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Recent Instrumentation, Software and Analysis Practices in Structural Health Monitoring

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ABSTRACT: Technological developments in instruments caused an evolution both at the number and the scope of the structural health monitoring applications for civil engineering structures. This developments also paved the way for structural health monitoring to be the unique realistic technique for studying the dynamic building behavior, today, moving the civil engineering laboratories to real-world. Taking precautions and preventing failures against severe earthquakes and other damaging effects started to become possible by monitoring the integrity of the structure in real time. A number of instrumentation combinations entered into the picture forcing the researchers, consultants, building owners and authorities to choose the best fitting methodology. Building codes are being modified today, including the instrumentation and monitoring. This study covers different instrumentation approaches based on real-world application experiences including high-rise buildings, hospitals, and historical structures with dynamic monitoring using accelerometers under ambient vibration, and also static monitoring with tilt sensors, crack gauges, inclinometers. This study also opens a new window to a solid methodology that can be used for decision support, with the real-time and post process, analysis and reporting. This approach is called as Health Monitoring Center Substructure and provides the tools for ending up with deliverable results from a huge amount of data coming from the sensors.

1 INTRODUCTION

Every civil engineering structure has an estimated lifetime. Engineering science intends to find and apply the most suitable and economical solution. However, due to an excessive loading (i.e. earthquake, flood, explosion, deep excavation etc.) or repeated loading (fatigue) or aging, the structure can be damaged or become unsafe. Evaluating the risks on the structure to perform repair and strengthening or evacuating and demolishing the structure at the correct time with enough information and data is quite important. The process of mostly real-time monitoring as well as reporting the behavior and probable damage condition of civil engineering structures under earthquake or other severe damaging effects with the help of the installed sensors is named as Structural Health Monitoring(will be abbreviated as SHM). This leads to a decision support tool related to the safety of the building. Scope of this study consists of the instrumentation methods, devices, sensors, electronic systems, software and application practices used in structural health monitoring especially for buildings and among a wide range of civil engineering structures. Çelebi (2002) emphasizes the importance and positive contribution of seismic monitoring and accelerometer based structural health monitoring applications on buildings, describes the methods and recommends common use of seismic instrumentation on federal buildings in the report prepared for USGS (US Geological Survey). It has been stressed that the information that will be collected as a result of these monitoring studies will form a unique database of knowledge for the practice of earthquake resistant design. Real-time structural health monitoring is one of the most recent technologies which produce unique results. :By the start of 21st century, SHM became more reachable at lower costs due to technological developments, and began to spread out rapidly. There are descriptions and directions about seismic instrumentation and application of accelerometers at high-rise buildings both at San Francisco Building Code (2014) and Los Angeles Tall Buildings Structural Design Council Consensus Document (2008). Guidelines and Implementing Rules on Earthquake Recording Instrumentation for Buildings (2015) defines the Structural Health Monitoring standards for high-rise buildings (above 50 meters) in Philippines. Strong Motion Instrumentation of buildings in New Zealand is summarized by Deam and Cousins (2002). Section 13.8 of Turkish National Earthquake Building Code published by Disaster Management Authority of Turkey (AFAD) brings the obligation to health monitoring of high-rise buildings above 105 meters

1.1 Types of structures to be monitored

Nearly all types of civil engineering structures can be monitored by SHM solutions. However, the motivation to monitor, planning and philosophy of the instrumentation can change from structure to structure. This section classifies the structures, monitoring options and ideas according to needs.

1.1.1 High-rise buildings

High-rise buildings are one of the most vulnerable structures to the earthquakes. Recorded responses of 2 high-rise buildings during the Loma Prieta earthquake were analyzed by Şafak and Çelebi (1991). When high-rise structures are monitored using accelerometers, modal analysis and finite element model update can be carried out, modal frequencies can be monitored for life-time. Any sudden or unexpected change in the modal frequencies after a severe earthquake will warn the decision makers to take precautions. After an earthquake, the damaged buildings can be detected to a certain probability within hours. Soyoz et al. (2010) studied the structural reliability estimation with vibration-based identified parameters. Furthermore the data gathered from these buildings will form the most realistic database to evaluate the effectiveness of the building codes, for next revisions.

