# Fibre Optic Technologies: A Promising Potential for Geotechnical Applications

**B. Brimo**
B.E., Ph.D., MIEAust
ADFA, UNSW, Australia

**Summary** Constant monitoring of ground parameters during construction and under service conditions could enhance the safety of structures by providing the possibility of predicting any potential failure and giving the responsible authorities an early warning so that low cost maintenance measures can be taken on time. The developments achieved in fibre optic sensing technology have provided the necessary tool to implement powerful ground sensing systems. This paper presents an overview of fibre optic technologies, their evolution and the advantages of their use. The current research trend in applying these technologies in monitoring civil structures is summarised and the potential applications in geotechnics are examined. Several problems are still to be solved before an effective ground sensing system can be implemented.

## 1. INTRODUCTION

In recent years, there has been growing interest in applying fibre optic sensing technologies in different engineering fields, after their successful application in the military sector. This interest is best demonstrated by the US$5M OSMOS (acronym for Optical fibre Sensing system for MOnitoring of Structures) project, which was funded by the European Community for a three year period with the aim of demonstrating the industrial feasibility of manufacturing optical fibre smart structures for Civil Aeronautics and Civil Engineering.

The evolving of fibre optic sensing technologies in the eighties along with significant developments in signal processing and communication technology (table 1) has created new concepts in the design and construction and paved the way for building what are called "Smart Structures". Improvements in performance in each of the three areas were tremendous and can be approximated as being two orders of magnitude between the eighties and the nineties, while prices of their components have fallen sharply as shown in Figure 1.

Table 1 : Evolution of fibre optic sensing technologies [2]

| 1980 | 1990 | 2000 |
|---|---|---|
| 64-kB memories | 4-mB memories | 256-mB memories |
| 8-bit computers | 32-bit computers | 128-bit computers |
| entry of personal computer market | entry of neural networks parallel processing wide spread PC | widespread use of neural networks |
| laboratory fibre sensors | fibre sensors entering the market | fibre sensors dominate many sensors market |
| fibre communication links enter market | fibre communication links dominate land-based market | fibre communication links dominate worldwide fixed-site telecom market, provide fibre to home services |
| | limited fibre optic smart structure demonstrations | fibre optic smart structures begin to enter the market |

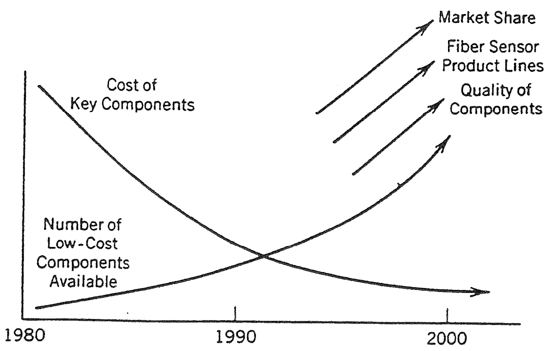



Figure 1. Relationship between Cost and the Number of Low-Cost Components Available.

Smart structures can simply be described as structures with enhanced safety features and reduced maintenance requirements. They are capable of:

- maintaining a constant vigilance over their structural integrity and indicate if damage is inflicted or fatigue problems developing
- evaluating the loads imposed on them and monitor their static and dynamic impact
- monitoring the environmental effects such as air and soil pollution and its impact on foundations and the superstructure.

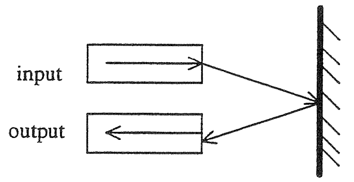
These functions could be attained using a *structurally integrated sensing system* which can monitor the state of the structure not only in the construction phase resulting in improved quality control but also throughout its working life providing very useful information to the owners, operators and designers of the structures.

Such sensing system could for instance monitor the following: strain, deformation or deflection, load distribution, pore water pressure, temperature or environmental degradation and give sufficient warning of its location and drive that low cost maintenance actions can be taken on time.

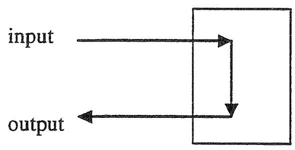
## 2. THE FIBRE OPTIC SENSING TECHNOLOGY

The first patents in fibre optic sensing date back to the mid sixties. However, serious research effort on what is now regarded as fibre sensing technology began about ten years later and has achieved tremendous advances since then.

