Proceedings of IPC2008
7th International Pipeline Conference
September 29-October 3, 2008, Calgary, Alberta, Canada

IPC2008-64231

A FIBER BRAGG GRATING SENSING SYSTEM AND ITS APPLICATION To MONITORING LANDSLIDES AND ASSOCIATED PIPELINES

Pengchao Chen
State Key Laboratory of Precision Measuring Technology & Instruments, Tianjin University, Tianjin,China
PetroChina Pipeline R&D Center
Langfang, Hebei, China

Jianping Liu
PetroChina Pipeline R&D Center
Langfang, Hebei, China

Jianbin Hao
PetroChina Pipeline R&D Center
Langfang, Hebei, China

Hongyuan Jing
PetroChina Pipeline R&D Center
Langfang, Hebei, China

Jianchun Zhao
Petrochina Qinghai Oilfield Company
Xining,Qinghai,China

ABSTRACT

The integrity of oil and gas pipelines is seriously threatened by landslides and other geohazards in tough terrain in western China. Monitoring the landslides with slow, continual movements and the strain build up in pipelines due to landslides is an effective way to maintain the serviceability of pipelines. In this paper, a monitoring system based on Fiber Bragg Grating (FBG) sensors is developed and applied. The system is made up of four related parts: the pipeline strain measurement of the with FBG strain sensors, the soil-pipeline contact pressure detecting with FBG soil pressure cells, the landslide inner deformation monitoring with pipe strain gages and the landslide surface monitoring with a special buried concrete beam with FBG sensors. The system is used to monitor a huge, slow moving landslide and the pipeline affected by it. The monitoring results are analyzed and the pipeline integrity is assessed basing the monitoring results. The FBG system has been proved to be suitable to monitor landslides and pipelines automatically and real-timely.

INTRODUCTION

With Chinese economy on fast track, more and more long distance oil and gas pipelines have being constructed in China. As being 2/3 mountainous region out of a total 9.6 million km^2 area, China is one of the countries in the world seriously threatened by geologic hazards, especially in western China. Therefore, some pipelines were inevitably laid through tough terrain and cases of oil and gas pipeline damage caused by landslides are common in mountainous region in western China.

Lanchengyu pipeline, which is 1250km long transporting product oil from Lanzhou, northwest China to Chongqing, southwest China, crosses numerous areas of active or potential landslides that may pose a significant threat to pipeline integrity. The Erlangmiao landslide, with accumulations of approximate 3×10^7 m^3 of the Quaternary Period, is a typical slow moving landslide that may subject Lanchengyu pipeline to significant deformations. Thus monitoring the landslide deformation and accumulated pipe stress due to the landslide is important in achieving an acceptable safety level and early-warning for the pipeline integrity.

Fiber Bragg grating (FBG) sensor has a number of advantages such as high sensitivity, quasi-distribution, resistance to corrosion, and immunity to electromagnetic noise and radio frequency interference, and has been widely applied in engineering monitoring. Moreover, comparing with GPS or TPS(Total Positioning System) system, FBG sensors can be easily buried underground and safely implemented for real-time landslide monitoring[1], avoiding the third party damage.

In this paper, a monitoring and warning system based on FBG sensors for landslides and the pipelines affected by them is introduced. This system includes pipe strain monitoring using strain sensors, pipe-soil contact pressure measure using FBG earth pressure cells, landslide deep deformation monitoring using pipe strain gage with FBG sensors, and landslide surface relative deformation monitoring using buried concrete beam with FBG sensors. The application of the system to Erlangmiao landslide and Lanchengyu pipeline is also introduced and its effectiveness is discussed.

