Research and Development of a Pilot Project Using GNSS and Earth Observation (GeoSHM) for Structural Health Monitoring of the Forth Road Bridge in Scotland

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Abstract: GeoSHM (GNSS and Earth Observation for Structural Health Monitoring) is a feasibility study project funded under the Integrated Application Promotion (IAP) program of the European Space Agency (ESA) in August 2013. Through integrated use of GNSS, Remote Sensing technologies and environmental data, GeoSHM can offer bridge owners an effective tool to assess the operational conditions of their assets. A reference system that consists of four GNSS receivers and two anemometers was installed on the Forth Road Bridge (FRB) in Scotland. This first stage monitoring system is producing precise 3D real-time displacements under different loading conditions. It can also provide essential land movement information to assess potential threats due to underground water extraction, geo-hazards and other industrial activities.

The GeoSHM Feasibility Study has proved that even a small scale monitoring system can make possible for the Bridgemaster of the FRB to fully understand the loading and response effect of the bridge, and identify unusual deformations under extreme weather conditions (wind gust, etc.). Furthermore, EO data has proved to be extremely useful for the subsidence detection, as the SAR interferometry images have shown that there is no significant subsidence of the towers of the FRB or in the surrounding area. Gathering real-time GNSS data has produced continuous and accurate estimation of the displacement time-series of the structure. The issues and gaps identified from GeoSHM FS will form a solid foundation for the next stage development of GeoSHM service – demonstration, which is a two-year project and have started in February 2016. A new consortium of GeoSHM has been formed, focusing on significant refinements to the system reliability, sensor integration, data acquisition, data transmission, data fusion and SHM information extraction. This further developed GeoSHM system will be installed on a few Chinese bridges and the reference monitoring system on the FRB will be expanded as a pre-operational system.

Keywords: GNSS, GNSS and Earth Observation for Structural Health Monitoring (GeoSHM), Forth Road Bridge (FRB)

1 Objectives and Scope of the Project

The feasibility study t "GeoSHM - GNSS and EO for Structural Health Monitoring of Bridges" started in August 2013 and concluded in March 2015. It was conducted by the University of Nottingham as Prime Contractor, a higher education entity in the UK and a world leading teaching and research university in geospatial science and civil engineering, three subcontractors that include GFZ (Deutsches GeoForschungsZentrum Potsdam), the

German national research centre for geosciences, UbiPOS, an SME situated in Nottingham on ubiquitous positioning and navigation solutions, LEICA Geosystems, a world leading manufacturer of precision GNSS equipment, and the Forth Estuary Transport Authority (FETA) as end-user that operate and maintain the Forth Road Bridge (FRB, Figure 1).

The objective of this study has been to determine the technical feasibility and economic viability of a Structural Health Monitoring (SHM) service that integrates GNSS and Earth Observation technologies to offer an integrated solution for the maintenance of different types of bridge assets.

The GeoSHM consortium intends to develop and demonstrate a novel system to tackle the issues in structural deformation monitoring of long bridges and other key infrastructure, starting with engaging the stakeholders for a clear definition of user requirements and through establishment of a reference monitoring system on the Forth Road Bridge.

Fig.1 The Forth Road Bridge in Scotland is over 50 years old and has a main span of 1006 metres long. This bridge is used as a test-best for GeoSHM project

2 Users & Stakeholders

The most important stakeholder identified in this feasibility study has been FETA which is in charge of the operation and maintenance of the Forth Road Bridge. The University of Nottingham has built research collaboration with the Forth Road Bridge of more than 10 years. The FRB is a suspension bridge in East Central Scotland opened in 1964. Over the past 50 years, the single direction traffic increased from the designed 30,000 vehicles per day to an average of 40,000 vehicles per day by 2010. The FRB authority admits that 60,000 vehicles per day are not uncommon for weekday travel.

This bridge is experiencing stressed sub-structures and components (e.g. tensile or compressive structures), unexpected deformations, high level of humidity inside the cables, etc. Extreme weather conditions such as high winds cause very often bridge closures. It is estimated that the cost for closing one lane is more than £650,000 per day. The maintenance of the bridge is at the moment determined by inspection, however due to their urgent needs for understanding loading-response effect and developing a condition-based maintenance program, bridgemaster of the Forth Road Bridge has been actively involved in the GeoSHM Feasibility Study. Their contribution has been essential in the definition of key parameters of the system architecture moreover they also partially financed the deployment of: dedicated fibre optic connection for data transmission, four GNSS reference stations and two anemometers to monitor their asset.