1.1.2 Historical structures

Certain doubts can arise about the structural integrity of historical structures when cracks or other signs of pre-failure are observed on the structure. Strengthening and restoration work involving high levels of forced vibrations and demolishing, re-construction work temporarily multiplies the failure risk. Real-time monitoring during construction activities will minimize the sudden failure risk. Crack, tilt, settlement and soil movement monitoring are most common options. In addition, operational modal analysis of the structure before and after the strengthening would form a quantitative comparison base to evaluate the strengthening.

1.1.3 Bridges and tunnels

Among all civil engineering structures, bridges & tunnels are two of the leading types that should be monitored by sensors due to their critical fatigue and creep behavior. Especially natural events such as earthquakes, floods, storms increase the importance of monitoring. Different types of instruments and sensors should be combined in health monitoring for railway/highway bridges, tunnels, tube crossings and subways. Although customization has a big importance in a specific SHM instrumentation project of a bridge or tunnel, accelerometers, strain/crack gauges, tilt, environmental sensors are the most preferred ones.

1.1.4 Hospitals with seismic isolators

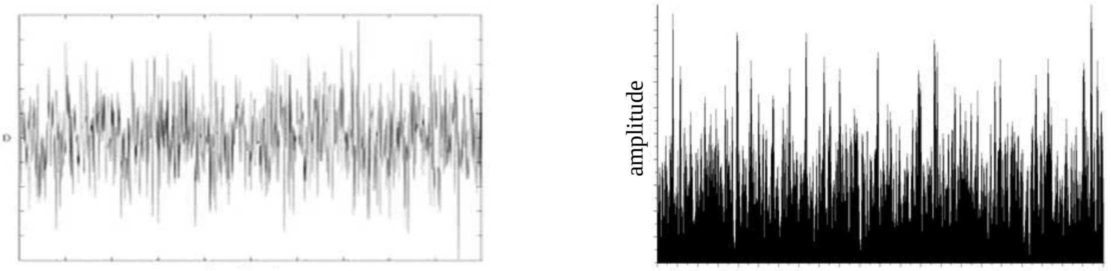
Hospitals are special type of buildings that have to function 24/7 and 365 days. Uninterrupted functionality is even more important after a major earthquake. Vibration levels are critical for sensitive medical equipment that can easily be affected by high level of vibrations and surgery rooms. For all these reasons recent hospitals being constructed in seismic zones are isolated by seismic dampeners installed under the foundation. However, proper functioning of seismic isolator afterwards is critical. Therefore the structure should be instrumented by accelerometers below and above the isolators, to monitor the performance of the isolators. Static and dynamic monitoring

Structural Health Monitoring can be carried out in a more static way (logging data, in less frequent terms like minute/hour or day based), more dynamic way (including vibration analysis by accelerometers) or a combination of both. In dynamic monitoring, accelerometers are the main sensors. Tiltmeters, crack-gauges, inclinometers are the main actors for static monitoring.

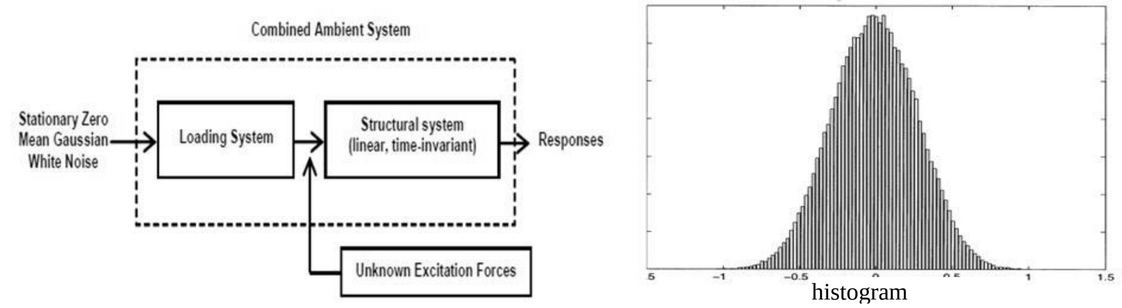
1.2 Modal analysis under ambient vibration

Álvaro Cunha et al (2006) investigated in detail, the evolution of dynamic identification and structural health monitoring studies from input-output techniques towards output-only, quite practical operational modal analysis intensively today. The theory of operational modal analysis is summarized at this section without going into the details of the mathematical model. Operational modal analysis is also called as ambient vibration testing as only the measurement of reactions are targeted under little daily vibrations. In this way it is possible to stay in the operational systematic of the structure and there is no need to externally force it. (Figure 1) On the other hand ultra-low noise and high precision accelerometers are required for being able to measure and acquire this micro-g level vibrations especially on buildings, in this technique.