FIBER BRAGG GRATING SENSOR

Fiber Bragg grating sensor is one of many types of currently available fiber optic sensors. Figure 1 demonstrates the sensing principle of FBG. When the FBG is illuminated by a wideband light source, a fraction of the light is reflected back upon

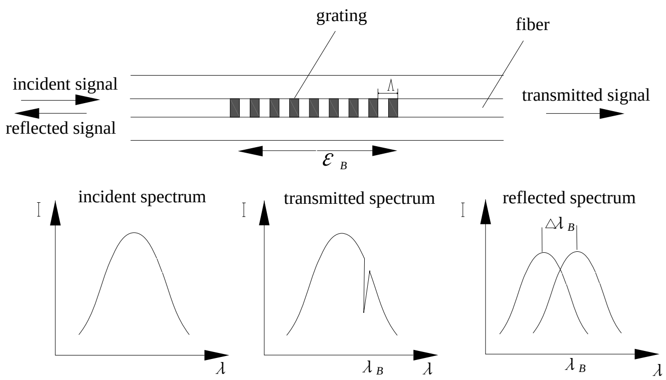

Figure 1. Sensing Principle of FBG

interference by the FBG. The wavelength of the reflected signal, or the Bragg wavelength, λ_B a function of the period of the index modulation, Λ and effective refractive index of the fiber core, n_{eff} as

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Longitudinal strains within the Bragg grating, ε_B induced by variations in temperature or stress can cause a change in Λ and thus a shift of λ_B, with the following relationships[2].

$$\Delta\lambda_B = 0.74\lambda_B\varepsilon_B \tag{2}$$

FBG PIPELINE STRAIN GAGES

For buried steel pipeline strain monitoring, sealing and protection of bare FBG are key issues. A type of thin, stainless steel sheet protecting FBG strain gage is fabricated. This type of strain gage can be easily stuck on the steel surface of pipe after removing the pipeline coating and cleaning the bare metal of the pipe, and then the pipeline coating can be conveniently rehabilitated. Figure 2 shows the pipeline strain gage sealed well. The sensitivity of strain gage is 1.5με/pm and the demodulation resolution of FBG is 1pm(10^{-12}m).

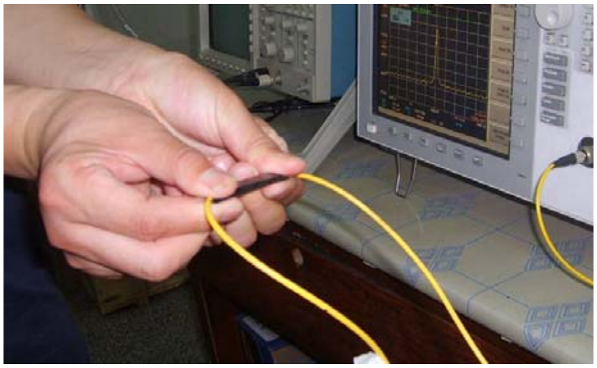

Figure 2. The Pipeline Strain Gage

As the primary strains of interest in soil movement areas are longitudinal strains[3], the instrumentation should be longitudinally-oriented strain gages. To completely define the longitudinal strain in the pipeline at one strain gage station, at least three longitudinally-oriented strain gages are needed. One typical three-gage array is the 90-degree array in which one gage is placed on the top of the pipe(12 O'clock), and the other two are placed at the 3 O'clock and 9 O'clock positions as showed in figure 3. This type of arrangement requires less excavation works of the monitoring pit than the other typical arrangement at the 12 O'clock, 4 O'clock and 8 O'clock positions. A temperature FBG sensor is mounted at 12 O'clock for the sake of temperature modification to the strain sensors.

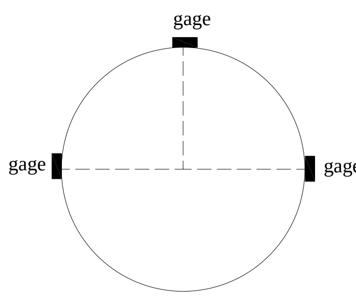

Figure 3. Strain Gages' Arrangement

The FBG strain gages reveal strain information only about the particular points, so the selection of measure intervals should keep the balance between technique and costs. In the reference [3], it is suggested spacing of 300 feet or more may be possible in areas where the movement expected to be relatively uniform, while spacing as close as 50 feet is indeed useful in an known critical area.

FBG EARTH PRESSURE CELLS

The amount of the contact pressure between soil and pipeline is a critical parameter in assessing the soil-pipeline interaction. For the interest of the contact pressure, a type of FBG earth pressure cell is delicately designed and used. Figure

4 shows a photograph of the cell. In the inner of the cell, a FBG strain sensor and a FBG temperature sensor required for temperature modification are set.

