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Automated structural health monitoring and data analysis of the first cable-stayed suspension bridge in Switzerland

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Abstract

Structural monitoring is of ever-increasing importance. It is now considered to be a prerequisite at many civil engineering sites and is critical to the safety of site operatives, infrastructure and machinery. To maintain a certain level of safety, information regarding the health and integrity of a structure is required. This information enables specialists to understand the impact of stresses and potentially predict structural failure so as to avoid catastrophe.

This paper presents a system in operation capable of acquiring geotechnical and geodetic data, analysis, presentation and distribution of the data and information for the monitoring site. The generation of information from the monitoring data is determined by the capabilities of the various measuring tools defined for the monitoring system. The monitoring system is introduced with its sensors, data acquisition and analysis tools. Converting the data into information is a very important component in a monitoring process.

It is critical to have the right information at the right time and in the right place. The system presented here can be configured to distribute automated PDF reports to the responsible persons at any given time. The reports show current and historical data and can be shared with multiple recipients, as well as used for general documentation purposes.

1 Introduction

Structural monitoring is of ever-increasing importance. It is now considered to be a prerequisite at many civil engineering sites and is critical to the safety of site operatives, infrastructure and machinery. In order to maintain a certain level of safety, information regarding the health and integrity of a structure is required. This information enables specialists to understand the impact of stresses and potentially predict structural failure so as to avoid catastrophe.

The administration of the department of transportation in St. Gallen recognised the value of this type of monitoring. The Rhine Bridge in Diepoldsau, St. Gallen, a 250 m-long bridge built in the 1980s, was the first cable-stayed suspension bridge in Switzerland at the time (Bänzinger 1985). The Rhine Bridge still serves as a very important traffic route to neighbouring Austria, with a high frequency of traffic of about 20,000 vehicles crossing per day (current as of 2010).

The stable pillars of the bridge are located in the sedimentation area, and even the smallest movement expected by the structural design should be monitored precisely. A meadow with two manmade dams located in the sedimentation area protects the local municipalities.

Figure 1 The Rhine Bridge — the object of monitoring

2 Bridge monitoring system

The monitoring system at the Rhine Bridge can essentially be divided into four core components. All the components are presented in Figure 2.

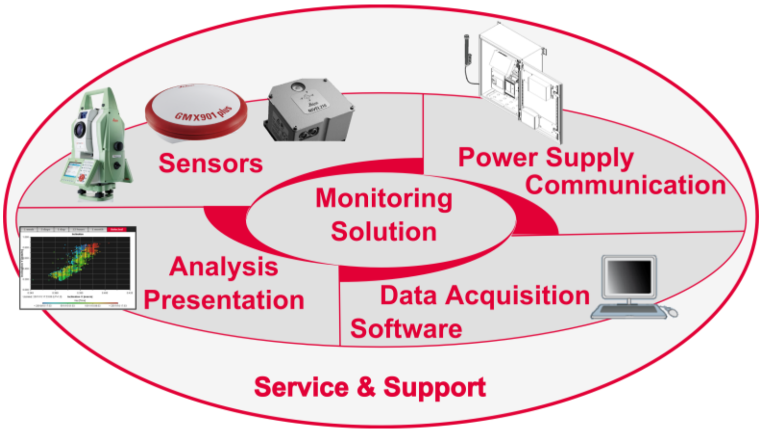


Figure 2 Components of the monitoring solution

The core components include sensors for generating data, communication, data acquisition and analysis of the data. The sensor data is provided with a unit ID and time stamp, forming a complete data set. These data sets must then be transferred to the data acquisition unit. The communication component uses modern transfer technologies such as radio links, mobile radio, WiFi and Ethernet. Interruptions in communication result in data outages where no information is available for monitoring. All data sets must be stored as structured data in a database. The stored data must be converted into information. This information is then used for data analysis and presentation.

In addition to the core components, a continuous supply of power to the site and maintenance of the monitoring system are important components for the successful operation of a monitoring solution.

2.1 Sensors

In the measurement concept, the sensors and location of the sensors shall represent the value of the monitoring object to be obtained. Proper selection of the sensors should answer two questions. Firstly, ‘What is the problem which necessitated monitoring?’ and secondly, ‘Which sensor can be used to measure this characteristic?’

The monitoring system at the bridge in Diepoldsau consists of several sensors. Figure 3 provides an overview of these sensors.

