Contribution on Geotechnical and Structural Instrumentation by Means of Fiber Optic Sensors

SHAHRYAR KHOSROKHAH

A Thesis

in

The Department

of

Building, Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements
For the Degree of Master of Applied Science in Civil Engineering at
Concordia University
Montreal, Quebec, Canada

October 2003

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisisitons et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 0-612-91058-X
Our file Notre référence
ISBN: 0-612-91058-X

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou aturement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this dissertation.

While these forms may be included in the document page count, their removal does not represent any loss of content from the dissertation.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de ce manuscrit.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

Abstract

Contribution on Geotechnical and Structural Instrumentation by Means of Fiber Optic Sensors

Shahryar Khosrokhah

Instrumentation is a tool to verify the stability, performance and functionality of natural and man-made structures in short, medium and long term. In this study, all efforts has been made to answer numerous questions which always arise in civil works in terms of instrumentation, such as why, where, and when do we use instruments; how can we benefit from instruments optimization in construction projects; what kind of problems may come out with selecting improper instruments; what type of instruments exist in the market and what sort of phenomena could be measured by instruments, etc.

The emphasis is on a new generation of instruments called “Fiber Optic sensors” which is an appreciable revolution in geotechnical and structural instrumentation industry.

The main objective of this study is to compare Fiber Optic sensors with conventional instruments and accordingly Tehran telecommunication/TV tower has been selected as a first existing instrumented tower by both: classical instruments and fiber optic sensors.

Dedication

I would like to thank my supervisors Dr. H.B. Poorooshasb and Dr. K. Saleh for their encouragement, guidance, patience, and support. Especial appreciation to Dr. P. Choquet for his wonderful assistance, without them the accomplishment of this study would not have been possible.

Thanks to my parents and family. This study is dedicated to my father for I honestly could not have made it without his support and I will always remember him as my best teacher I have ever had.

Thanks due to Dr. Knoll for his valuable advices. Also I would like to acknowledge Roctest Company staff for their collaboration.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATION

LIST OF TABLES

CHAPTER 1

Introduction

Instrumentation is used in every phase of a construction project by civil, geotechnical, structural and mining engineers as below:

1-During site investigation: instrumentation is used to assess the suitability of a site and highlight potential problems. Data obtained from the instrumentation is used to design the structure (earth slopes, excavations and foundations, etc.). Instruments can also be installed to determine the state of adjacent structures and to set base-line measurements for data obtained during construction.

2-During construction: instrumentation is used to verify design assumptions by comparing actual behavior with the numerical analysis used to design the structure, and it allows modifying the model if required. As construction progresses, instrumentation can provide engineers with data to substantiate design changes and value engineered solutions. Instrumentation is used to control construction activities and provide an early warning of potentially hazardous conditions. Data from Instrumentation can provide valuable legal protection where construction activities affect adjacent properties, and can provide early warning of errors in design or construction allowing timely remedial action.

3-After construction: instrumentation is used to monitor the long term performance to ensure that the conditions assumed when the structure was designed do not change, and to enable repairs to be carried out at the earliest signs of distress. Early warning systems provide alarms that can warn the public of potential hazards.

In other words, the instrumentation of large civil works (dams, heavy buildings, underground works, high cuts, high slopes, and landslide monitoring) has conventionally two basic purposes [23]: 1) Monitoring the safety, including verifying the design assumptions and 2) checking the behavior for improving future design.

Knowledge is familiarity gained by actual experience. In the engineering world, knowledge is based on information derived from theoretical concepts, experimental methods, measurements and visual observations.

Consequently, reliable and adequate information is a prerequisite to any successful engineering venture. The role of instrumentation is to get information which is otherwise unobtainable [15].

The end product of instrumentation is information, both qualitative and quantative. Thus field measurements have a potential for many scientific and economical returns provided, of course, that the appropriate parameters are measured and that this has been done with level of accuracy required for the subject being investigated.

As mentioned before, there are two general categories of measuring instruments which will be discussed in detail in the upcoming chapters.

The first category is used for in situ determination of soil or rock properties, for instance, strength, compressibility, and permeability, usually during the design phase of a project.

The second category is used for monitoring performance, usually during the construction or operation phase of a project, and may involve measurement of different physical parameters as pressure, stress, displacement, load or strain [17].

Providing proper measuring instruments in the design of large civil works is as vital as their monitoring during construction and operation. The French word for this kind of instrumentation is “auscultation” from the medical term meaning “listening to signals which produced within a body as a means of detecting evidence of disorders” And obviously, the patient does not necessarily have to be ill to be auscultated [23].

Criteria for selection of instruments

When it comes to select the instruments then the question will arise that what capabilities must the instruments have? The following criteria should be sought for selecting instruments as discussed more in detail in chapter 2.

- Accuracy
- Simplicity
- Self verification
- Durability(Robustness)
- Repeatability
- Longevity
- Resolution

Transducers principle

It is important to know that most Geotechnical and Structural instruments could consist of a transducer, a data acquisition system and a communication system between transducer and data acquisition [17]. Transducer or sensor converts a physical parameter such as pressure, displacement, inclination, stress, temperature, etc into a signal in order to get measured and interpreted. Due to the principles of transducers, they have been developed and categorized over the time in the following order:

- Mechanical
- Hydraulic
- Pneumatic
- Electrical
- Vibrating wire
- Fiber optic

It is always important to know the advantages and disadvantages of each type of the instrument for being capable to select one or the other in specific project. Hence, the characteristics of different type of transducers are discussed in the following chapters.

Mechanical instruments

Mechanical instruments are mainly simple to install and operate. Also they are inexpensive and usually have no delicate parts attached to structure. Also their calibration can be performed at any time if needed [19].

The problem with this kind of instruments is that their accuracies in some cases are limited and in all cases there is a need to access to the instruments, also one person has to be responsible all the time to take the measures. The other issue is their size.

Hydraulic instruments

Basically hydraulic instruments are reliable and inaccessible components have no moving parts. Also long successful performance record is an advantage for this kind of instruments.

The main primary issues that cause error in this type of instruments appear to be discontinuity in the liquid, liquid density changes caused by temperature variation, and surface tension effect. The size is also a disadvantage.

Pneumatic instruments

Pneumatic instruments have several advantages as: short time lag, minimum interference to construction, no freezing problems.

The issue in this type of instruments is that all pneumatic transducer are sensitive to diaphragm displacement which could affect the resulting reading. Another issue also is that errors may occur by any variation in the rate of gas flow so pneumatic transducers got to have no gas leaking in the inlet tube and at the diaphragm closure arrangement. It is not easy to achieve though, while quick-connect fittings are used between inlet tube and readout unit, indeed a little dirt or damage to the O-ring seal in the fitting may cause a leak [19].

Electrical instruments

Electrical sensors are easy to read and they show a good performance for short term monitoring. Some types are even suitable for dynamic measurements. In most cases readout can be automated.

The major problem with electrical instruments is lightning which can damage this type of instruments in three ways:

- power surges caused by a nearby strike
- induced transients caused by a nearby strike
- electromagnetic pulses induced by the magnetic field of a strike

Also in some cases errors owing to moisture have been seen. It should be noted that electrical instruments are not recommended for medium and long term monitoring.

Zero drift has been reported as a disadvantage for electrical instruments as well.