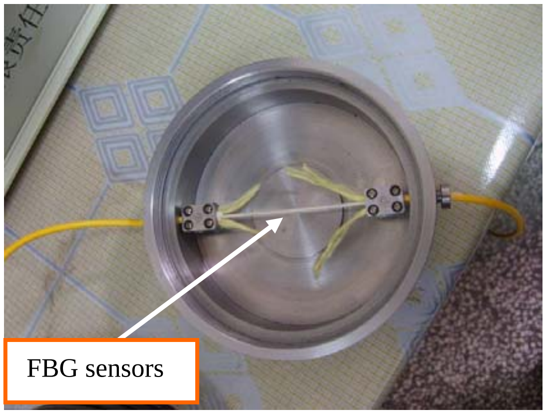

Figure 4. FBG Earth Pressure Cell

PIPE STRAIN GAGE WITH FBG SENSORS

Takada（1965）[4] has reported the idea of a pipe strain gage to measure ground displacement. A series of strain gages are attached to the outside of a plastic pipe at constant intervals. This instrumented pipe is then grouted in the ground. The strain gages measure the flexural strains,ε experienced by the pipe as it is forced to deform with the ground. According to the mechanics of materials, the lateral displacement y relates to ε as

$$y = \frac{1}{r}\int\left(\int \varepsilon dx\right)dx + eX + f \qquad (3)$$

where

r = outside radius of the pipe;

e,f = integration constants;

x = depth;

X = full length of the pipe.

For the resistance type strain gages and the vibrating wire strain gages, every strain gage demands a separate cable for power supply and signal transmission. Thus the drawbacks of limited accommodating space in holes, electro-magnetic interference and short circuit of numerous cables can't be overcome. With its small size and the capability of multiplexing, the FBG is ideal for instruments where multiple sensors are required. A pipe strain gage with FBG sensors can be equipped with many strain measurement points, without the hazards of electronic/mechanical parts or bulky cables. The reference[5] introduced a kind of FBG pipe strain gages applied in monitoring dike deformation, however, no publications have mentioned the FBG pipe strain gages used to monitoring landslide deformation.

For the case reported herein, a type of PVC pipe strain gage with 80mm OD is applied to measure lateral inner displacement of a huge landslide as showed in figure 5. The FBG sensors distribute on one side of the PVC pipe which is subject to maximum tensile stress due to landslide deformation.

Figure 5. The Pipe Strain Gage Being Inserted to a Bore Hole

The FBG spacing can vary with the expected variation of the displacement along the depth of landslide. In the vicinity of the slip surfaces of landslide, the spacing may be as small as 0.5m, and in some other ordinary sections, the spacing may be of 5m.The ends of the PVC pipe segments are equipped with connectors so that multiple segments can be assembled into a single, continuous monitoring tube during field installation. With a 70mm inner diameter, the pipe strain gage is compatible with some common commercial mobile inclinometers. Or, an inclinometer can insert into the pipe strain gage to measure the angle of inclination along the pipe in order to verify the FBG's measurement.

BURIED CONCRETE BEAM WITH FBG SENSORS

It is impossible to measure the strain or deformation of soils through fixing the sensors to soils directly, as soil is a mass of granules and easy to leads to nonlinear large deformation. Thus, some constructions of concrete or other materials which can adhere well to soil may be used to detect the deformation of soils on the landslide indirectly.

In this way, A buried concrete beam with FBG sensors is built herein through the surface of the landslide. Figure 6 and figure 7 demonstrate the placement of the concrete beam in soil and its structure. A corrugated steel bar, which is mounted with FBG strain sensors at constant intervals, is laid continuously through the center of the section of the concrete beam. The axial direction of the beam is perpendicular to the landside moving orientation. As a result, any soil movement of local area can lead to the tension of the beam, and well then, the steel bar in the beam is likely to take the tensile strain. The conversion from the strains of the construction to lateral landslide surface deformation is significant and should be based on some simplifications that no slippery between soils and the beam occur during soil moving, the sections of the beam on which the strain readings approximate zero are seemed to be relative stable, and the distribution of the lateral displacement of active sections is assumed to be a triangle.