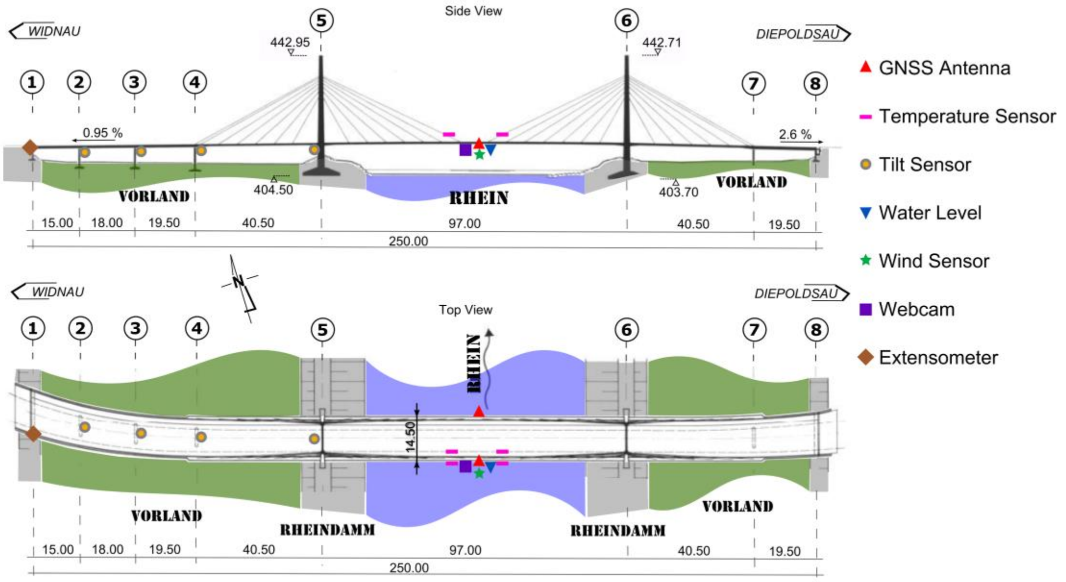
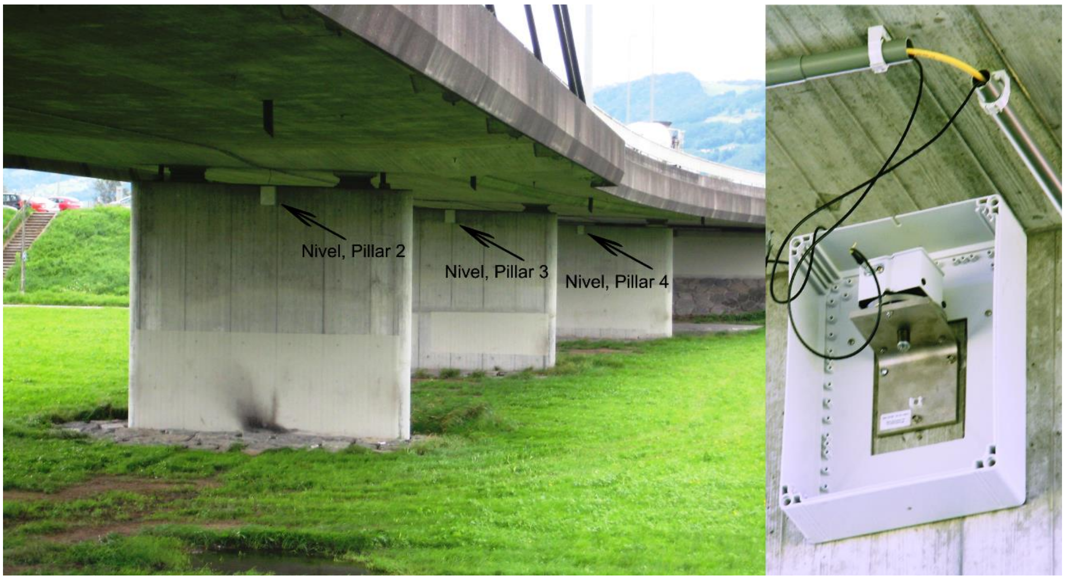


Figure 3 Location of sensors at the bridge in Diepoldsau. Map based on Bänzinger (1985)

Spring snowmelt causes the Rhine River to swell. If this is compounded by rain, the water could rise to a critical level. The floodplain (Figure 3: ‘Vorland’), which consists of unconsolidated rock material, could be flooded. There is a risk that the bridge pillars could move, resulting in structural damage.

A supersonic water level-sensor is installed in the middle of the bridge (Figure 3). A webcam is also installed there. The webcam can be used as a visual sensor for checking the Rhine water level. The inclination of the pillars located in the floodplain is observed by four high-precision tilt metres. These tilt sensors (Nivel 220) can detect even the smallest inclination of about 0.001 mrad. Figure 4(a) shows three of four installed Nivels at the bridge and Figure 4(b) shows a single Nivel.



(a) (b)

Figure 4 Mounting of three Nivel sensors at pillars 2, 3 and 4

An extensometer is installed over the expansion joint at the beginning of the bridge. Figure 5 shows the extensometer. The sensor is connected to a datalogger, which converts the analogue signal to a digital value. This sensor is of type rod extensometer and up to 200 mm length change of the expansion joint can be monitored. The digitalisation of the signal is done by the datalogger and gives a resolution of 1 mm.

Figure 5 Mounting of the extensometer at position 1

A Global Navigation Satellite System (GNSS) point is installed in the centre section of the bridge at each outside lane. Here, two Leica GMX902 receivers and Leica AR10 antennas are used to determine the absolute positions of the road pavement. These instruments can be used to stream real-time positioning data and more precise post-processing positioning data. The nearby IGS reference station (International GNSS Service) in Bregenz serves as an accurate positioning solution. The absolute positions of the bridge deck can be used to observe settling of the bridge deck and to determine the tilt of the lane.