Other stakeholders such as UK's Highways Agency, Network Rail, etc. also were involved in the activity as they attended the project workshops and provided essential inputs to the definition of the user requirements and the assessment of the performance of the GeoSHM reference monitoring system installed on the FRB. COWI is a world leading consulting group and Bridge, Tunnel and Marine Structures form a major business line of COWI. Flint and Neill (F&N) as a world leading SHM firm and part of COWI joined all the public and internal workshops and provided essential inputs to the definition of user needs and data dissemination strategy. Other actors that showed interests in the GeoSHM service include SHM services providers, such as Strainstall (SHM contract of new Forth Road Bridge), Moniteye and Skanska, who have shown their great intentions to buy GeoSHM service for their immediate maintenance work or projects.

The GeoSHM team has during the study, reinforced collaboration and investigated opportunities in the Chinese market. China has been constructing more than 10,000 bridges a year in the past 30 years and has built 350,000 new bridges so far. China owns the largest world bridge reserve of different sizes and types and these bridges are exposed to different geological conditions. China Rail, as a strategic partner of GeoSHM in China, through its Bridge Reconnaissance and Design Institute Co., Ltd. (BRDI) - a primary large bridge design institute, also assisted to the user need definition, shared their rich experience in the establishment of bridge monitoring systems, attended promotion activities of GeoSHM in China, and received the site visits by the key GeoSHM consortium members.

3 Outline of system architecture and service description

Figure 2 shows the overall structure of GeoSHM that consists of a sensor network, a data transmission module and sub-systems for data processing and visualisation. The sensor system consists of: one reference GNSS station set on the top of the office building of the Forth Road Bridge, three monitoring GNSS stations with two sets on each side of the middle span and one set on the west side of southern tower, and two ultrasonic anemometers with one on the west side of middle span and the other close to southern tower site. Automated data acquisition is carried out by these sensors and the acquired real-time data are sent, via the optic fibre network laid underneath the bridge, to a local hub before they are streamed to the data processing centre set up at the University of Nottingham via public Internet. The received raw data sets are processed in real time or a post-processing manner. The raw data are also sent to the processing facility set up at GFZ in Germany, for backup storage and for demonstrating the technical feasibility of a distributed processing approach.

The resulting bridge displacement information together with wind loading data is released to the Bridgemaster of the Forth Road Bridge through a dedicated web-based GeoSHM interface (Figure 3) developed by the Consortium during the feasibility study in line with the FRB needs.

In order to acquire data of local environmental effects and of long-term structural trends, interferometric SAR (InSAR) measurements are evaluated. PUNNET EO software that is entirely developed by the University of Nottingham has been used for processing EO images. PUNNET is based upon the Small Baseline Subset (SBAS) methodology but it has been improved to provide land deformation over rural and vegetated areas using the novel ISBAS (Intermittent SBAS) approach. The software is able to give a much clearer picture of deformation over a wider set of land cover classes than many other methods. It can be used for specific area surveys or for mapping regional deformation and it is capable to observe deformation also over vegetated regions.

Integrated analysis is then carried out to combine the results from the sensor system and from remote sensing technology.

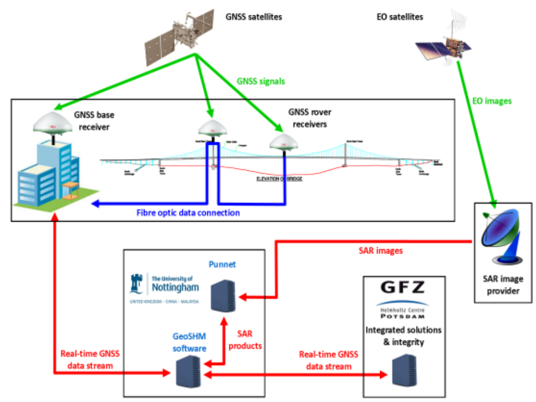

Fig. 2 The GeoSHM System Design

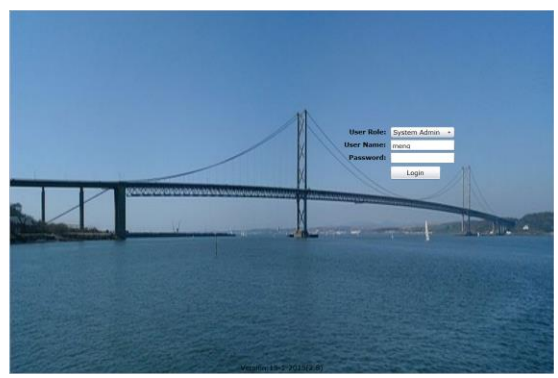

Fig. 3 The dedicated GeoSHM Interface

4 Deployment and test on the Forth Road Bridge

Figure 4 shows the locations of the three monitoring sites where GNSS receivers and anemometers are installed. Since GNSS use a different coordinate system this figure also shows the definition of the GeoSHM coordinate system which uses the bottom of west side of southern tower as the origin, and from this origin the Z axis is defined as pointing to up direction. It defines the along-direction of the bridge deck as X axis and the cross-direction as Y axis.