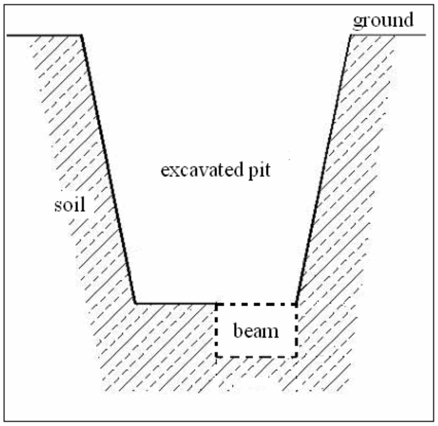

Figure 6. Buried Concrete Beam with FBG Sensors in Soil

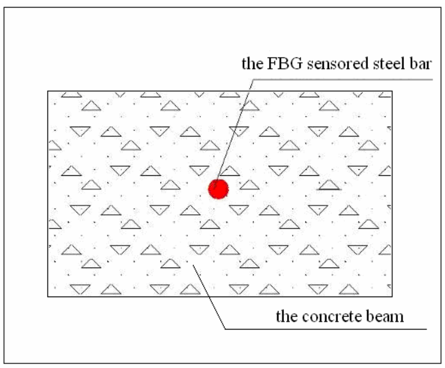

Figure 7. The Structure of the Buried Concrete Beam

APPLICATIONS OF THE PIPELINE AND LANDSLIDE MONITORING SYSTEM

Pipeline and Landslide

At the middle section of Lanchengyu pipeline which comprises 1250km, a huge landslide named Erlangmiao landslide in Sichuan province was found to be moving slowly in 2004, just two years after the pipeline began operation in 2002. This landslide laying on rocks contains approximate 30,000,000 m3 huge accumulations, with a length of 1200m, an average width of 800m, an average depth of 30m and an average slope of 25°.

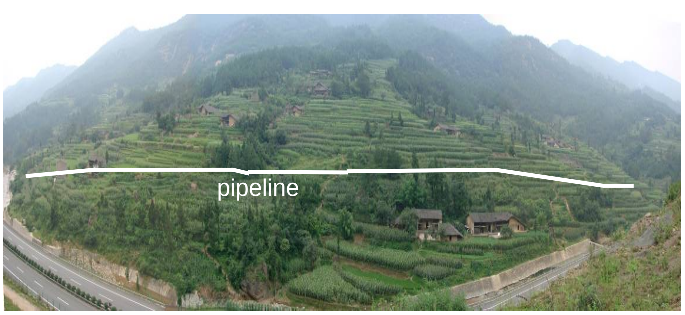

Figure 8. The Erlangmiao Landslide

Constructed of 508mm diameter, X60 steel pipe, the Lanchengyu pipeline crosses through the landslide perpendicularly to the movement direction of the landslide, at a depth of 1~1.5m,as showed in Figure 8.

Applications

In 2005, the pipeline owner carried out manually monitoring the landslide with a manual theodolite periodically. Nevertheless, these monitoring data cannot fulfill assessing the pipeline integrity or meeting an emergency timely, because this task is not able to give the added stress of the pipeline due to landslide moving, the landslide inner deformation, and the real-time information about stress and displacement in particularly. Although the GPS or TPS is capable of monitoring landslides automatically and without interruption, it is not wise to use this expensive equipment because to do so would expose it to high risk of being damaged or stolen by the third damage in the Chinese mountainous rural area. The system mentioned above based on FBG is well suited to automatic monitoring the landslide and the pipeline affected by it.

An experimental engineering was launched in August, 2007 and completed three months later. In this experiment, strains of six critical cross section of the pipeline were monitored, as well as the contact pressure between pipeline and soils in the same section. Four bores was drilled in order to accommodate the pipe strain gages with FBG sensors. The four pipe strain gages marked as 1#, 2#, 3# and 4# were 37m, 51m, 38m and 44m vertically long respectively. Two segments of buried concrete were constructed at north of the gully and south of the gully which divides the landslide into two parts,153m and 135m long respectively. The areas where two beams extended are of neighboring the pipeline and active areas in the landslide. Figure 9 describes the relative locations of four types of gages.