Vibrating wire instruments

The robustness, long term reliability and stability are considered as advantage for vibrating wire instruments [11]. Long term zero drift is controlled. Also vibrating wire is easily interfaced to automated data acquisition system and it is cheaper to design as well [28]. Also they are very tolerant of variations in the electrical characteristics of the cable. Study has shown that major sources of error in this type of instruments have been: wire corrosion; creep which occurs in vibrating wire when permanent tension is applied, slippage at the wire clamping points, and subsequently zero drift [17,19]. Also temperature changes would cause measurement errors. Further more, they are not suitable enough for dynamic measurement and also they can get damaged by lightning like electrical transducers.

It should be noted that because vibrating wire technology is mostly confined to geotechnical application so there is a limitation of suppliers [2].

Fiber optic instruments

Fiber optic sensors are a revolutionary development in geotechnical and structural instrumentation field. The fact that application of fiber optic sensors in geotechnical instrumentation is somehow new and experimental and accordingly expensive is unavoidable. But there is no doubt that in the near future, this type of instruments will be substituted of other instruments. Study showed, those of projects which has been instrumented by fiber optic sensors, are quiet satisfied with results [2].

CHAPTER 2

State of Art in Instrumentation

2.1 Introduction

The definition of instrumentation is not as easy as defining a regular technical word. On the contrary, it is very complicated and it is not possible to define it with dropping some lines and it needs to be interpreted in detail and it is unobtainable without many years of study and experience in this field both theoretically and practically.

Instrumentation is a tool to measure, so question will arise, what do we measure, or when do we measure. In fact, measurement exists wherever or whenever that a civil construction project either is going to be built or already has been built in order to determine the stability, performance and functionality of the structure in short, medium, long time.

It is important to remember that instrumentation is not a prescription that could be executed in any project. It would be studied case by case and it is the engineering duty to evaluate and select the proper instruments.

Furthermore, measurement is a comparison of unknown with known; of course, in geotechnical measurements this comparison is often remarkably indirect.

Using the certain instruments in a project does not guarantee approaching the correct and useful data and the following steps should be taken as a prerequisite in order to achieve the desirable result from applied instrumentation in any civil project.

2.2 The application of instrumentation in geotechnical and structural engineering

Here are the variety of instrumentation applications in geotechnical and structural engineering field: Dams (concrete, embankments, stone masonry) and power plant projects, tunnel and mining and excavation projects, buildings, bridges, towers, petroleum projects, nuclear projects, road projects, runways, and so on.

2.3 Steps for approaching the maximum benefit from instrumentation

As it has been discussed earlier, we can benefit from instrumentation in three phases of a construction project: before, during, and after construction. Therefore, to obtain maximum benefit from instrumentation at minimum cost, a general approach should include thorough formulation of rational instrument installation, proper outline of the project monitoring areas, selection of simple and reliable instruments must suitable to the site, and optimization of a number of instrumented monitoring points and measurement frequency [27].

2.3.1 Evaluate the project status

This step is a prerequisite of the instrumentation procedure. Project status should be determined, for instance, project type and layout, engineering properties of subsurface materials, groundwater conditions, adjacent structures status or other facilities, environmental conditions and planned construction method.

2.3.2 Prepare the geotechnical questions

First of all, a list of geotechnical questions must be prepared in order to estimate our inquiries by answering them. Every instrument installed on a project should be selected and placed to assist in answering a specific question [17].

Instruments should be supplied and used based on a need. If some instrument is used in a project that there is no need for it, then it is just a waste. In other words, preparing a list of geotechnical questions prior to select the instruments leads to optimize the instrumentation.

2.3.3 Clarify the purpose of instrumentation

In this step, should attempt to find out the reason that we are selecting particular instrument; for instance, usually the type of instruments which supposed to applied prior to construction are different from those which supposed to applied during or after construction.

Also there should always be installed a redundancy of instruments because of instrument failure attributed to malfunctioning equipment, deterioration of materials and improper installation procedure [14].

2.3.4 Verify the parameters to measure

Study shows that the most common parameters that can be measured or monitored are categorized as pressure and liquid level, displacement and movements, inclination and rotation, stresses and stress variations, loads and forces, strain, temperature [30].

Sometimes in some cases when there is parameter to be measured or monitor for a particular issue, this parameter could be considered as an effect of another issue then the cause of this effect got to be monitored and measured as well. For instance, in a slope stability issue, the main interest is displacement which can be considered as the effect, but the main cause is groundwater which should be measured and monitored as well. General speaking, determination of both cause and effect and the relation between them can be developed and it helps out to get rid of the effect by eliminating the cause. This subject will be discussed in chapter four in detail.

2.3.5 Foreseeing magnitude of changes

It is necessary to predict the magnitude changes in order to estimate the required instruments ranges and accuracy and sensitivity [17, 30].

2.3.6 Selection of instruments principle

As it was mentioned before, most instruments consist of: transducer, data acquisition system and communication linkage between the two. Next chapter will focus on the different type of transducers mechanism in detail and also about the data acquisition systems and eventually communications units between the transducers and data acquisition systems.

2.3.7 Instruments selection criteria

Instruments must be selected based on taking the following criteria into consideration. In fact these are prerequisites of selecting instruments as below [1, 17].

2.3.7.1 Accuracy

When a reading is obtained from the instruments, it doesn't guarantee that this reading is correct necessarily. There is no doubt that obtaining the accurate reading is our desire but mostly it is hard to achieve.

Usually accuracy is demonstrated as ± number: an accuracy of ± 1 mm means that the measured value has a possibility of being unrealistic within 1 mm, sometimes accuracy is showed as ± number %, for example an accuracy of ± 1% means that the measured value may be unrealistic within ± 1%.

It should be noted that sometimes accuracy is expressed as a percentage of full scale and that means the percentage applies to the full scale of the indicator instead of the measured value.

The question may arise, how to check the accuracy, the answer is either to measure the same quantity by two independent measuring systems or to have instruments which can be checked at intervals and recalibrated if applicable[17].

2.3.7.2 Simplicity

One of the most important characteristic that should be sought in selecting instruments is simplicity in terms of installation, performance, reading and interpretation and calibration.

2.3.7.3 Self Verification

It is considered as an advantage that reading can be verified in place (sometimes to check the zero drift) [21]. This term is not directly applicable to embedded parts of such instruments as open stand pipe or twin tube hydraulic piezometer.

2.3.7.4 Durability

All components of instruments must have adequate robustness and longevity in order to be able to survive against physical or chemical attacks as corrosion, electrolytic breakdown, impact, temperature variation, pressure changes, sun light, moisture, and so on [21].

2.3.7.5 Repeatability

Generally repeatability is demonstrated as ± number. For instance, ± 1.00 stands for a higher repeatability than ± 1.0.

The difference between accuracy and precision is illustrated in figure 2.1; the ball eyes represent the true value. In the first case the measurements are repeatable but not accurate. These errors are systematic. In the second case the measurements are not repeatable but if adequate readings are taken, the average would be accurate. These are random errors. In the third case the measurement are both repeatable and accurate [7].

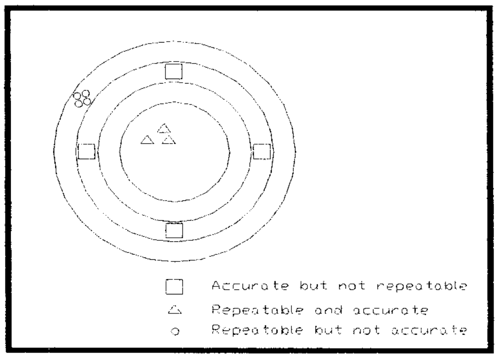


Figure 2.1 Accuracy & Repeatability

2.3.7.6 Resolution

Resolution is the smallest division on the instrument readout scale. The resolution for a digital display is one digit of change in the last digit [10].