Environmental parameters can also influence the structure, which is why multiple temperature, pressure and humidity sensors are installed on site. A wind sensor completes the meteorological observation set-up and measures the wind speed and direction. Figure 6 shows the installation of one GNSS point, webcam, wind sensor and supersonic water-level sensor. The phase centre of the GNSS antenna represents the coordinates of the GNSS point. The antenna is connected to the receiver which is built in the communication box at pillar 5.

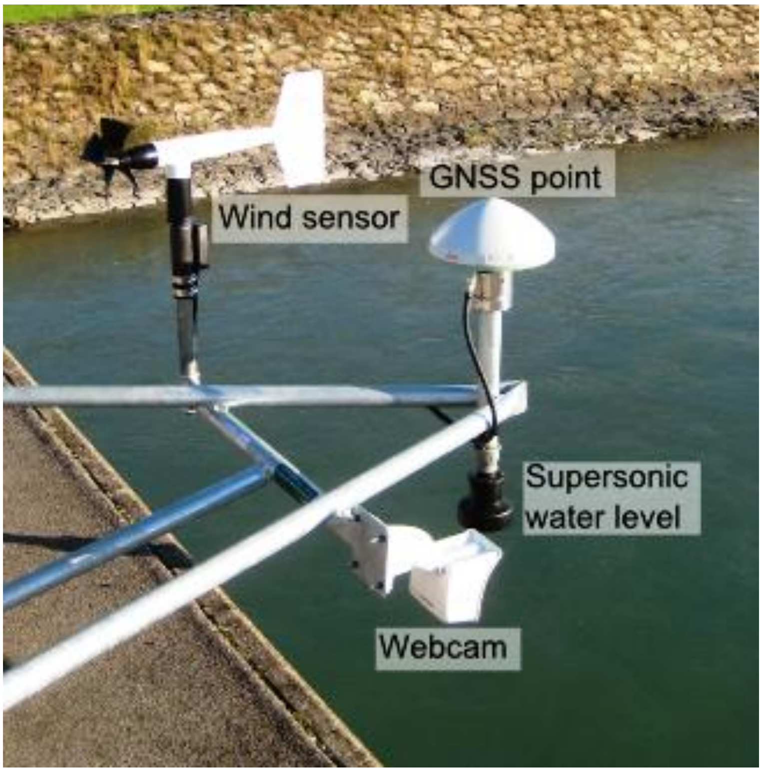


Figure 6 Wind sensor, GNSS antenna, webcam and supersonic water-level sensor located in the centre section of the bridge deck

2.2 Communication

All sensors are linked to a communication box. In this case, the Leica M-Com family is used. The data is transferred via a WiFi connection to a nearby receiving station and then to a wired Ethernet connection. Should the WiFi connection break down, the data is sent over a 3G mobile link used as a fallback communication line. Kostadinov and Merk (2011) describe the details of the communication set-up and hardware used. All data is routed through the Internet to the analytics centre.

2.3 Data acquisition

Data arriving at the data centre is stored in an SQL database. For further evaluation and an improved data structure, each data set is linked to a 3D point. With this approach, the monitoring data can be plotted on a map. Data acquisition is carried out with the Leica GeoMoS Monitor (Hill & Sippel 2002). In the newest version of GeoMoS, the software runs as a continuous Windows system service. This is the smallest possible interruption resulting from a failure of the PC (reboot).

All geodetic and geotechnical sensors installed on the bridge structure are connected to this software. GeoMoS Monitor controls the automated measurement cycle and stores the data of each sensor at defined intervals. The intervals defined for each sensor can range from 10 seconds to once per day.

Data which has already been retrieved can be used in a so-called virtual sensor for additional observations, e.g. observing the tilt of the bridge using the opposing GNSS antennas in the centre section of the bridge.

GeoMoS Monitor checks the incoming measurement value against a defined limit for the observation type. If the threshold is exceeded, it notifies the responsible people via email or SMS. Even a siren or warning lamp can be switched on or off through a digital I/O connection. The software is used for an initial rough analysis, and a simple time-line diagram is plotted for each point.

3 Analysis and presentation

When operating a monitoring system, analysis is crucial for the generation of information from basic data and the distribution of this information to the right people. In this project, we use GeoMoS Now!, a web-based solution for data analysis and presentation. GeoMoS Now! uses data from GeoMoS Monitor. In this project, all monitoring data acquired is sent to the cloud version of GeoMoS Now!. The benefits of this are that the resulting information is available over the Internet and the database in the cloud serves as a back-up of the local monitoring database.

There are usually three requirements for analysing software for monitoring purposes. The first is to evaluate the data and create information from it, e.g. studying the coincidence of temperature and expansion/shrinking of the structure, showing sensor data over time, studying the precision of the GNSS position with a scatter plot etc. The second requirement is to document the current analysis, e.g. by creating a webpage with the analysis results or printing a PDF report with the results. The third requirement is to distribute the information to different groups of customers. Groups can include engineers who need the current status of the monitoring system and latest values to check the progress of a work site and the safety status (has a limit been exceeded?), management who want to see an overview of the system in operation and/or public customers (the mayor, municipality and public) who want to learn about the work site or progress, for example.