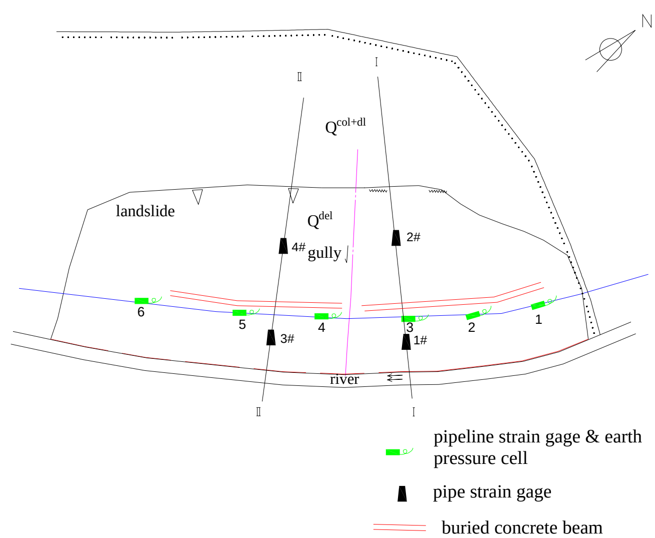

Figure 9. The Locations of Four Types of Gages

A resident's room on the landslide was rented as the automatic monitoring station where a computer controls the data collection executed by an FBG interrogator and sends the data to a transmitter which transmits the data to the terminal 2000km away through GPRS. At the terminal, a program was developed to analyze the monitoring data and warn if any analyzed parameter (such as added pipeline stress, hole tip lateral displacement, etc.) exceeded the given thresholds. Considering the cost, just parts of all sensors were selected to be automatically monitored.

Data Analysis

The changes of pipeline stress and contact pressure between 2007/11/18 and 2008/1/15 are shown in Figure 10 and Figure 11.The max added pipeline stress change is -0.8MPa, less than 1% the added stress threshold suggested in the reference [3] for X60 pipe. The max added contact pressure 1.3kPa, is very small compared to tens of kPa of the ultimate contact pressure for cohesive soil in the reference [6].

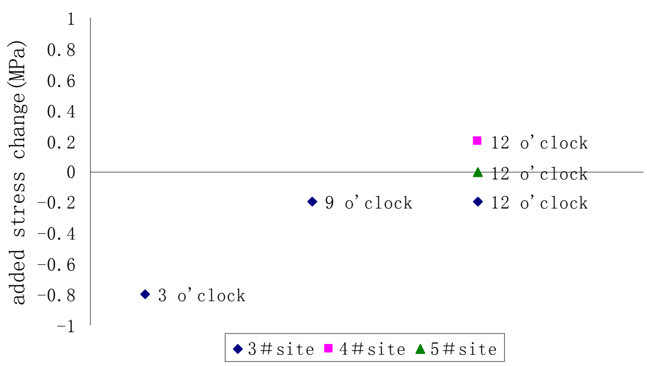

Figure 10. Added Axial Stress Change in Pipeline

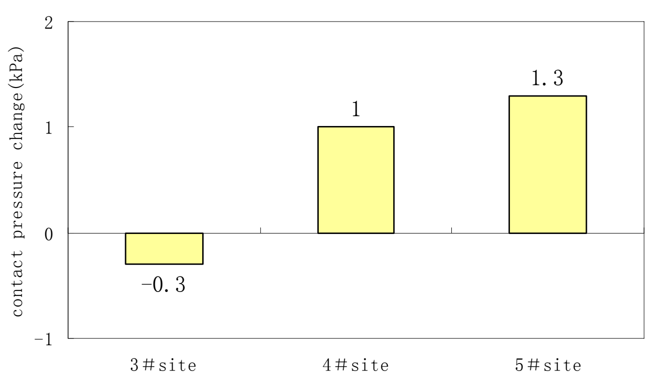

Figure 11. Change of Contact Pressure

Using the formula 1 and the linear interpolation method, two curves of lateral displacement with the depth of 1# bore hole and 3# bore hole are plotted in Figure 12. The lateral displacement of two bore hole tips are 1.04mm and 1.12mm respectively, and corresponding displacement rates are about 5.6mm/yr and 6mm/yr. Thus it can be concluded generally that the landslide is developing in the phase of creep.