At the analysis stage, besides simple peak picking, advanced techniques are proposed. Frequency Domain Decomposition-FDD (Brincker et al 2001) in frequency domain and Stochastic Subspace Identification (SSI) (Peeters et al, 1999) in time domain are two of the most preferred techniques.



time domain frequency



histogram

Figure 1. White Noise-Time/Frequency domain, histogram, Combined Ambient System

2 APPROPRIATE SELECTION OF THE EQUIPMENT

Since SHM is a new and innovative technique, deciding the best fitting equipment can be confusing. An important number of monitoring projects fail because of the inappropriate instrument selection. Confusion is mostly caused because of the requirement to combine the different monitoring motivations/strategies and structure types with a bunch of different sensor technologies, resolution, sensitivity and precision requirements related to the measurement site, the distinguishable physical parameters to be reached at the end. Accelerometers (Enough vs. more than enough or not enough) For dynamic monitoring and modal analysis under ambient vibration the most critical component is the accelerometer. Taking sufficient selection parameters into consideration will dramatically affect the project budget. Under-qualified selection of the accelerometers will cause almost no interpretable data at the end. On the other hand, over-qualified selection of the accelerometers, will directly increase the project budget considerably, generally resulting into insufficient number of sensors or totally unaffordable solution at the end.

2.1.1 Results of the accelerometer sufficiency comparison tests under ambient vibration

An important comparison test was conducted in TDG Scientific Laboratories, in 2016. This building was a 4 story concrete building including the basement floor. The test took place on the 2nd floor directly on the concrete area next to a column as an ambient vibration test which aim to log data over-night, when the vibration was at the minimum level. TESTBOX2010-4 channel digitizer was used. This digitizer has 4 24-bit, simultaneous sampling, input channels, 137dB dynamic range. 3 sensors compared: (2nd channel left empty.) 1st channel: R-Sensors-MTSS1031A, 130 dB dynamic range, 130 ng/√Hz noise density at 10 Hz, manufactured with force-balance based, Molecular Electronic Transducer (MET) Technology.3rd channel: Silicon Designs SD1521, 100 dB MEMS technology. 5 µg/√Hz noise density. 4th channel: Colibrys-SiFlex SF1500A, 120 dB force-balance based, MEMS, 300 ng/√Hz. (obsolete now)

Test results showed that, while R-Sensors MTSS1031(green) and Colibrys SF1500A(red) successfully senses the modal frequencies under ambient vibration, base noise level of the SD1521(blue) was far over the building acceleration response level, not enough to differentiate the modal frequencies. (Figure 2)

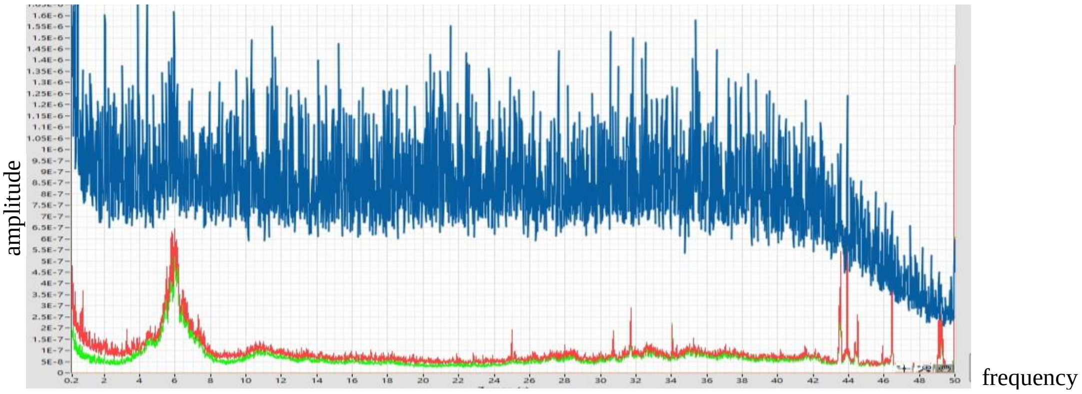


Figure 2. FFT- building frequency response under ambient vibration / 3 accelerometers compared