3.1 User management

The monitoring project at the bridge in Diepoldsau was established in cooperation with the municipality of Diepoldsau. One requirement was that the municipality have access to the monitoring data. The administrator of the monitoring system created users and assigned user roles to them. GeoMoS Now! offers editor accounts and observer accounts. Editors are authorised to create information from the data and store them on the web page, dashboard or in a report. An editor can specify which information is shown to the observer. Observers are authorised to view all of these pages and reports. The viewing of real-time data is protected and requires logging in to access the monitoring project. This enables experts, managers, customers and other interested people to access the information and ensures that these people are working with the right information.

3.2 GIS functionality

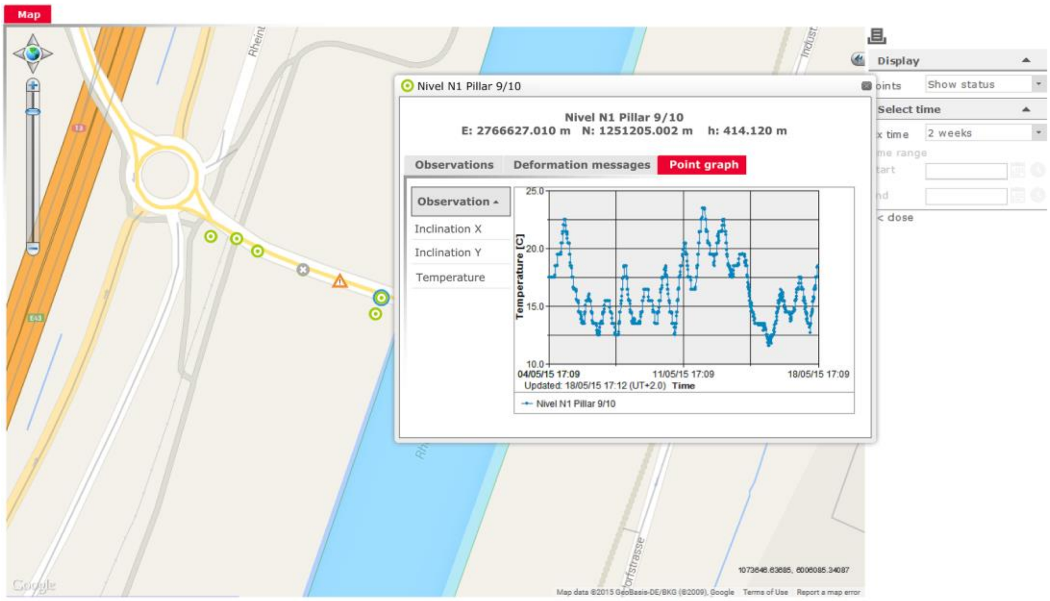
Opening the web interface of the monitoring project provides you with an overview of the system. Sensors are shown on a map which provides much more spatial information about sensor location and measurement values. Figure 7 shows the overview of the monitoring site. The sensor location is georeferenced in the base map material. Google maps, shape layers from OpenStreetMap and a georeferenced image are used for the base layer. All the layers must be in the same coordinate frame. The coordinate frame for the monitoring sensors is a UTM projection. As the map control contains information on the coordinate frame, it can transfer the data. Individual layers can be activated or deactivated using this map control.

Points: Show status

Fix time: 1 month

Figure 7 Map control with different layers

Until now, no additional information has been displayed on the map. Switching over to show the status on the map, the editor and observer immediately sees the status of the monitoring system. Figure 8 shows the selected shape layers and the status information above. A green circle indicates that data is available and that there are no deformation messages regarding this point and the selected time period. A red triangle indicates that there is a deformation message. If no data is available for the selected time period, this will be indicated by a grey x in a circle. Clicking any point opens a new window allowing you to read the latest observation values linked to that point, display the latest deformation messages linked to the point or create an on-the-fly graph of a linked observation type.



Nivel N1 Pillar 9/10
E: 2766627.010 m N: 1251205.002 m h: 414.120 m

Updated: 18/05/15 17:12 (UT+2.0)

oints: Show status

x time: 2 weeks

Figure 8 Map control showing deformation status and point graph

The status on the map/image provides an overview of the entire monitoring site. Critical areas can be identified immediately. A quick analysis of the point can be done without changing the location and going to another website. The Graph Designer can be used to analyse the data in more detail.

3.3 Generating information

When generating information from monitoring data, diagrams are generally used. In this monitoring project, GeoMoS Now! was used to create the graphs. The Graph Designer offers a host of graph templates for visualising data in several variations. The Graph Designer (Figure 9) can easily create graphs in just three steps: select the point of interest, define the graph template and select the observation types (series).