2.3.8 Identifying instrument location

After selecting the instruments, it is time to specifying each instrument location individually. In some cases, there is limitation for choosing the location and if it is the case then appropriate instruments should be selected based on the site conditions.

Although the final exact location will be assigned in the site, and for this reason emphasis should be more on structurally weak zones, most heavily, or zones where highest pore water pressure is applied. If there is no such a zone, then priority would be typical cross section at or near the maximum structural vertical section and afterwards they are less critical sections that behave similarly to mentioned zones in order to have a comparison just in case of incorrect selected zones[30].

It is essential to note that instruments utilized in the less critical zones should be as simple as possible and also should be installed at the more critical zones in order to compare the readings later to assure that instruments are working properly.

2.3.9 Procurement, installation and data collection

The next step is purchasing instruments based on verified specifications from a reliable manufacturer who does fulfill our requirements. The worst case in procurement instruments procedure is purchasing through the bid because obviously better quality causes more expenses and the high quality instruments are not able to compete with low quality ones in terms of price so it depends on the costumer to find out what level of quality is being required.

After purchasing instruments, it is time to do installation by skilled technicians, engineers or experts if necessary due to the drawings which should be already prepared and data collection must be collected frequently as much as possible and then interpretation of obtained data by assigned engineers. Furthermore, calibration should be performed according to the manufacturer recommendation [17].

CHAPTER 3

Instruments structure

As it was mentioned in section 2.2.2., all instruments consist three major parts. In this chapter the construction of each one of them and their different types will be discussed.

3.1 Transducer

Transducers is a device that converts a physical change into a corresponding output signal and there are different types of transducer which has developed one after another as following:

3.1.1 Mechanical transducers

There are two type of mechanical transducer which is most common for measuring the displacement: dial indicator and micrometer [17].

Dial Indicator:

This unit converts the linear movement of a spring-loaded plunger to a large and visible movement of a pointer that turns around above a dial. This unit consists of a rack and pinion and gear train. Accuracies are either ± 0.001 in. (± 0.025 mm) or ± 0.0001 in. (± 0.0025 mm) with the range up to 2 in. (50 mm).

Micrometer:

Rotation of a delicately threaded plunger causes the plunger to go in or out of housing. Longitudinal moment of the plunger is measured, using a scale on the housing, to indicate the number of revolution of the plunger. Fractional of revolutions are determined using graduations marked around plunger and a vernier on the housing. Accuracies are limited to about ± 0.001 in. (±0.025mm).

3.1.2 Hydraulic transducers

There are two type hydraulic apparatus in the geotechnical instrumentation for measuring liquid pressure: bourdon tube pressure gage and Manometer [17].

Bourdon tube pressure gage:

A bourdon tube is made by flattening a metal tube and coiling it into a c-shaped configuration. When the tube is pressurized internally, the flattened cross section expands and causing the tube to straighten. The uncoiling motion is transmitted through a mechanical linkage to a pointer (Figure 3.1).

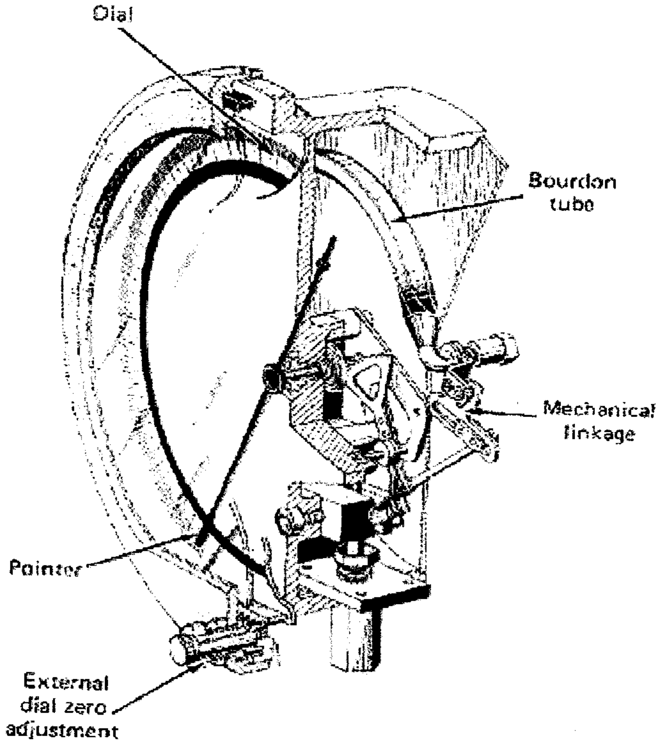


Figure 3.1 Bourdon tube pressure gage

Manometer:

Manometer is formed by a liquid-filled u-tube. A pressure on one side of the u-tube is balanced by an equal pressure on the other side (Figure 3.2).