2.1.2 Precision (Dynamic Range – Noise Density)

Most confusions about the precision of the accelerometers arise from the conflicting figures on the data sheets prepared by the manufacturers. Some data sheets present dynamic ranges, while the others give noise density figures. Even the dynamic range of the same sensor models may differ in different data sheet versions of the same sensor. Furthermore, the noise density for a specific sensor can be different for different frequency ranges. For example a very high dynamic range (DR) can be observed for 0.1- 1 Hz, and the DR is considerably lower for 1-10 Hz or for 10-100 Hz. Manufacturers generally present the highest DR they observe. Although extremely high figures (more than 160 dB) exist on some parts of the data sheet, this does not represent overall sensing performance. The positive conclusion among all these conflicts is that, an accelerometer over 120 dB overall DR successfully detects the building response under ambient vibration. DR above 120-130 dB, while dramatically increasing the sensor costs, is usually more than enough for buildings. For more flexible structures like bridges, there are well examples that even 100 dB sensors can lead to meaningful data. (Pakzad et al, 2008) But, for buildings, less than 120 dB accelerometers would be useless. There are a number of experimental researches on ambient vibration testing conducted with the accelerometers of this dynamic range and noise level.) (Soyöz et al, 2013)

2.1.3 Measurement range and frequency response

In general what is expected from an accelerometer used in SHM under ambient vibration, is the ability to differentiate the modal frequencies (mentioned in detail above) and at the same time to log the unclipped acceleration data during an earthquake. For this reason generally a range of ±2 g is preferred. Modal frequencies for a structure starts from 0.2-5 Hz and can go up to 50 Hz for higher degree modes. When the building is a high rise one (above 100 meters) the 1st mode can is generally below 1 Hz. For these reasons a frequency response of 0.1 Hz to 50 Hz (or 100 Hz) will be adequate for all cases.

2.1.4 Manufacturing technology

Tests and data sheets show that accelerometers with different technologies can satisfy the major parameters for ambient vibration analysis. Conventional force-balance technique is the oldest manufacturing method. Even this technique has capacitive and inductive sub-solutions. Alternately, Molecular Electronic Transducer (MET) based force balance, piezo-electronic and MEMS based force balance technologies exist. Summary of the main selection criteria for SHM under ambient vibration. As a result, manufacturing technology is not a determining parameter in sensor selection. Table 1 summarizes of the parameters that should be considered for accelerometer selection.

Table 1: Accelerometer Selection Criteria for SHM under Ambient Vibration

Parameter	Appropriate Values
Precision (based on Dynamic Range)	120 dB (min.)
Precision (based on Noise Density)	300 ng/√Hz (max.)
Measurement Range	±2 g
Frequency Response	0.1-50Hz (or 100 Hz)
Manufacturing Technology	Conventional Force-Balance or MET or Piezo

2.2 Digitizers

The digitizer is the component of the system that converts the analog data to the digital value that can be logged, monitored and analyzed by computers. Like the sensor, the digitizer is the vital part of the system.

2.2.1 Resolution, dynamic range, SNR

The golden rule for the digitizer precision is to select it according to the highest sensor precision, in the SHM system. For SHM under ambient vibration, only 24-Bit digitizers will support the accelerometers discussed in the previous section. Resolution itself is not the only parameter. Dynamic range should also be considered. Different 24-bit digitizers generally have different dynamic ranges. If the accelerometer is selected as 130 dB the digitizer should be slightly above that. Usually digitizers between 130-140 dB would meet the requirements.

2.2.2 Sampling frequency and simultaneous sampling (time synchronization)

As the maximum frequency response of the accelerometers will change between 50-100 Hz, digitizers with 100-200 Hz (100-200 samples per second per channel) should be used according to Nyquist theorem. Besides, for dynamic monitoring for operational modal analysis with accelerometers, time synchronization is the main issue. The synchronization can be classified as (i) the synchronization between the channels inside one multichannel digitizer and (ii) the synchronization between more than one digitizer. For the first one, a multi-channel digitizer must be chosen to be fully simultaneous sampling among its input channels. The second issue is generally solved with GPS based time synchronization. For this all the separated digitizers should have a GPS antenna and be able align their time base with respect to satellite time.