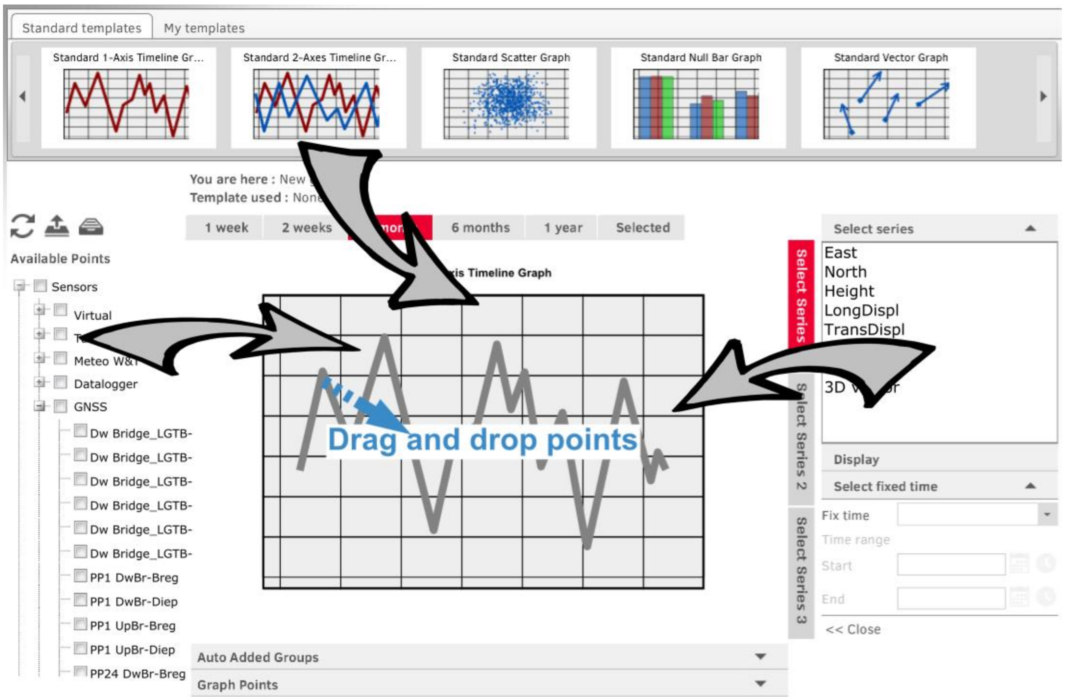


Figure 9 Using the Graph Designer to create graphs based on templates in just three steps

Common graphs include the timeline diagram and the timeline diagram with two axes for displaying different units in the same graph. Figure 10 (top right) shows the wind speed with superimposed limits. Here, the limits regarding the official wind speed terms are named. By evaluating the coincidence in the data, the scatter plot can be used to show the relationship with the same or different observation types (Figure 10, top left). The scatter plot shows the precision of the two GNSS antennas on the bridge. The measurement values are the result of 1 hour of post-processing. Point UpBr-Diep has a precision of less than 5 mm in both coordinate directions. The opposite point has a precision of less than 1 cm. The results are not corrected by bridge movement in the north and east. This shows that, in these directions, the bridge is quite stable. Figure 10 (bottom left) shows a vector graph of the GNSS antenna heights. To get a better understanding of the locations, a background image can be used. The amount of the vector is, in this case, the current measurement against the reference measurement. Figure 10 (bottom right) shows a picture of the webcam; this is a visual check of the environment and the height of the Rhine River.