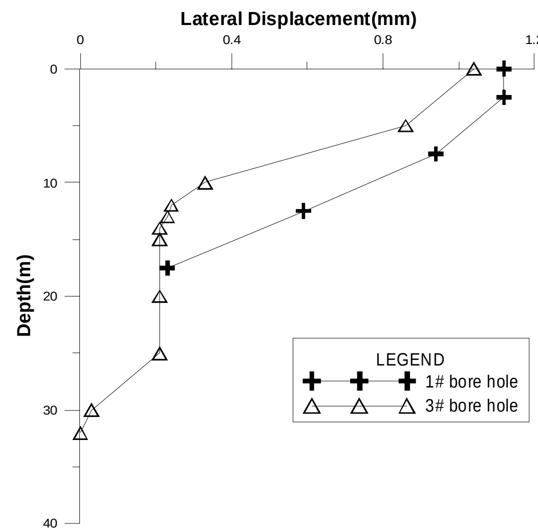

Figure 12. Inner Lateral Displacement of Landslide with Depth

The lateral displacement of surface soil given by two beams is showed in Figure 13 and Figure 14.The maximum lateral displacements in the northern beam and the southern beam are 28mm and 16mm respectively. These amounts data show that the surface soil of the landslide had collapsed locally, though the assumption of triangular distribution of local lateral displacement may make the maximum displacement bigger in the vertex of the triangular in some extent.

Considering the amount of added strain in the pipeline and the situation of the creeping landslide, the risk of the pipeline exposed to the landslide can be concluded to be acceptable at the present time.

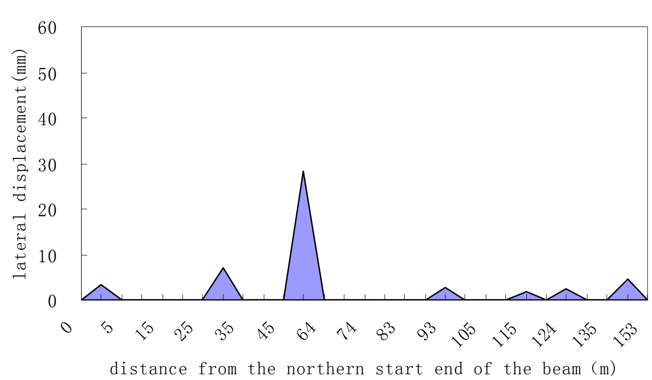

Figure 13. Lateral Displacement of Surface Soil in the Northern Beam

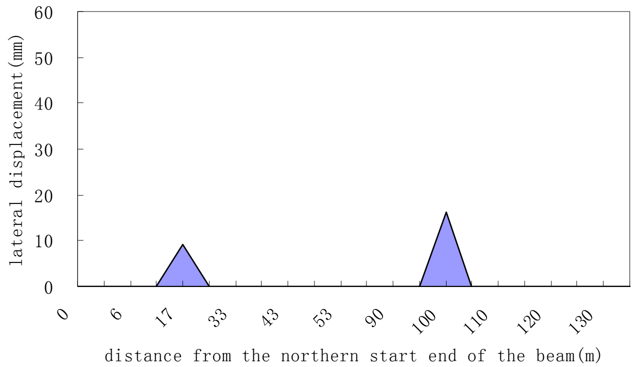

Figure 14. the Lateral Displacement of Surface Soil in the Southern Beam

CONCLUDING REMARKS

In this paper, four types of new gages are introduced, as well as their applications to a huge landslide and the associated pipeline affected by it. The four type gages can detect required deformation both of landslides and pipelines, so they can comprise a system regarding the landslide and pipeline monitoring. The field experiments have demonstrated that this new system can be practical and provide adequate results to assess the pipeline integrity. The advantages of optical fiber sensors and real-time monitoring make the system based on FBG much more desirable than the conventional methods.

ACKNOWLEDGEMENT

This study was supported by National Natural Science Foundation of China (NO.60534050).

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