3 MONITORING PRACTICES

In last 5 years TDG completed a number of comprehensive monitoring projects. Among the high-rise buildings, some of them were (i)Emaar Square Libadiye-Uskudar Istanbul : Two Building with 30-31 Floors -Centralized Solution –8 channel digitizers, 1 triaxial and 5 units of uniaxial 130 dB force-balance accelerometers were installed on the buildings, (ii) Levent 199, Sisli/Istanbul : 40 Floors, 161 meters, one of the highest buildings in Istanbul – Centralized Solution – 16 channel digitizer, 16 units of uniaxial 130 dB force-balance accelerometers were installed on the building. (iii) Zorlu Center, Besiktas Istanbul : 4 Towers with 20 Floors, 161 meters– similar centralized system was installed. 5 recently built City Hospitals of Turkey with seismic were instrumented with accelerometers. The primary motivation behind was to monitor the performances of the seismic isolators. The general strategy was installing triaxial accelerometers below and above the isolators. Another accelerometer was installed at the top floor. In this way it is possible to record the seismic acceleration on the ground, then above the foundation of the building isolated by the dampeners, then the maximum acceleration of the building at the top.130 dB force balance based Molecular Electronic Transducer(MET) type accelerometers were used. For historical structures undergoing strengthening and restoration work, 2 most extensive monitoring projects were Galataport Project in Istanbul and Ulu Mosque in Sivas Divrigi. In both, a combination of static and dynamic monitoring were used. In Galataport 5 different buildings were instrumented. (106 tiltmeters, 21 accelerometers, 5 environmental, 13 units of multi-channel digitizers). Tiltmeters were used there for the first for settlement analysis. In Sivas Divrigi, Ulu Mosque project, tilt and crack monitoring were established, mainly. (8 tiltmeters, 25 crack meters, 11 accelerometers, 4 laser displacement sensors, 2 in wall humidity sensors, 6 wall surface temperature sensors, 6 environmental, 5 units of 16 channel digitizers) Force-balance 130 dB accelerometers were installed in both projects. Another comprehensive project was in Ankara. Historical headquarters of Ziraat Bank, being one of the first structures of Republic of Turkey, was instrumented during a strengthening process. Settlement analysis with tiltmeters method was re-used in this project. (30 settlement, 26 tiltmeters, 8 crack, 2 environment, 6 inclinometers, 4 units of 16 Channel, 1 unit of 8 Channel Digitizers). Clock Tower and Oshki Church in Erzurum, Selimiye Mosque in Edirne, Eyup Sultan Mosque in Istanbul were some of the other monitored historical structures by TDG. For all projects the data was transferred to the Monitoring Center of TDG. Real-time analysis software was active to trigger alarms 7-24 to the project owners. A web-based frontend allowed the engineers to follow the data online. Monitoring systems were very effective ensuring the safe construction work all the project long.

4 HEALTH MONITORING CENTER SUBSTRUCTURE

The real-time and post process, analysis and reporting that can be used for decision support is as much important as the instrumentation itself. TDG developed an approach for this which is called as Health Monitoring Center Substructure and provides the tools for ending up with deliverable results from a huge amount of data coming from the sensors. (Figure 3) Several software components are included in this flow, which are continuously being developed further.