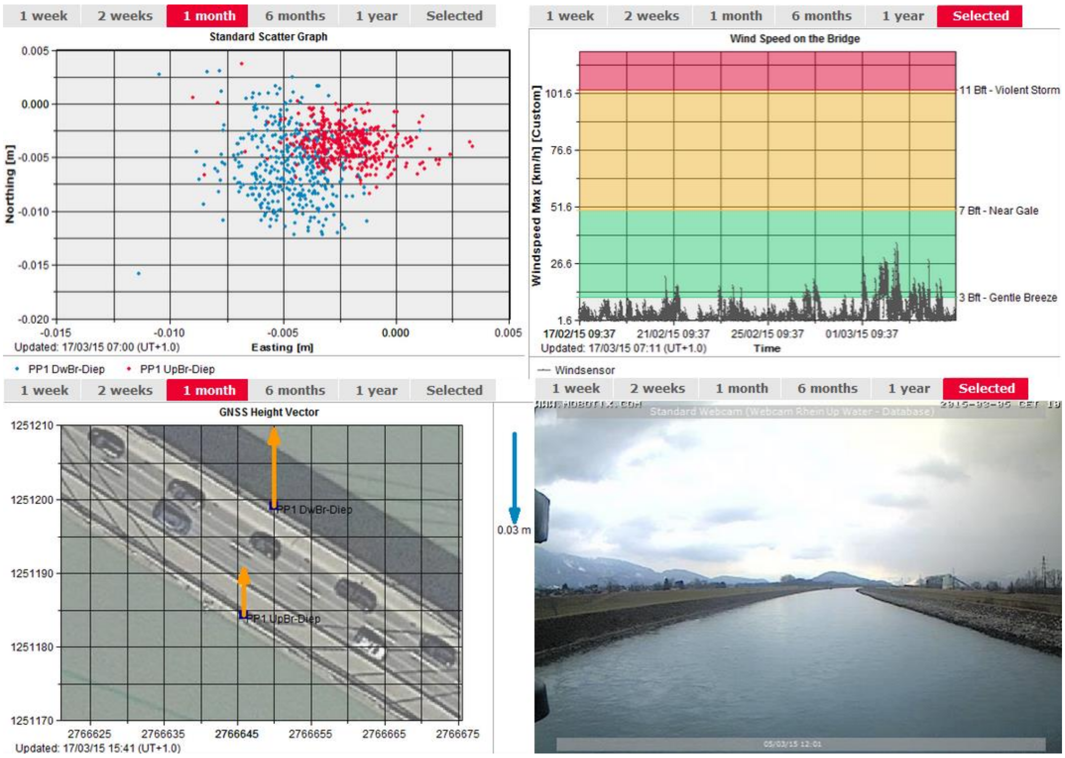


Figure 10 Standard graphs for analysing monitoring data

For advanced analysis, a velocity graph (one and two axes) is available. Figure 11 shows the gradient of the GNSS antennas (height component). The time range for the derivative is 24 hours. The graph shows that the usual change in height is around +/-2 cm per day. This can be explained by diurnal variations of the temperature. The cables of the bridge expand and shrink, so the height changes. The changes for the height are equal for both bridge sides. The lines in Figure 11 are overlapping each other. This means the bridge deck makes same movement over time. The analysis of the absolute position shows that the bridge is quite stable in Easting and Northing. The height of the centre section is moving.

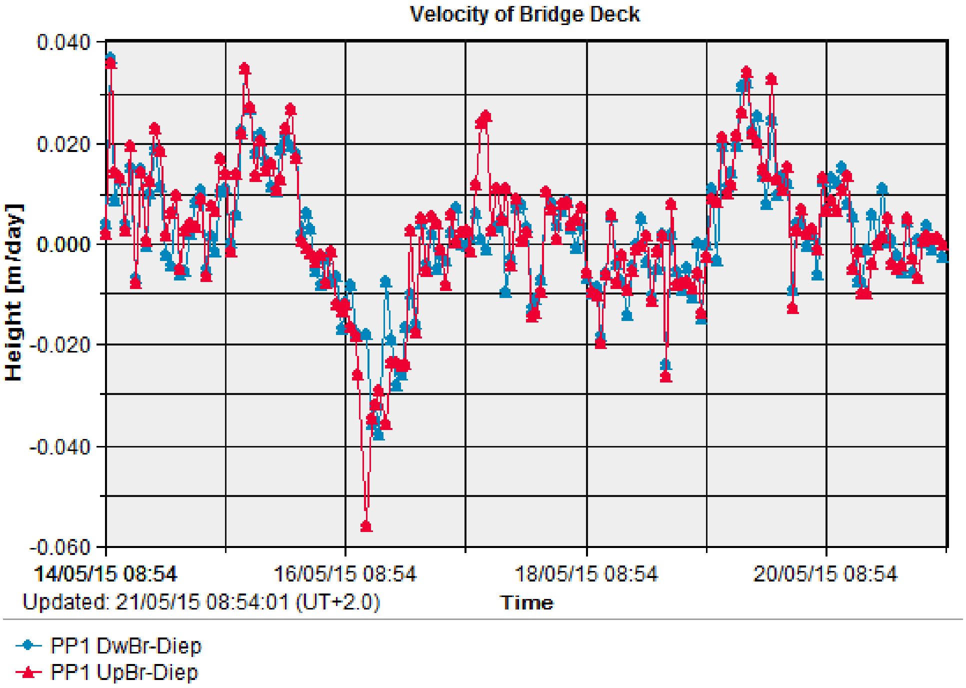


Figure 11 Height gradient of GNSS points

The bridge is exposed to local weather conditions. This means the bridge structure will deform regarding changing, e.g. temperature. Figure 12 shows smoothed data of the extensometer for the last 18 months. A moving window filter with filter length of 24 hours is used for smoothing. The maximum deformation over one year is about 15 cm. The local temperature is superposed to the extensometer data. The two lines show an opposed diagram. The correlation between temperature and expanding/shrinking of the bridge is obvious. In summer during the hottest temperatures the expansion joint is smallest because the bridge structure is expanding. Vice-versa in winter the expansion joint is at a maximum expansion.

