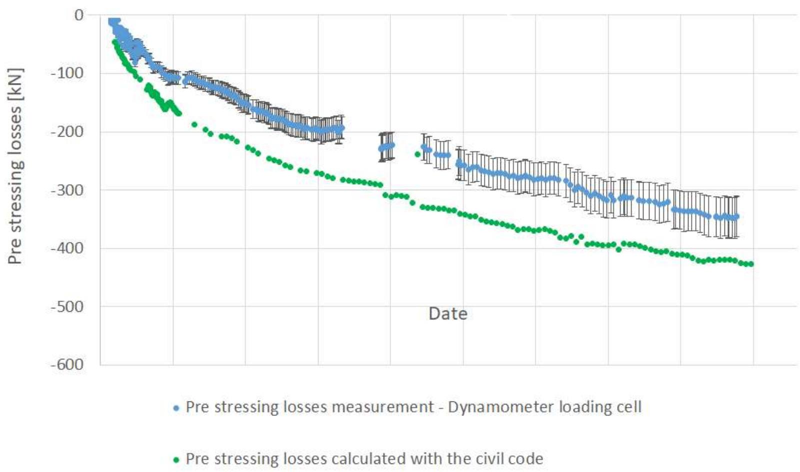


Figure 5: Comparison of measured and calculated pre stressing losses

Mechanical behaviour of the containment during the SIT

Instantaneous concrete strains are measured during the periodic pressure tests (SIT each 10 years). The concrete strains measured by the VWSG and the displacements measured with the pendulums and invar wires allow a periodic verification of the linear and reversible behaviour of the containment. Those devices correspond respectively to local and global analysis of the building.

Thanks to the measurement accuracy of the different sensors, it is possible to detect a potential mechanical evolution in an instrumented area, since the beginning of operation. In the example below, the strain amplitudes with pressure evolved between the ISIT and the last SIT, by a factor of around +25%. Despite this amplitude evolution, the monitoring devices allow to verify that the global behaviour still elastic. It is also possible to assess the evolution of the containment structural modulus, calculated analytically with the vertical and tangential concrete strains. In this particular example, it is possible to note that this mechanical evolution is diminishing since the 2 last SIT.

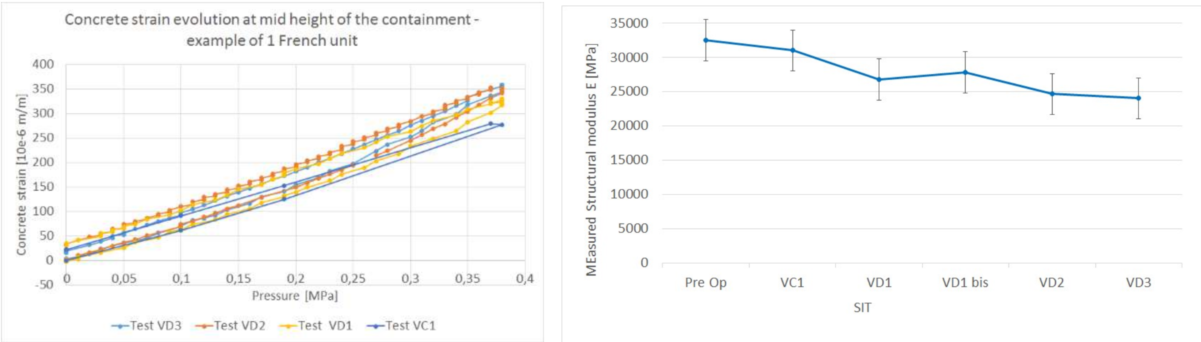


Figure 6: Example of strain monitoring during periodic SIT

Detection of singular concrete behaviour
In some cases, the structural monitoring allows to detect potential change in the concrete behaviour. The example below illustrates concrete expansion due to pathologies like ISR or AGR, whose detection was possible thanks to the presence of VWSG in the raft.