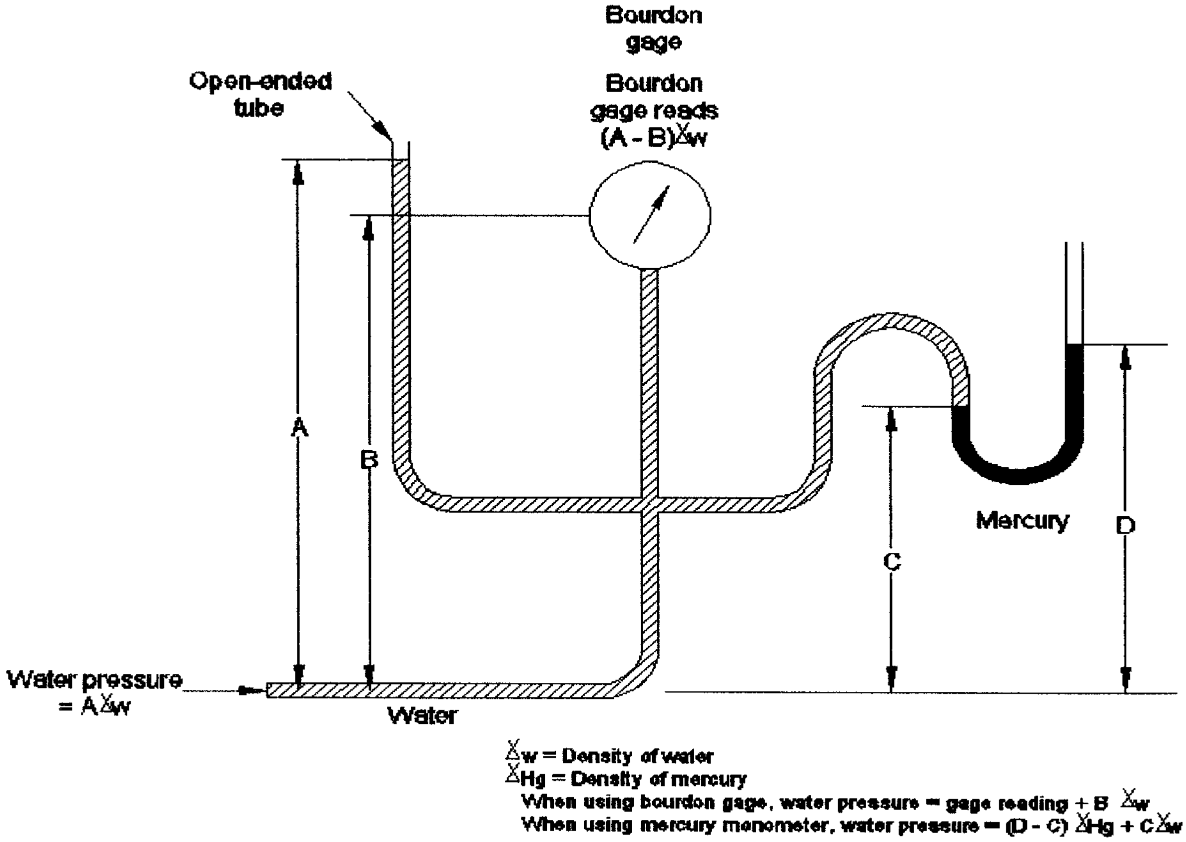


Figure 3.2 Manometer

3.1.3 Pneumatic transducers

There are two kind of pneumatic transducer called: Normally closed in terms of circuit and normally open. The most popular apparatus is the first type shown in Figure 3.3, which a measurement is taken under a condition of no gas flow. The pressure P is the pressure of concern. An increasing gas pressure is applied to the inlet tube and while the gas pressure is less than P, it may merely build up in the inlet tube. When the gas pressure goes over P, the diaphragm turns aside; allowing gas to circulate behind the diaphragm into the outlet tube, and flow is recognized using a gas flow detector. The gas supply is shut off at the inlet valve, and any pressure in the tubes greater than P bleeds away, such that the diaphragm returns to its original position when the pressure in the inlet tube equals P. This pressure is read on a bourdon or electrical pressure gage [30].

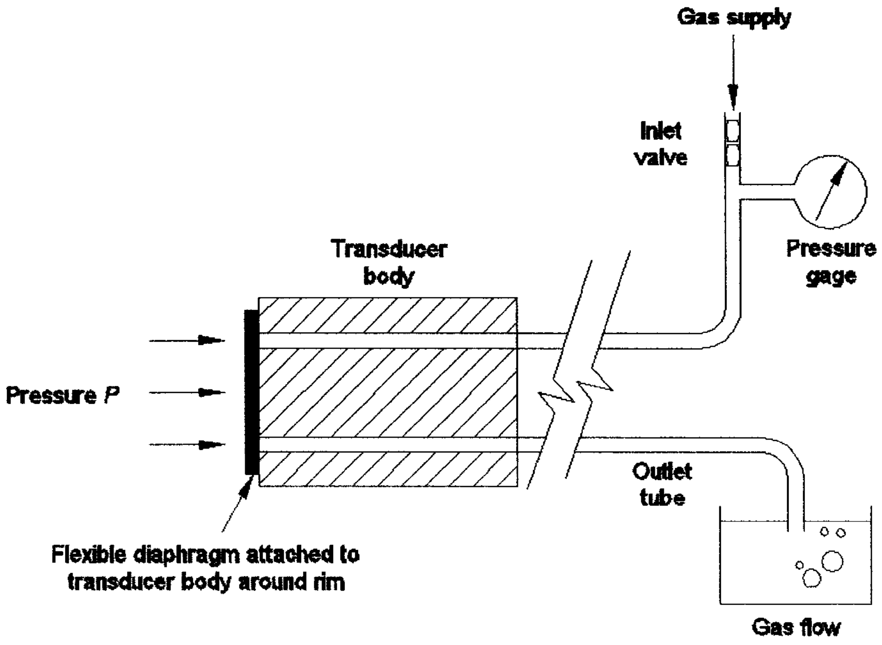


Figure3.3 Normally closed transducer (under a condition of no gas)

3.1.4 Electrical Instruments

Electrical resistance strain gages:

This kind strain gages have been used in many measurement units and it is made of a conductor which resistance changes in accordance to change in length. The following correlation between the parameters is given [30]:

$\Delta R/R = \Delta L/L \times GF$

Where:

ΔR is Resistance change

ΔL is length change

GF is given by gage factor

Electrical resistance strain gages are subdivided to five different types as bonded wire, unbounded wire, bonded foil, semiconductor and weldable [30].

Bonded wire strain gage is made of a fine copper-nickel or nickel-chromium wire rounded around back and forth, and bounded to a thin elastic mounting of paper or plastic, which in turn is bounded to the member being measured shown in figure 3.4.

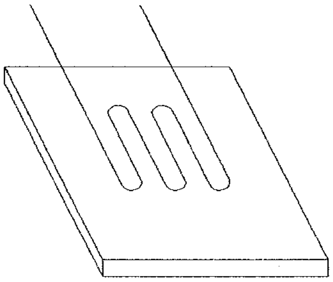


Figure 3.4 Bonded wire resistance strain gage

Unbounded wire strain gage is made of a wire which is rounded around two sets of electrically insulated posts which are attached to a member being measured (Figure 3.5).

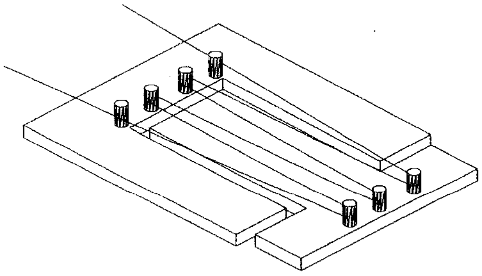


Figure 3.5 Unbonded strain gage

Bonded foil strain gage is made of a thin foil resistance alloy bonded to a thin plastic film, which in turn is bonded to the member being measured (Figure3.6).

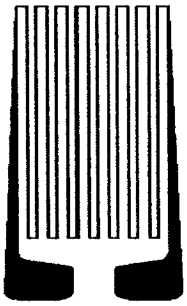
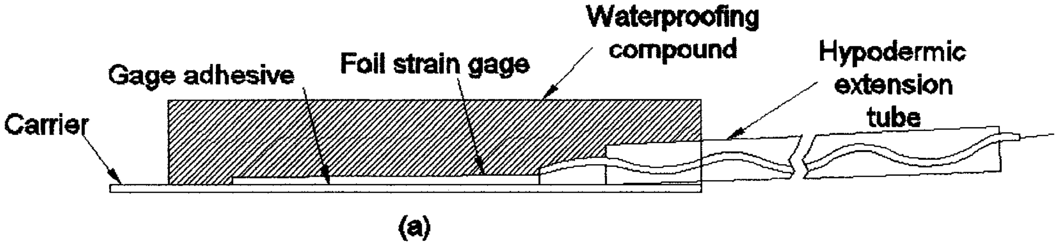


Figure 3.6 Bonded foil strain gage

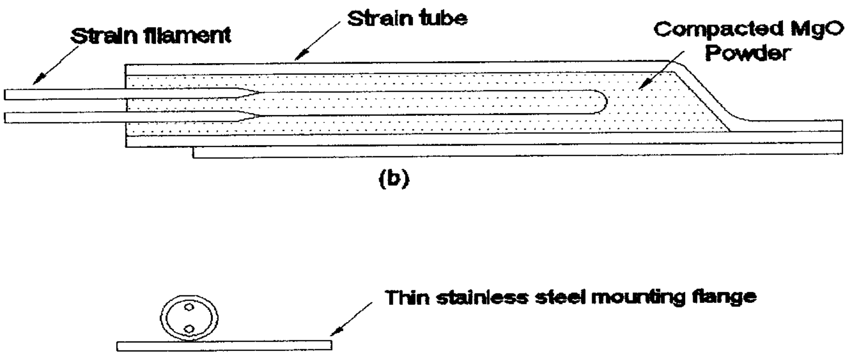
Semiconductor gage is made of highly doped semiconductor crystals of silicon or germanium and while the strain is applied to the crystal, it undergoes a change in resistance proportional to the strain.

Weldable strain gage is made of a permanent resistance element which is attached to a thin stainless steel mounting flange. The resistance element could be either a bonded foil gage, (Figure 3.7) or a strain filament encased in a small tube (Figure 3.8).