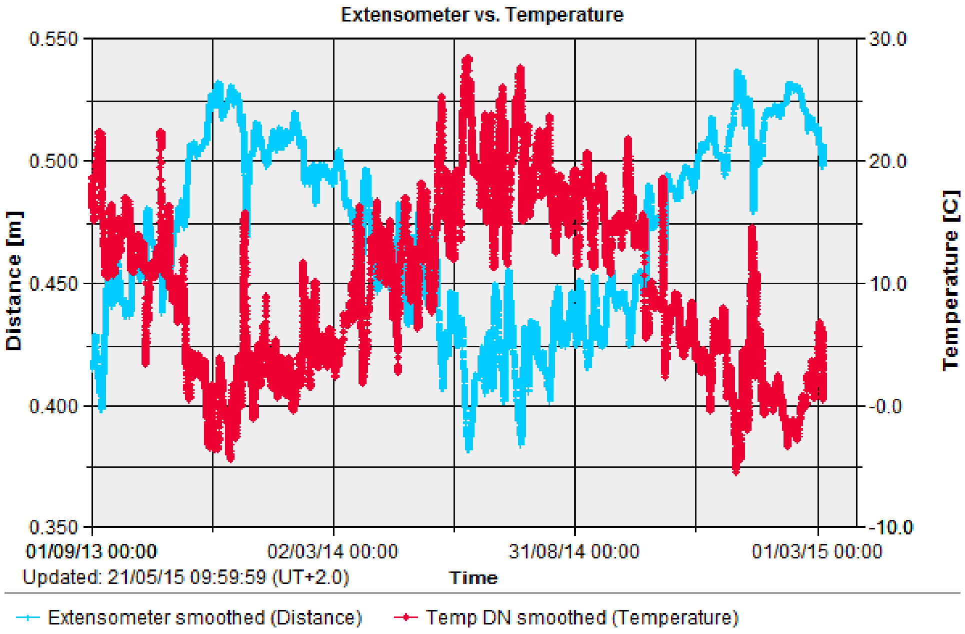


Figure 12 Extensometer data versus local temperature

This movement, induced by different environmental parameters, has an influence on inclination of the pillars. Figure 13 shows the correlation between the extensometer and the inclination of pillar 2. Inclination Y shows in direction along the bridge. The data of the extensometer and inclinometer show a clearly daily trend. The correlation between these two sensors is obvious. The inclination of the pillar for a day is about 10 mgon (32.4”) and the pillar height is app. 6.5 m. This results in a residuum on top of the pillar of about 1 mm. The extensometer shows a difference of 1 cm per day. Most of the movement will be absorbed by the abutment of the pillar.

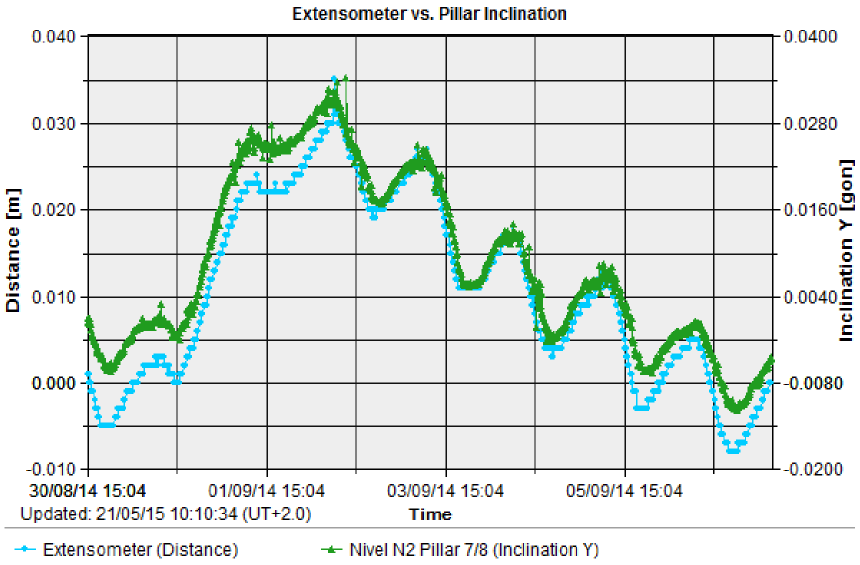


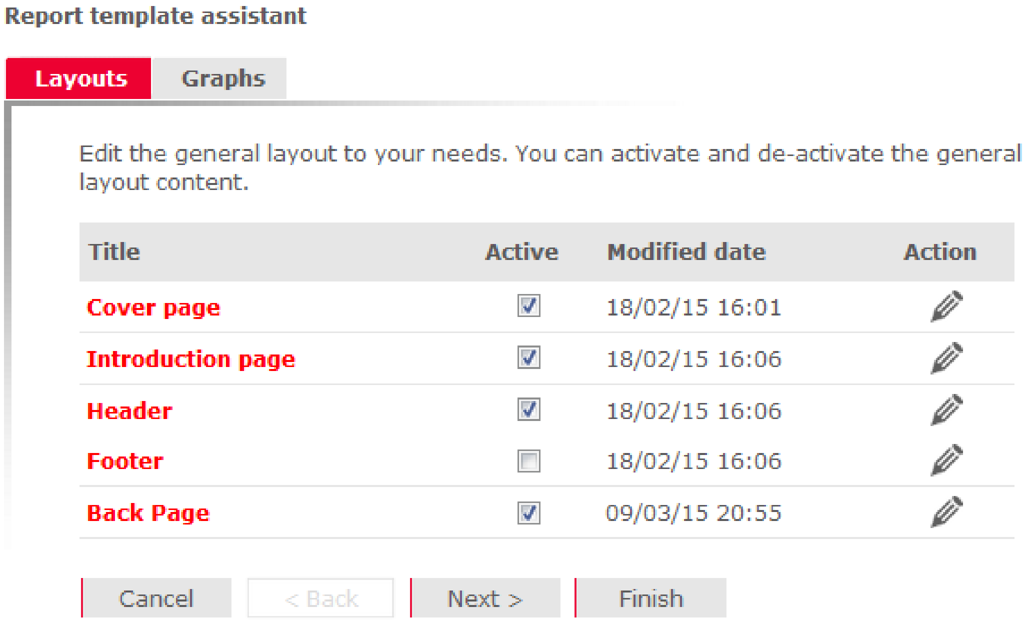
Figure 13 Extensometer data versus the inclination of a bridge pillar

For monitoring the pillars it is clearly seen that a high-resolution and high accurate sensor is needed. The movement of the structure influenced by temperature variations can also be seen the inclination of the pillars.