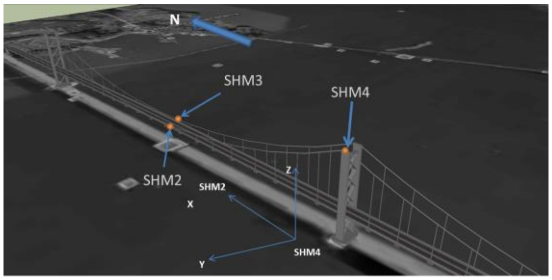

Fig. 4 Installation & deployment of GeoSHM service on FRB and its reference system

Figure 5 shows the GNSS antennas and the boxes for storing receivers and convertors located at the two middle span monitoring sites SHM2 and SHM3.

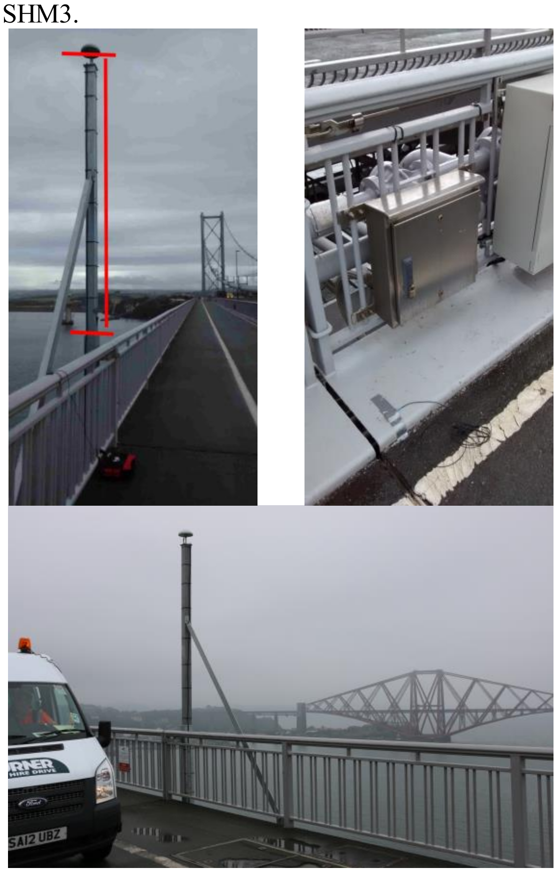

Fig.5 GeoSHM antenna setting-ups at middle span sites

Figure 6 is part of the web-based GeoSHM interface developed for the FRB bridgemasters which displays the 3D deformations of three test sites (i.e. SHM2, SHM3 and SHM 4). It is evident that both middle span sites SHM2 and SHM3 have similar deformations, especially in the vertical direction, which is the red curve.

Fig. 6 An interface that shows real-time 3D deformations

The GeoSHM system has been deployed and started producing real-time deformation data in September 2014 and since then up to today, it is able to provide essential parameters to FRB Bridgemaster.

The FRB bridge master commented the performance of the GeoSHM system by saying "*These parameters are extremely useful for understanding how much the bridge can move under extreme weather conditions and help me to make decision when I have to close the bridge based on precise deformation information. I knew that the bridge can move significantly under high wind loading but for the first time I know that the bridge moved 3.5 metres laterally and 1.83 metres vertically under wind speed of 41m/s (91miles per hour) (as it is presented in Figure 7). Other information extracted from the current GeoSHM system is also important to define reliable alarm thresholds for issuing right alerts in the right time.*"

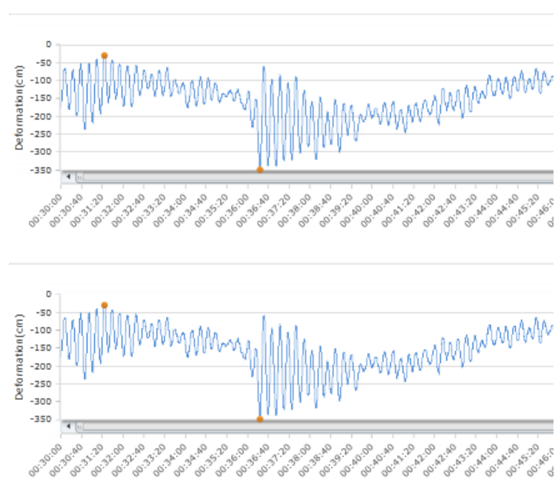

Fig.7 Lateral deformations measured by SHM2 and SHM3 under wind loading of 41m/s

The GeoSHM consortium has long heritage in using remote sensing technologies for ground movement monitoring. In this feasibility study it has also proved that EO is a powerful tool to monitor both regional land movement and the displacements of key components of the bridge.