Optical fibre sensors are a means whereby light guided within an optical fibre can be modified as a result of an external physical, chemical biological, biomedical or similar effect. Light from an optical source with constant relevant optical properties is launched into a fibre and guided to the point at which the measurement is to be taken. If the light is allowed to exit the fibre and be modulated in a separate zone before being launched into either the sensor or a different fibre, the sensor is then called an extrinsic sensor (fig. 2-a). If on the other hand, the light can continue within the fibre and be modulated in response to the measurand while still being guided, it is then called an intrinsic sensor. (fig. 2-b).




a) extrinsic




b) Intrinsic

Figure 2. Schematic Diagram of Intrinsic and Extrinsic Fibre Optic Sensors

The measurand can be virtually any physical or chemical influence and the range of optical fibre sensors is extremely diverse. Various properties of the optical signal can be modulated embracing state of polarisation, phase intensity, doppler shifts etc.

The *main advantages* of fibre optic sensors are due to the fact that the modulated signal can be transmitted to and from the sensing area without resource to electrical power. This results in several features as follows:

1. immunity to radio frequency interference (RFI) and electro-magnetic interference (EMI)
2. electrical isolation, removing problems with ground plane separation and electrical safety regulations
3. explosion-proof
4. highly accurate
5. small size and weight
6. allow access into normally inaccessible areas using alternative technologies such as the measurement of current and voltage in very high electro-magnetic interference environments
7. ability to interface with data communication systems
8. potentially resistant to ionising radiation.

## 3. THE APPLICATION OF FOT IN CIVIL ENGINEERING

Applying fibre optic sensing technologies in civil engineering is still in its infancy. The results of the laboratory tests carried out so far are very promising and some institutions have started carrying out tests on full scale structures.
The main areas of civil engineering investigated by *laboratory tests* were the use of fibre optic sensors to measure physical quantities in concrete such as temperature, detecting cracks by intensity transmission measurements and interferometric strain measurements. Other laboratory experiments have used bonded fibre optic strain gauges on concrete beams for measurements of strain due to flexural deformations. [9]

The development of a fibre optic sensor that is capable of measuring the amount of air entrained in fresh concrete was also reported. [5] This could indicate the resilience of concrete to freeze-thaw cycles. The idea of this sensor is to measure the index of refraction caused by air bubbles in the concrete. If the concrete does contain air bubbles, light will reflect back from the end of the fibre and can be evaluated.

The principle of fibre microbending has been used to measure the dynamic propagation of cracks in concrete beams under bending. The same principle has also been adapted to measure bonding between reinforcing bars and the concrete matrix. Debonding at the concrete-steel interface will affect the light transmitted into a fibre run through the predrilled reinforcing bar as the probe is loaded.[6]

Further tests were carried out to monitor overheating of power transmission lines using the ability of wrapping optical fibre into a metal rope, so that the strain along the length of the metal rope can be detected.[7]

There are currently few structurally integrated sensing systems implemented on *large-scale* structures. Some of them are :

* Fibre optic displacement gauges have been installed in two dams in Germany to measure horizontal and vertical shifting between segments with an accuracy of approximately 0.05mm [8]
* Fibre optic sensors were installed into the (five-storey) Stafford building at the University of Vermont (US) to measure the impact-response of elastic waves propagating through the different elements of the building, the strain level of the reinforcement bars within the concrete and thermal deformations caused by sun. Similar installations have been carried out at the Winooski One dam and a railway overpass bridge in Middlebury, Vermont.
* Fibre optic sensors were used in the core of polystar prestressing tendons of the Shiessbergstrasse triple-span road Bridge in Leverkusen (Germany) to check the integrity of the tendons or locate any damage.
* A set of sensors were embedded into the precast concrete deck support girders of a highway bridge in Calgary to monitor the strain relief experienced by the carbon fibre and steel prestressing tendons over an extended period of time.
* Different FOS installations were carried out to measure the weight of motor traffic vehicles in motion with the objective of making the following information available (after processing the data): vehicle classification, tyre pressure anomaly, vehicle damping anomaly, road temperature fluctuations measuring. [10] [11]

Examples of some important measurements that could be undertaken for large civil structures are as follows: [12]

- vibration frequencies of: support columns, floors, windows, bridge decks and cables....
- spatial vibration modes of: walls, floors, bridge decks and cables....
- thermal strain and deformations caused by sunlight to one side of the structure
- construction loads (excessive loadings, pressures, impacts... )
- wind monitoring and wind pressure on: bridges, buildings .....
- shear forces on bridge bearings
- internal strain distribution and hydropressure for dams
- onset of internal crack formation in concrete structures
- impact detection and localisation
- debonding of reinforcing bars and prestressing tendons in concrete structures
- corrosion degradation
- chemical sensors for : acid rain, smog, deicing salt solution
- real time vehicle weight and load distribution
- traffic flow patterns (number of vehicles, weight and velocity)
- ground creep or seismic movement.