Only a small selection of graph templates is shown here. Templates for a bar graph, time range colour-coded scatter plot, contour plot, scanning image with deformation or circular level graph are also available in the Graph Designer. Even external images available on the Internet or a local network can be integrated as a graph. All graphs can be edited in terms of their time range, observation type and graph type. The editor of the project can easily evaluate the monitoring data. The created graphs can be stored and reused on the website or dashboard or in the reports.

3.4 Documentation

The operator of a monitoring system must present evidence to the client. In most cases, manually written reports containing the current status of the monitoring system are provided. In this monitoring project, an automatic report is used. The report only needs to be defined by the editor once. The editor can create graphs and link them to a report. When the report is created, the current data is shown in the defined graphs, and the graphs are created dynamically. Additional static information like a cover page, introduction page, header, footer and back page of the monitoring project can be added to the report (Figure 14). This report is based on the HTML web language. A WYSIWYG editor helps you create the pages for the report (Figure 15), so advanced knowledge of HTML is not needed. Experts in HTML can change the source code and edit the outcome directly. Finally, the report is converted to the PDF file format.

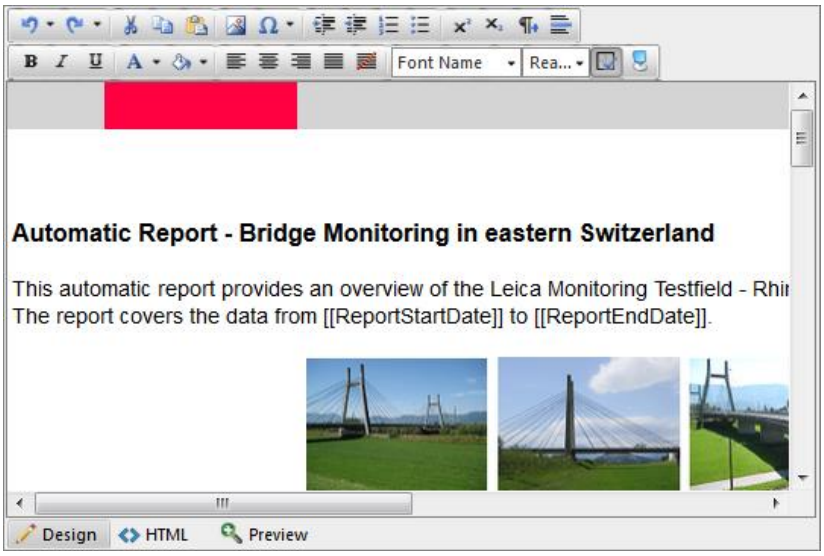


Report template assistant

Edit the general layout to your needs. You can activate and de-activate the general layout content.

Title	Active	Modified date	Action
Cover page	☑	18/02/15 16:01	✎
Introduction page	☑	18/02/15 16:06	✎
Header	☑	18/02/15 16:06	✎
Footer	☐	18/02/15 16:06	✎
Back Page	☑	09/03/15 20:55	✎

Figure 14 The Report Assistant for creating automatic reports



Automatic Report - Bridge Monitoring in eastern Switzerland

This automatic report provides an overview of the Leica Monitoring Testfield - Rhi
The report covers the data from [[ReportStartDate]] to [[ReportEndDate]].

Figure 15 The Report Assistant WYSIWYG editor

Once the report set-up is complete, the automatic report is sent by email to the responsible people. A report can be defined for different user groups.

Reporting enables information to be distributed very easily.

4 Conclusion

This paper presents a case study of a complete monitoring solution. The monitoring object is a cable-stayed suspension bridge in Switzerland. The stable pillars of the bridge are located in a sedimentation area, and the municipality is protected by two manmade dams with a floodplain in between. There is a potential risk of structural damage to the bridge due to flooding. Multiple sensors represent the monitoring object and the environment. A WiFi connection is used for communication between the sensors and the data analysis centre, and there is a fallback physical connection as well. All the sensors are controlled by the GeoMoS Monitor software, which stores all the data in a database. This paper demonstrates that it is important to convert the data into usable information, done in this case with the GeoMoS Now! software. The GeoMoS Now! software also enables you to evaluate the data. Using the Graph Designer, it is easy to generate new information from the monitoring data. The software informs the customer about the current deformation status of the monitoring system and makes it possible to document the current deformation status in a PDF file.

This paper presents the workflow of acquiring data, transforming the data into usable information and distributing the information to the right responsible people. This paper shows results of the monitoring system and shows that all integrated sensors can record the movement effects of the structure independently.

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