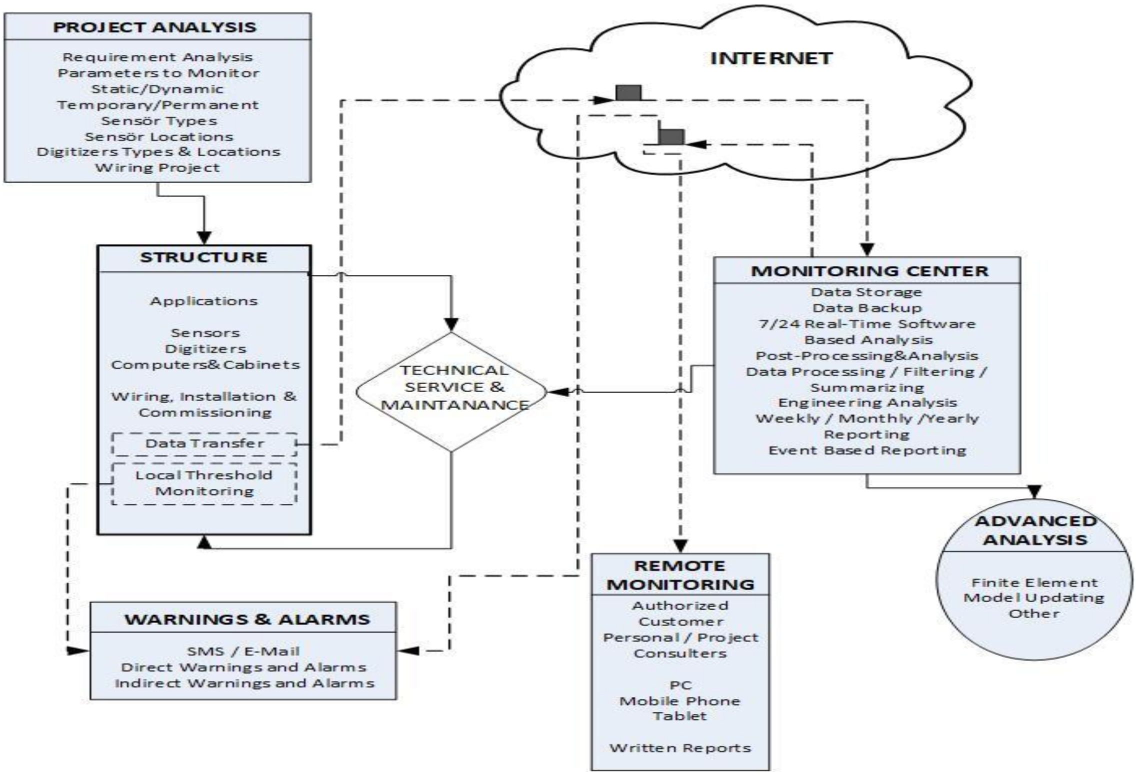


Figure 3. Health Monitoring Center Substructure

The most comprehensive part of the software functions at the monitoring center for real-time analysis. Real-time analysis is essential for coping with large amount of data. Analyzed and summarized resulting data and graphs are logged and presented to the decision makers. Web-based data monitoring is developed for this purpose. Currently natural frequency domain comparison analysis for buildings are carried out based on FDD (Frequency Domain Decomposition) technique. Both short-term and long-term changes of the first 3 translational and torsional modes are compared in real-time. Seasonal changes of the frequencies throughout the year are compared with past years, for long term analysis. Any degradation or long term rigidity loss due to aging or fatigue analyzed. After an earthquake of M5.0 epicenter close to the structure the structure is checked for a major loss of integrity. Also dynamic top displacements and seismic isolator displacements are calculated from acceleration values using high-pass filtering, double integral and offset correction techniques. For static monitoring components, threshold values are determined and updated periodically.

5 CONCLUSION

Structural health monitoring today is the unique technique for studying the dynamic behavior of existing buildings, moving the civil engineering laboratories to real-world. Taking precautions and preventing failures against severe earthquakes and other effects started to become possible by monitoring the integrity of the structure in real time. High-rise buildings, historical structures, hospitals, bridges and tunnels are the main types of structures commonly being monitored in recent years. Both dynamic and static monitoring are being applied on these structures. From a number of current instrumentation possibilities selection of the accelerometers and digitizers are of vital importance. Among current accelerometer technologies (i) conventional, electro-mechanical force-balance (FBA), and (ii) molecular electronics (MET) type FBA accelerometers are the best-fitting and commonly used technologies. However any accelerometer having a dynamic range above 120 dB, noise density below 300 ng/√Hz, measurement range of at least ±2 g, and a frequency response at least in between 0.1-50Hz DC is adequate for operational modal analysis under ambient vibration. For the digitizers, a minimum of 24-bit resolution, 130 dB dynamic range with a sampling frequency of at least 200 Hz/channel is needed. One vital parameter for the digitizers is synchronization. Simultaneous sampling is required for operational modal analysis. When the digitizers have to be separated 1-10 micro-second timing resolution is required and this is generally reached by GPS time synchronization. Whenever possible (semi)centralized installation architectures with low-noise permanent analogue cables should be preferred. Analysis and reporting the data for decision support is at least as important as installing the best-fitting instrumentation. A monitoring center approach with a real-time analysis software at the core has been developed in order to deal with the large amount of data coming from the instrumentation. This provides the tools for ending up with deliverable results from a huge amount of data coming from the sensors.

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