(a) Figure 3.7 bonded foil transducer

Output from electrical resistance strain gage will be measured using a Wheatstone bridge circuit, (Figure 3.9) which the circuit composed of four resistances R1, R2, R3, and R4. A voltage is applied between A and B and the resistance R4 is altered until no current flows between C and D, at this point the needle of the galvanometer is not deflected and the bridge is balanced under the condition of R1×R4 = R2×R3.



(b) Figure3.8strain filament encased in small tube

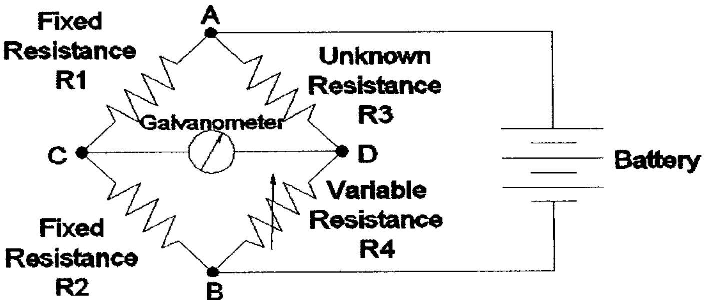


Figure 3.9 Wheatstone bridge circuit

Electrical transducers for measuring linear displacement:

a) Linear variable differential transformer (LVDT) is made of a movable magnetic core passing through one primary and two secondary coils (Figure 3.10) [30]. An AC voltage is applied to the primary coil, thereby inducing an AC voltage in each secondary coil, with a magnitude that depends on the proximity of the magnetic core to each secondary coil.

b) Direct current differential transformer(DCDT) which is similar to LVDT , except that unwanted cable effects associated with LVDTs are avoided by using DC voltages, requiring miniaturizing the electrical circuitry and placing additional components within the transducer housing [30].

c)Linear Potentiometer is made of a movable wiper which makes electrical contact along a fixed resistance strip, as shown in figure 3.11. A regulated DC voltage is applied to the two ends of the resistance strip and the voltage or resistance between B and C is measured as the output signal. The voltage between A and C varies as the wiper moves from point A to point B [30].

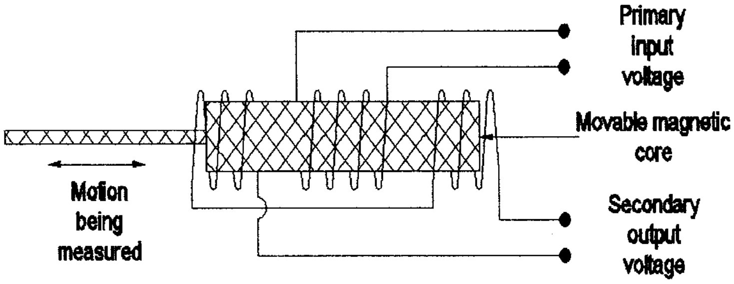


Figure 3.10 LVDT

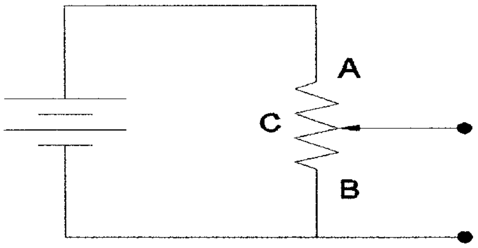


Figure 3.11 Linear Potentiometer

3.1.5 Vibrating wire transducers

Vibrating wire sensor is a compact low profile and appears to be demonstrating good long term stability [11]. Vibrating wire technique has been known for more than one hundred years, however measuring strains using the vibrating wire was developed in 1930 in France by Telemac Company and in Germany by Maihak [24].

The vibrating wire gages measures strain by verifying the change in frequency of a tensioned piano wire clamped between two end blocks to a surface of member being measured (Figure 3.12) [17].

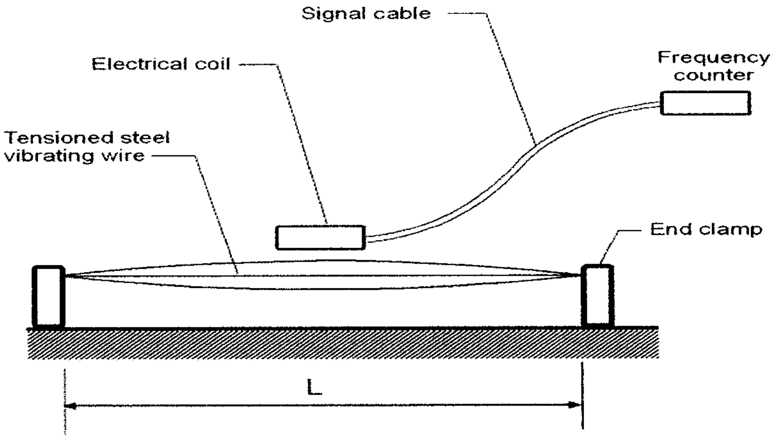


Figure 3.12 Vibrating wire strain gage

The equation in below represents the relationship between vibration frequency and tensioned wire.

$$f = (1/2L)\sqrt{\sigma g/\rho}$$

Where:

f = natural frequency (sec^{-1})
L = length of vibration wire (in.)
σ = stress in the wire ($lb/in.^2$)
g = acceleration due to gravity ($in./sec^2$)
ρ =density of the wire material ($lb/in.^3$)

The vibrating wire gage can be utilized as a sensing element in a variety of pressure cells, load cells, temperature gages, and deflectometers.

As Pressure transducer, the wire is attached to a sensitive diaphragm. Any pressure change causes a deflection of diaphragm which consequently changes the tension wire.

Vibrating wire pressure transducers are utilized in total pressure cells, load cells, piezometeres and settlement sensors [24].

As displacement transducers, it consists of a vibrating wire connected in series with spring(s) and a sliding shaft, movement of the shaft changes the tension in the spring and the vibration wire. As a force transducer, the different weight changes wire tension [24].

Vibrating wire sensors reading methods:

There are two methods for reading the vibrating wire: pluck and read, autoresonant

Pluck and read method

This is a simple method and has been used traditionally. An electromagnetic coil is placed at middle very close to the wire.

This technique only needs two wires connected to a single coil, an electrical pulse is introduced into the coil varying the magnetic field and it makes the wire to vibrate at its resonant frequency then during this time after the initial pluck, the same coil transmits the received signal via the same wire to the readout unit [24].

Auto resonant method

In this method two coils are utilized instead of one. One coil is to drive the wire at its resonant frequency and another one is to sense the wire vibration and feeds the amplified resonant frequency back to the driver coil in a phase looked loop [24].

Advantages and disadvantages

As discussed briefly earlier, vibrating wire instruments like the other type of instruments are not faultless and ideal and have disadvantages which are reported by users, for instance the most common issues are Corrosion, creep, slippage , zero drift, error caused by temperature changes, lightening.

However, best effort had been made by some manufacturer to minimize the issues that occur in practice, for example, a protection against lightning (Figure3.13).

In the recent years experience has shown that vibrating wire instruments have been performed frequently in most projects and they had satisfactory performance but again they are not ideal in compare with fiber optic instruments.

As advantages, the most considerable points are: long term stability [9], unaffected by moisture (from manufacturer prospective), frequency not affected by long cables, having rugged construction [24].

3.1.6 Fiber optic transducers

Fiber optic instruments are a new generation of instruments which are completely immune to all interferences (lightning, radio waves, high voltages, etc.) [2, 13]. They are extremely stable and their long term performance is expected to be as good as vibrating wire instruments, if not better. One of their foremost advantages is that they can be read in static or in dynamic mode, in case of earthquake, for example.