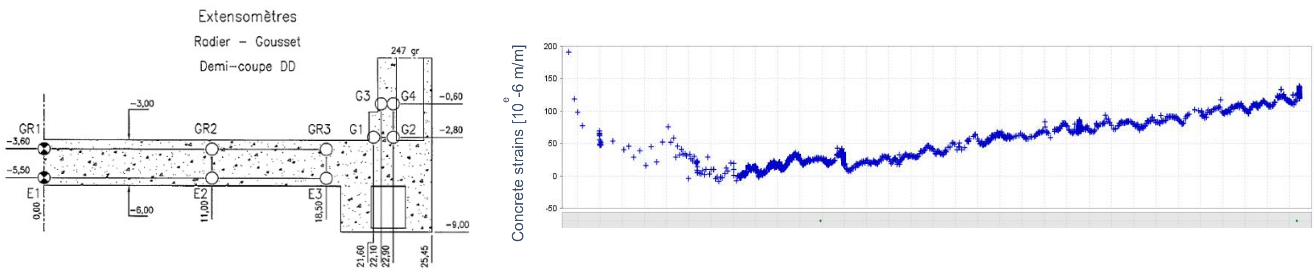


Figure 7: Example of strain monitoring during operation, evidencing elongation due to concrete pathology

In such a case, the embedded VWSG allows to quantitatively justify long-term kinetics of the pathology and avoids in some cases destructive measurements (on extracted samples).
Such devices complete the standard surveillance based on visual inspection.

EDF Feedback on containment monitoring
Care should be taken when interpreting the results of the monitoring. Response of the structure to environmental and operating conditions (e.g. temperature, humidity) as well as volumetric changes in concrete and long term relaxation of the post-tensioning tendons in the given environment should be well understood in order to confirm design assumptions and ensure that pre stressing force losses are within acceptance limits and sufficient margins are maintained at all times during service life of the plant. If necessary, structural analysis should be update with actual ambient conditions and material properties

Instrumentation should be proven, calibrated and reliable and should have sufficient redundancy. Instrumentation should be of sufficient accuracy to be able to identify a small change in the mechanical behaviour, so that the integrity of the concrete containment structure is not compromised. Instrumentation should be strategically located in the areas of high stresses and strains; location of instrumentation should allow for easy comparison with the theoretically estimated values.

Today, after 20 to 40 years of operation depending on the site, it appears that certain sensors have suffered from failures, in spite of the precautions taken in selecting the most durable sensors. Furthermore, extension life strategies require operators to review the durability of containments monitoring systems. It therefore appeared important to define Optimum Surveillance System (OSS) in order to prove that the pre stressing level of the containment continues to fulfil the safety requirements. Among sensors constituting the OSS, some are originally embedded in the concrete of the structure, and as such cannot be replaced with the same models. This strategy led EDF to install alternative surface mounted instrumentation capable of measuring the same physical values as the embedded sensors.

Some requirements and recommendations based on French monitoring feedback were incorporated in the last versions of AFCEN codes (RCC CW 2021), in particular the chapters related to the containment, in the Construction chapter (CCONT) and in the Ageing Management chapter (AMCONT).

PROSPECTS AND POTENTIAL EVOLUTION

Addressing containment ageing: what about concrete water content monitoring?

It is clearly established for concrete that one of the main influence factors governing shrinkage and creep is the “water content” or “moisture”. Indeed, the amount of water within the pores of concrete is a key parameter in the civil structures ageing phenomena, and in particular for delayed strain development. Hence, the question of the relevance of the measurement technologies for in-situ water content monitoring is arisen.