## 4. THE APPLICATION OF FOT IN GEOTECHNICS

The geotechnical field offers a variety of opportunities for the application of fibre optic technology. A geotechnical monitoring system (GMS) could be part of a comprehensive system used in a structure (smart structure) where in addition to the measurements of soil parameters, data concerning loads, concrete, erosion, temperature etc. are measured, processed and evaluated.

The development of such a system could be achieved following the steps :

a) Determining the soil parameters that are considered to be critical in the structure.
b) Determining the limiting values of the critical parameters. If these values are exceeded, an unacceptable degree of damage to the structure could occur.
c) Designing the sensing system including type of sensors to be used, their locations, data storage capacity, evaluation software. (special map could be developed).
d) Setting out the sequence of installation steps.

The location of the sensing points "hot spots" (where measurements should be taken) depend on the characteristics of the individual structure under consideration (shape, load, materials, etc.). These spots should be identified in the design stage and a plan for a sensing network be developed along with the implementation procedure for the network.

A diagram illustrating the pattern of activity in a geotechnical monitoring system is shown in Figure 3.

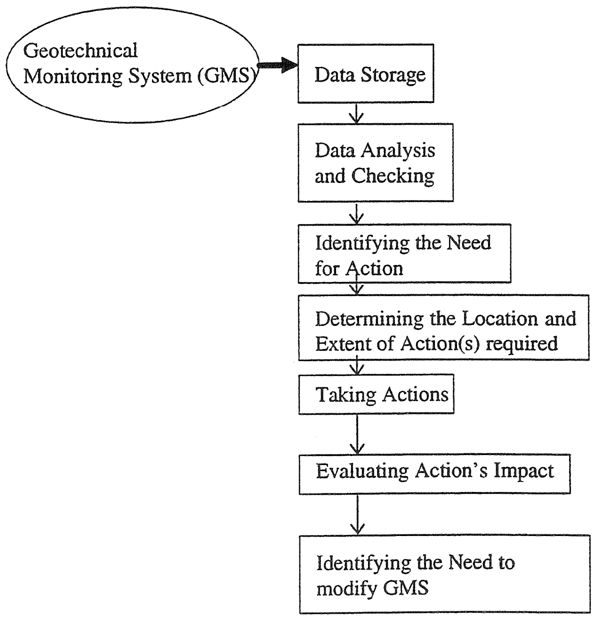



Figure 3. The pattern of activity in a Geotechnical Monitoring System (GMS)

So far, few sensors which can be used in such a system have been developed (or under development) and tested mainly in a lab environment.
One of the early laboratory studies was reported by the Centre for FO Sensing Systems & Smart Civil Engineering Structures at Florida Institute of Technology in the early 1990s. Microbend pore water pressure sensor has been developed and tested in the laboratory. It is capable of measuring water pressures up to 690 kPa and loads of 50 lb (222.4 N). Accuracy of sensor measurements are about 5% and are being improved upon.

The development of strain and deflection sensors for monitoring pipelines were reported and tested by G2 systems Corporations. [13] [14]
A distributed fibre optic system was successfully tested to monitor the strains/deflections in pipelines subjected to loads. The system could help in preventing environmental, health and economic disasters resulting in pipelines failures. Low profile strain sensors have been attached to a pipe at selected lengths for pipe bending tests. Deflection of the pipe, in the plane of the sensor translate the pipe tension to microbend-induced attenuation of the structurally coupled sensor, as measured by an optical time domain reflectometer (OTDR). Not only the longitudinal strain change can be monitored but also the transverse direction of the pipe movement by means of two or more circumferentially-positioned sensors mounted along the pipe. Deflections of as little as 0.127 mm corresponding to longitudinal strains as small as 0.001% could be resolved.