Also its lighter weight and small dimension should add up to advantages of fiber optic sensors [18].

Structure of fiber optic sensors and its advantages in detail will be discussed in chapter 5.

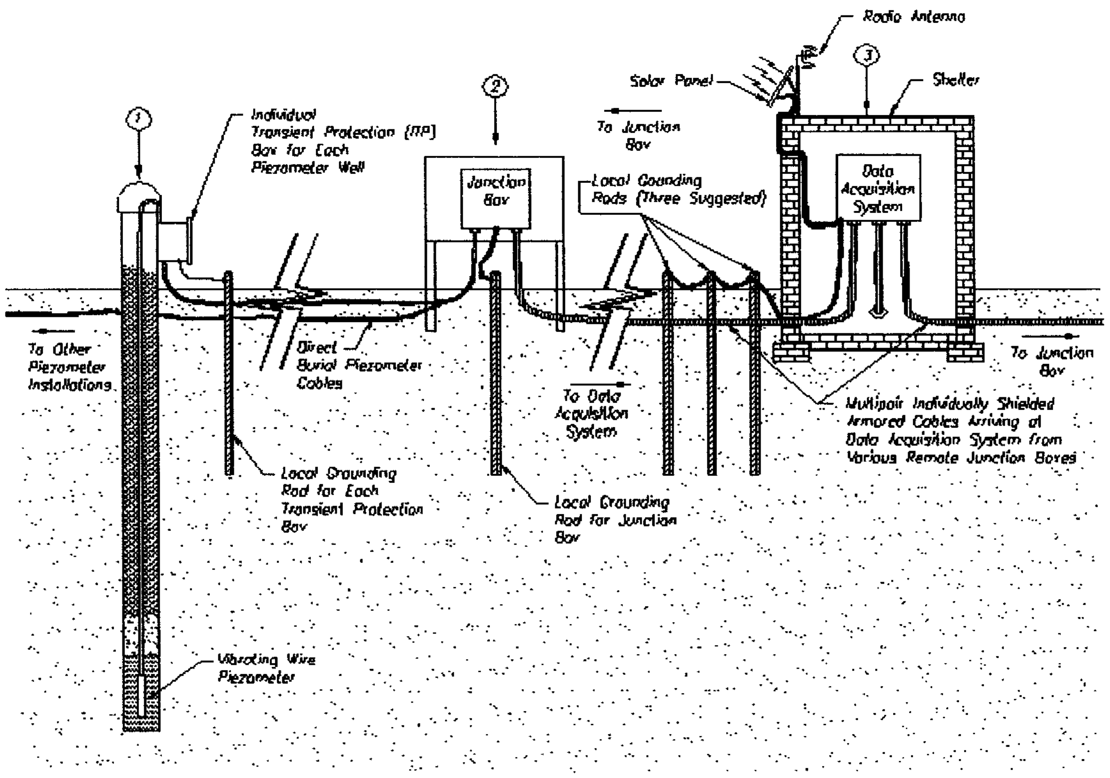


Figure 3.13 Lightning protection

3.2 Automatic data acquisition systems (ADAS)

Automatic data acquisition systems play a major role in entire instrumentation procedures and selecting proper data acquisition systems is as critical as selecting proper instruments. Without having an appropriate data acquisition system, instrumentation would be nonsense. Also data acquisition equipment and methods vary from one project to another [16].

Automatic data acquisition systems are designed to collect data obtained from instruments through a communication system which could be Telephone/Modem, cellular, microwave, satellite, cable or radio. In fact, methodology of collecting data from transducers has been replaced since few years ago and automatic data acquisition systems substituted the traditional manually recording method and obviously this substitution had advantages and limitations more and less as bellow.

New technology of collecting data enables:

1- To collect data more frequently.

2- To reduce man power for reading instruments and related costs.

3- To transmit data over a long distance especially when there is no access to instrument for whatever reason.

4- Increasing data accuracy.

5- Fast tracking data collection.

This technology has some limitation as lightning affects by variable voltage potential, possibility of accepting data without being aware of correctness, needing a reliable and continuous power supply.

3.2.1 Configuration

Configurations of automated systems can be categorized in one of the three types in below.

Datalogger:

This electronic component collects data from connected instruments upon the operator request. The system can be modems for remote communication; usually it is required that the intelligence and operation be external to the system though [30].

SCADA (Supervisory Control and Data Acquisition):

It is a host computer that controls remote monitoring units (RMUs) which are intelligent data loggers. RMUs obtain data and report them upon request from the host computer.

The remote unite can handle the data acquisition and store the information as long as it has a communication with the host computer. The host computer is an intelligent system which is programmable for frequency and scheduling of data acquisition [30].

Distributed intelligence:

All the linked Computers to a central computer (CNM) are placed at each remote monitoring unit in the network and communication can be taking place with central computer also with each other. The remote unites are responsible for the frequency and scheduling data acquisition and also for initiating communications [30].

3.2.2 Communications

Communication in instrumentation procedure can take place at three different places such as transducer to data logger, remote data logger to central computer, and central computer to remote office (Figure 3.14). Usually the communication between transducers and data logger are electrical transmission through cables or sound (acoustics) transmission through the air.

Mostly the communication between remote unites and host or central computer is by electrical cabling or radio transmission and communication from project site to the district office is normally by telephone, microwave, radio, or satellite [30].

Power resources for supplying energy for automatic data acquisition systems could be provided by current, battery, wind and water powered generator, diesel and gasoline generators or solar panels. It should be noted that the size of power supply and the site condition leads us to select one of the mentioned options [2].

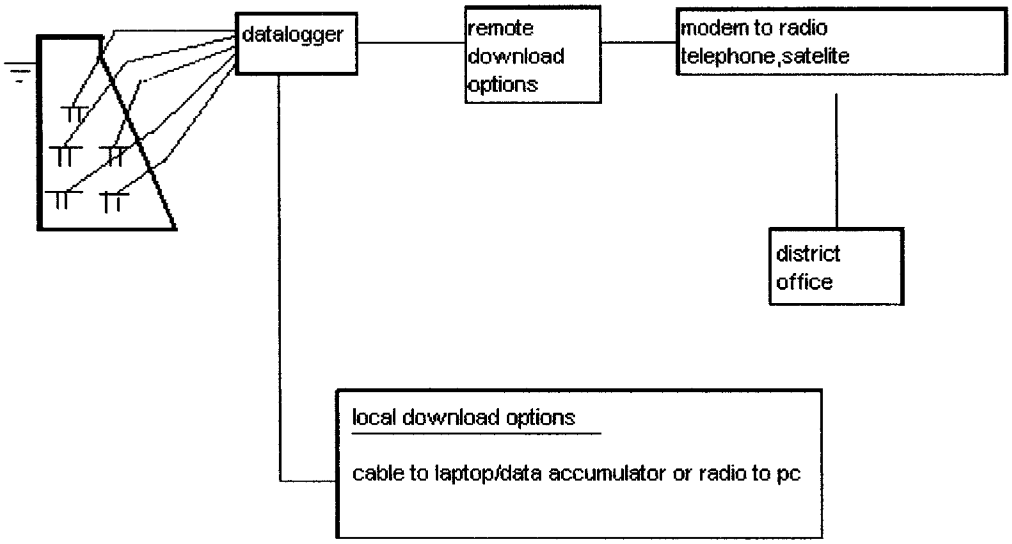


Figure 3.14 Datalogger configuration

CHAPTER 4

Parameters to be measured

Introduction

Typically measuring the parameters by instruments are categorized in the seven main sectors as:

1- Pressure and liquid level
2- Displacement and movements
3- Inclination and rotation
4- Stresses and stress variations
5- Load and forces
6- Strain
7- Temperature

For measuring each of the mentioned phenomenon there are certain instruments to be used which will be discussed individually.