Recent papers propose simple approaches to determine how the knowledge of the concrete water content these structures could improve the predictions of their mechanical behavior, periodically undertaken as part of the safety case for the facilities (Courtois et al., 2020) (Courtois et al., 2022). These analysis address monitoring data uncertainties propagation through the models and the effects of these uncertainties on the extrapolations to the end of the structure lifetime. It turns out that current water content monitoring device should be improved to get a better benefit to containment ageing management. In particular, the measurement uncertainty should be enhanced to enable more relevant concrete creep prediction at the end of containment building lifetime. However, an extensive spatial sampling of the moisture profiles can compensate somehow current lack of water content devices for concrete monitoring.

EDF is currently testing some researches on thick structures and in the nuclear industry have been reported, dealing with Time Domain Reflectometry (TDR) (Guihard et al., 2017), (Courtois et al., 2015) or capacitance hygrometers (Oxfall et al, 2016). But it is recognized that the real metrological performances of these techniques should be better assessed to benefit from them in the long-term operation of nuclear power plants. To our knowledge, our analysis suggests that up-to-date concrete moisture or water content measurement system have not reached the required performance yet, which open a path for further research.

Distributed strains measurement feedback

The evolution of surveillance needs of civil structures, including the pre stressed containments but not only, leads to the development of measurement technologies which can be complementary to the ones used historically in the pre stressed containments.

Among these alternative or complementary technologies, we can mention the distributed strain measurement sensors, which allows the acquisition of local concrete strain profiles on large areas of the structure and, after integration, the estimation of the global displacements of the structure. Those developments should be used for buildings in operation, in case of malfunctioning of embedded sensors for example, and for future buildings to complete, if necessary, the “historical” surveillance devices.

In the objective of qualifying the distributed strain sensors technology, VeRCoRs mock-up is a very important tool, with an intermediate scale between the laboratory scale and the real building scale.

The paper (Galan et al 2022) shows that these distributed monitoring systems are complementary of traditional local strain sensors like VWSG and global displacement sensors like pendulums and invar wires.

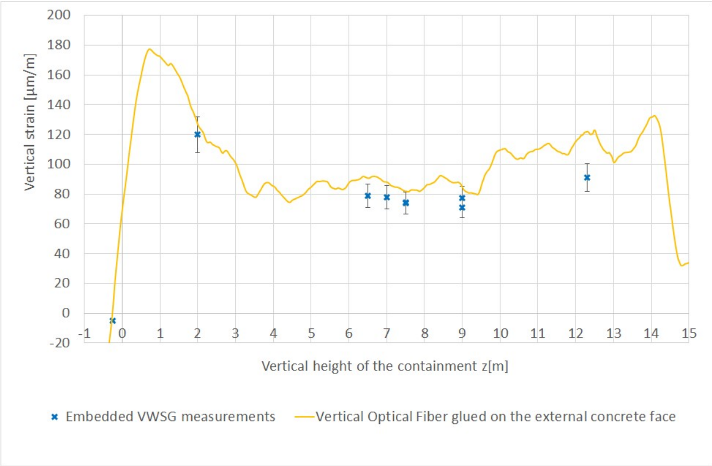


Figure 8. Vertical concrete strain measured with VWSG and glued optical fiber during VeRCoRs VD5 pressure test

CONCLUSION

The monitoring system of nuclear containments was initially designed to check the design hypotheses. This system also ensures that pre stressing meets the safety requirements throughout reactor containment lifetime. An Optimum Surveillance System (OSS) which guarantees satisfactory monitoring of containment behaviour was defined by EDF. The OSS sensors have to be made permanent.

In accordance with these principles and precautions, the long-term monitoring of mechanical behaviour of containment will be guaranteed and the operator will achieve the required control over the ageing of containment.

This very fine surveillance is also possible thanks to the use of a dedicated software, used for the surveillance of large civil structures (containments, dams, cooling towers) which allows to perform post-processing (thermal correction), to make a continuous surveillance of the phenomena, by generating potential warnings if some criteria are exceeded.

For new structures, data collection should start during construction (at least at the beginning of the tensioning of the cables) so that the initial state, i.e. baseline parameters could be established at the end of the construction period.

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