Figure 8 shows the movements of six bridge locations (supporting towers of FRB) computed by adopting the PUNNET EO software and it confirms that over a time scale of seven years there are no apparent displacements occurred on the supporting towers and surrounding areas.

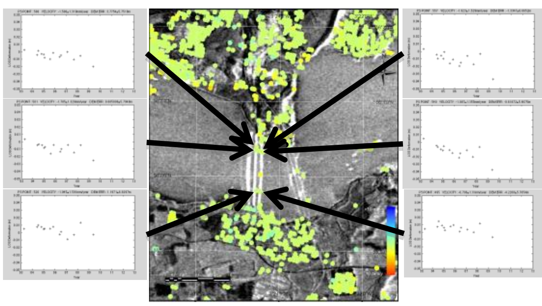

Fig.8 Time series of 6 sites on bridge towers that show no apparent movements

When analysed in China, InSAR images have shown ground subsidence around bridge sites located in two mega cities, Shanghai and Wuhan in China, that was caused by the underground engineering and water extractions.

5 Target market sector and related challenges

GeoSHM service will generate various direct and indirect cost benefits such as:

- Long-term and continuous monitoring with no data gaps, which will provide an efficient, fast and reliable service that will in turn lead to cost efficiencies, whilst helping to answer some fundamental questions such as correlation between individual loading and deformation;
- Online analysis and remote access require less data preparation and reporting which leads to time saving & maintenance cost savings through an automatic system that reduces human errors;
- Multiple bridges can be managed simultaneously with smaller teams;
- Planned target inspection is based on real conditions instead of a-priori scheduling;
- Precise information on specific elements of the infrastructures that needs replacing or maintenance is provided to the bridge masters.

GeoSHM solution initially will be used mainly for monitoring long span bridges (bridges with a main span greater than 400m). As for February 2015, there are more than 260 such bridges around the world and nearly half of them are situated in China. The GeoSHM consortium has established links with other bridge owners in the UK and direct access to most bridges in China through BRDI.

The GeoSHM service has potential also for shorter span bridges such as Hammersmith Bridge, Millennium Bridge and other bridges in China over the Yangtze River. Potentially GeoSHM will play an important role in monitoring other type of infrastructure, for instance wind onshore & offshore turbines, masts & towers, dams & reservoirs, viaducts, high rise buildings / skyscrapers, etc.

To make GeoSHM more flexible in order to tackle the monitoring problems of various type of infrastructures, further research and development work is required which will be explored and carried out in the following stage, the GeoSHM demonstration project. For instance, current issues such as data gaps, high data volume and converting data into useful information for the bridge master, and "data rich but information poor" will be addressed.

6 Conclusions

During the GeoSHM project time the technical feasibility and economic viability of using integrated GNSS and EO for bridge monitoring have been investigated and proved through setting up targeted research and development objectives and carrying on extensive key stakeholder requirement studies. This study has proved that even with a small scale monitoring system it has been possible for the Bridgemaster of the FRB to fully understand the loading and response effect of the bridge under normal loading conditions. The Bridgemaster can also easily identify unusual deformations under extreme weather conditions (for instance strong wind gusts). EO data has proved to be extremely useful to detect subsidence movement at millimetre level. SAR interferometry images have shown that over the years there have been no significant movements on the supporting towers and in the areas surrounding the FRB. In contrast, SAR images have been used to spot ground subsidence around bridge sites located in the mega city of Shanghai in China, caused by extensive underground construction and water extraction. Real-time GNSS data has produced continuous and accurate estimations of the displacement time-series of the structure. The initial work by the GeoSHM consortium has successfully demonstrated the potential of GeoSHM in reducing maintenance costs and safeguarding critical transport infrastructure. Due to the huge market demand in structural health monitoring there is no doubt about the commercial sustainability of GeoSHM. The issues and gaps identified in the GeoSHM Feasibility Study will form a solid foundation for the next stage development, the GeoSHM Demonstration Project, which will last two years. A new consortium has been formed and the focus of the future work has been determined, which includes significant refinements of the system flexibility, reliability and scalability, development of an effective and smart strategy for sensor integration, data acquisition, data transmission, data storage, fusion and presentation, and SHM information extraction to support various bridge maintenance operations. During the demonstration phase, the GeoSHM system will be installed on a selection of Chinese bridges and the reference monitoring system on the FRB will be expanded to a pre-operational system.