Some of the Instruments which are used in geotechnical and structural instrumentation frequently are brought under each phenomenon in below.

4.1 Pressure and liquid level

4.1.1 Piezometer

Piezometer is used to measure pore water pressure [29]. The most common type of piezometer is the Vibrating Wire Piezometer which contains a vibrating wire sensor in a cylindrical steel protection (Figure 4.1). They can utilized either embedded in earth fills at concrete interface or in unconsolidated fine grain materials such as sand, silt, clay , or in direct burial applications or as a pressure transducer. In general they can be used in a variety of application as foundations, dams, embankments, hydraulic structures, tunnels, excavations, waste repository sites and so on and so forth.

A proper piezometer maintenance plan is a key to benefit the maximum performance which involves checking against siltation by measuring the pipe depth annually and performing the piezometer response test every five years; cleaning silted piezometers when necessary; restoring the damaged piezometer; checking the pipe top elevation every three to five years; replacing the deficient piezometer if it is impossible to restore due to a bent or blocked pipe, silted or carbonated filters, etc [27].

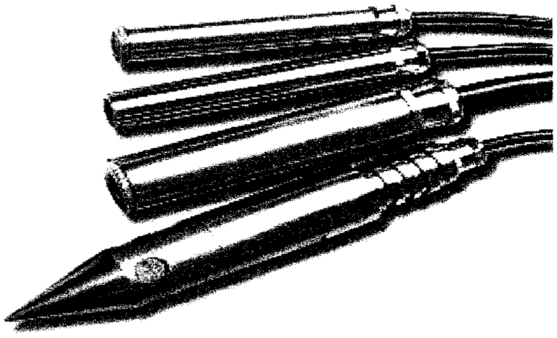


Figure 4.1 Vibrating wire piezometer

4.2 Displacement and movement

4.2.1 Borehole Extensometer

There are several types of extensometer for different applications as following [2, 17, and 29].

4.2.1.1 Retrievable borehole extensometer

It contains 4 major parts (Figure 4.2): the mechanical anchor, the measurement module, the extension tubing and the centralizer. Several measurement modules would be installed in series in some borehole, each of them is mounted on the length of extension tubing required to span a lower and upper mechanical anchor. Displacement measurement will be made in the hole, in sections distributed along the borehole length.

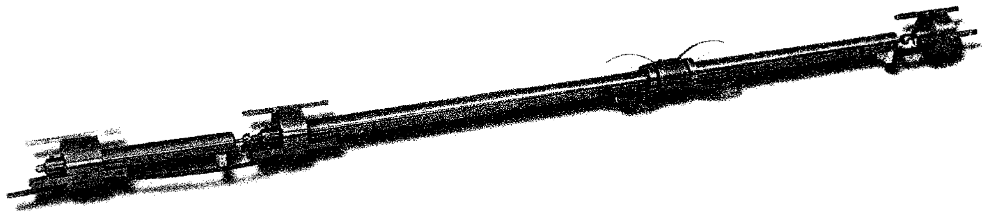


Figure 4.2 Retrievable borehole extensometer

4.2.1.2 Incremental Extensometer

This type of extensometer is designed as a mobile extensometer probe to perform high accuracy displacement measurement (Figure 4.3) in any direction including vertically upwards in rock and soils. It would be placed inside of the borehole so that two inductive sensors face two reference rings, the sensors reading is verifying the exact position of the reference rings and subsequently reaching measured distance between two reference rings. It could be applied in surrounding deformation during underground excavation, settlement caused by near surface tunneling, settlement of all types of foundation, inclination.

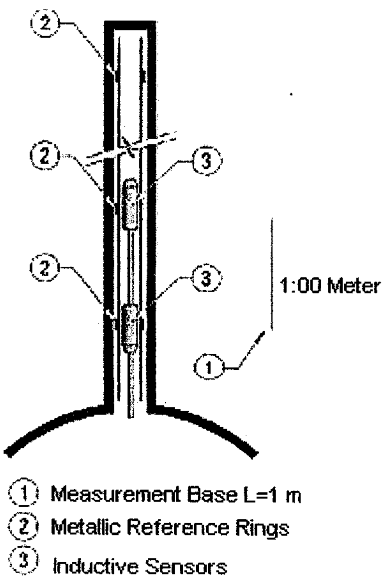


Figure 4.3 Incremental extensometer

4.2.1.3 Rod extensometer

Rod extensometer measures the deformation of rock surrounding underground openings and it offers a simple operation and low cost and it consists of two expandable rock bolt anchors which can be quickly set by means of a socket wrench into drilled boreholes in the rock. A rod connected to the deepest anchor projects into a hole drilled through the shallow anchor. The tip of this rod is sensed by means of a depth micrometer and its position relative to the outer face of the shallow anchor is precisely measured. Any movement of the rock between the anchors is detected and measured in this way.

4.2.2 Surface Extensometer

4.2.2.1 Vibrating Wire Jointmeters

Vibrating wire jointmeter is used usually in a wide variety of applications as fault movements in rock, separation of shotcrete from the rock face of tunnel walls, lifts in a dam, strata deformation in boreholes, construction joint at contact with the foundation rock, crack separation in concrete or stone structures. As shown in Figure 4.4, it could be surface jointmeter or embedment jointmeter [2].

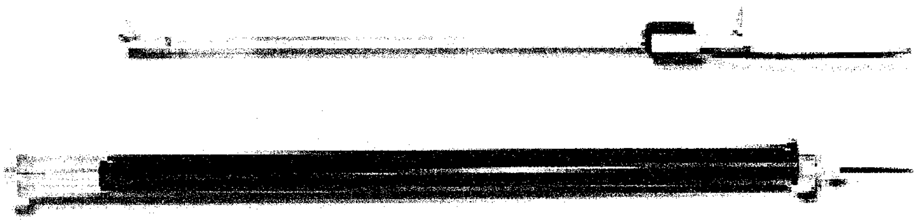


Figure 4.4 Vibrating wire jointmeter

4.3 Inclination and Rotation

4.3.1 Inclinometer

This type of instrument are suitable to monitor the depth , magnitude and rare of lateral deformation and movement in soil or rock masses and furthermore the application in structure include: embankment and dam stability, deflection of bridge piers and abutments, natural and cut slope stability, delineating landslide zones, heave or settlement and subsidence control. It composed of the inclinometer sensor, the inclinometer probe, the cable, and the read out unit. By inserting the inclinometer probe into the preinstalled casing, the inclination automatically would be obtained (Figure 4.5) [29].