Further lab tests were conducted by G2 systems Corporation to evaluate pressure sensing and OTDR response for a continuous medium. This test involves monitoring freezing and thawing soils. A pressure sensor of 8-inch length was embedded in moist soil in a cell, which was then subjected to controlled freezing. As the soil cools, hardens and contracts, pressure is exerted on the sensor which responds by losing light as traced by the OTDR. Direct applications of this technique could be the monitoring of freezing and thawing effects on highway, roadway and airport runways.

In the environmental field, various sensors to measure mainly chemical substances in the soil were developed. The Centre for Fibre Optic Sensing System and Smart Civil Engineering Structures at Florida Institute of Technology has lately reported the development of a sensor to measure chloride concentration in the ground water. The chloride causes the colour of a chromate strip to be changed. This change is detected by the increase in the intensity of the light propagating through the fibre. This sensor can be applied in measuring salt concentration in leachate percolating through landfill liners, it can also be used to indicate the degree of steel corrosion in reinforced concrete structures. [15]

According to a lab experiment carried out by the University of Texas, it is also possible to determine the stress inside the concrete and subgrade of a rigid pavement when it is exposed to an external force by embedding single-mode optical fibres inside the pavement and measuring the birefringence caused by the stress on the fibre.

## 5. CONCERNING ISSUES IN APPLYING FIBRE OPTIC TECHNOLOGIES IN GEOTECHNICS

There still are some critical issues to be tackled should the development of a geotechnical monitoring system be successful. Some are related to the technology itself and some are related to the harsh environment and the complexity of the soil behaviour.

### 5.1 Soil Properties

Embedding optical fibres in the soil could have an influence on the soil properties particularly if casing or pipes are to be used. Although this effect seems to be minimal it could play an important role by forming channels for water seepage and consequently affecting the permeability of the soil under consideration.

### 5.2 Sensor and Fibre Properties

Depending on the soil properties and the type of chemicals it contains, careful consideration will have to be given to the type of fibres and sensors coating, if they are to be embedded within the soil and function correctly with no performance degradation for the design life of the structure. The coating could be an important factor in optimising the sensor's sensitivity and performance life by reducing the high stress concentration in the vicinity of the fibre (if no casing to be used) and also by eliminating the unwanted environmental effects.

### 5.3 Sensing Systems Properties

The sensing system has to be fairly robust and degrade gracefully when the structure suffers modest damage. In addition to appropriate coatings, a careful choice of location and orientation may help in reducing premature failure of the sensing system. The use of a cellular type of sensing architecture could minimise the degradation of sensing capability associated with any particular set of optical fibres.

### 5.4 Sensing System Architecture

Depending on the type of measurements to be undertaken, the fibre optic sensors could be localised or distributed, while the nature of the structure determines the number of layers required to perform the measurements.

Some other important factors to be considered are:

- optical fibre orientation and placement
- spatial resolution
- constraints imposed by the optical fibre finite bend radius
- the power budget
- signal to noise factors
- sensing system damage vulnerability
- ease of fabrication

### 5.5 Multiplexing Techniques

Multiplexing is the merging of data from several channels into one channel. The main multiplexing techniques use the following parameters: wavelength, time, frequency, phase and space. For large civil structures the time-division multiplexing is recommended because of its practicality and cost. [17]

### 5.6 Structural Interconnect/Interface

Using some form of multiplexing technique, the problem of each fibre optic sensor having its own input-output, which result in a bundle of single-mode optical fibres have to egress from the structure, is overcome. However, this requires the design of a structural interface, which must have minimum structural perturbation and be easy to build.

The development of a multi-sensor signal processing optoelectronic chip would provide solution to the interface/interconnect problem and make the realisation of sensing systems a cheap option.

## 6. CONCLUDING REMARKS

It is necessary for structurally integrated sensing systems to comprise geotechnical monitoring, should the health of a structure effectively and comprehensively be monitored.

To date, only two laboratory experiments are reported in the literature aiming at developing fibre optic sensors for soil applications. These are a pore water pressure sensor and a chemical sensor.

An understanding of the material and the micro-mechanical behaviour present at the interface region between the soil and the fibre as well as their connection to the measurand is still to further mature in order to achieve real advances in the development of reliable, accurate and durable sensors.

To expand the range of soil parameters monitored by fibre optic sensors, a comprehensive experimental research is still required mainly to tackle problems of embedding, long-term stability, durability, coating and micro-mechanics of load transfer.

In this regard, the collaboration and coordination between researchers in the fields of geotechnical engineering and fibre optics could play a major role in enhancing the research efforts and accelerating the evolution of production ready solutions.

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