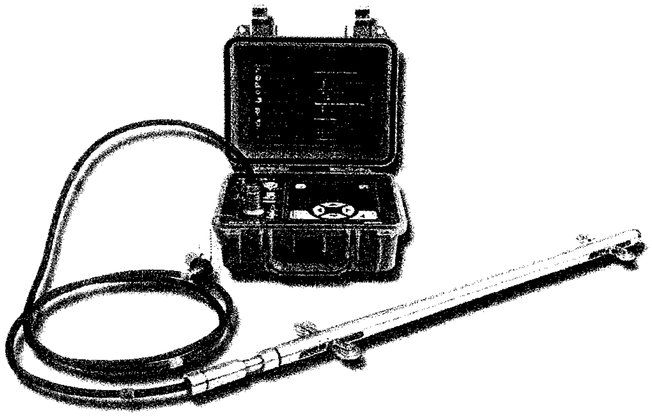
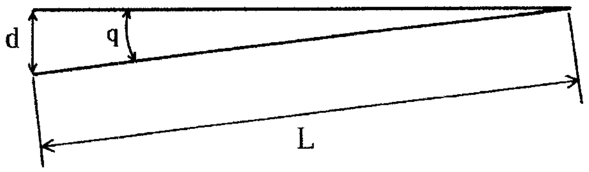


Figure 4.5 Inclinometer

4.3.2 Tilt Beam Sensor

Tilt beam sensor is designed to detect rotation between two fixed points (Figure 4.7). Tilt sensor is mounted on a rigid beam usually in three meter length, fixed at each end to the structure under measurement so the tilt changes could be converted to displacement since the measure rotation takes place over the defined length (Figure 4.6).



Displacement (d) = L sin q

Figure 4.6 Tilt converted to displacement

For measuring of the length more than the length of instrument, beam sensors can be connected end to end in order to determine cumulative displacement along a horizontal or vertical profile.

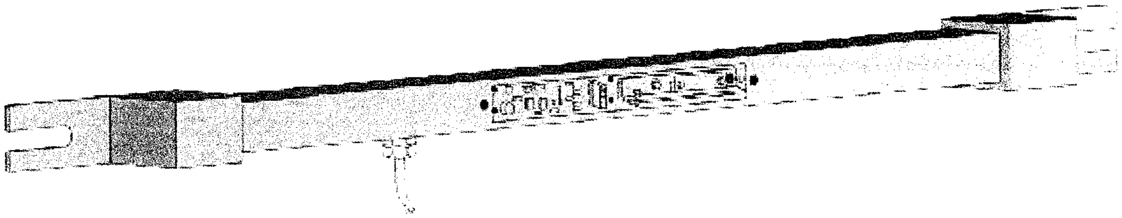


Figure 4.7 Tilt beam sensor

some of it's applications are as monitoring the movement of tunnel walls; monitoring the rotation of dams, retaining walls, piles and pipelines; monitoring the effect of excavation and tunneling on existing structures; monitoring the performance of bridges and structures under load [2].

4.4 Stresses and Stress Variation

4.4.1 Total pressure cells

The total pressure cells are capable to measure total pressure in fills and embankments as well as contact pressure on retaining walls, piers, culverts, bored piles and tunnel linings and stress in concrete.

Total pressure cells come in two different shapes, either circular or rectangular and also in different stiffness. All cells contain a sealed distribution pad composed of two plates welded together around the periphery and filled with de-aired oil. The pad is linked to a pressure transducer through a steel tube. The changes in load applying to the pad affect the oil pressure which would be measured by transducer (Figure 4.8) [17].

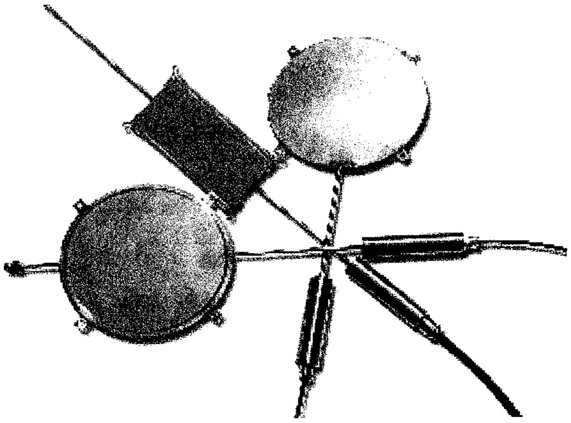


Figure 4.8 Total pressure cells

4.4.2 Instrumented Cylinder of Sherbrooke University (CIUS)

The CIUS is a simple, reliable and robust technique which can meet the requirement of the principle for monitoring the variations of stresses and deformation over a long period of time inside the host mass in civil and mining structures. It is a cylindrical concrete inclusion instrumented with vibrating wires. The CIUS can be connected to a dummy cylinder whose role is to detect all forms of environmental phenomena. The dummy cylinder is equipped with a vibrating wire extensometer and is placed in a hallow cylinder at both ends (Figure 4.9) [3, 4, 5 and 8].

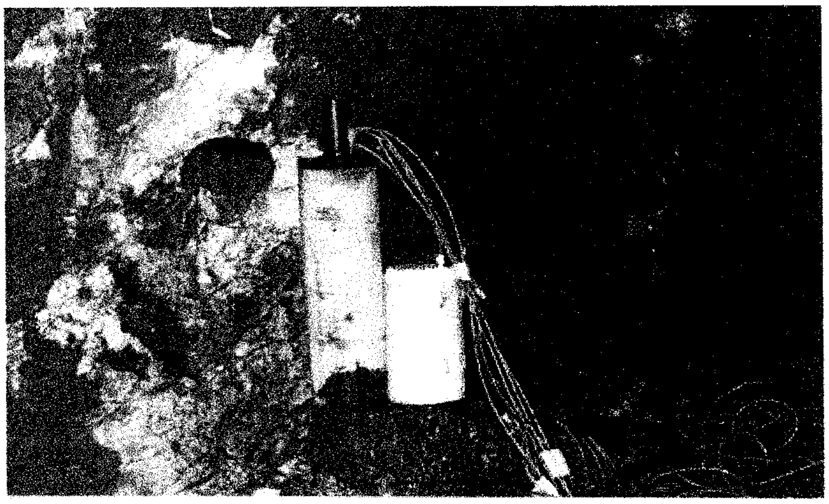


Figure 4.9 CIUS and Dummy Cylinder

In order to measure the variation of stress and of the three-dimensional deformation, it is necessary to have six extensometers in six independent direction (Figure 4.10). These extensometers transform their relative deformation in frequency and also provide the temperature of the medium.

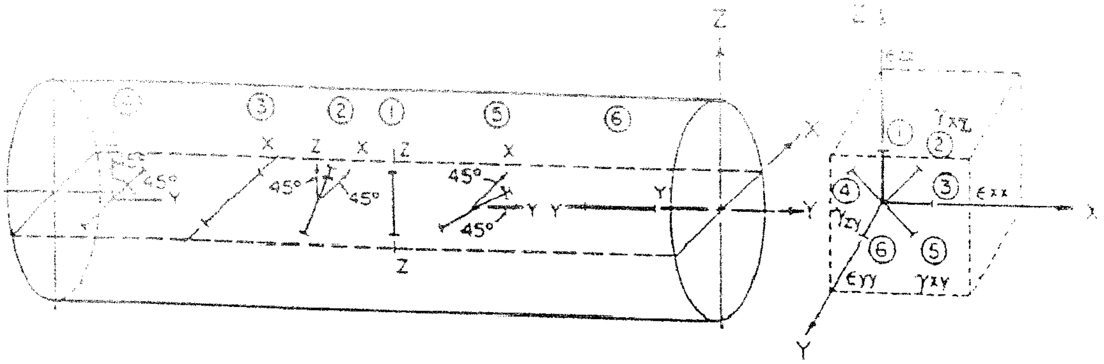


Figure 4.10 Instrumented cylinder

4.5 Load and Force

4.5.1 Vibrating wire load cell

The vibrating wire load cell are designed rugged and waterproof in order to measure loads in foundation anchors, tiebacks, struts or tunnel supports, rock bolts. Also they are designed to fulfill the adverse and severe environmental conditions usually associated with construction or mining demands.

They are designed in two models, one to monitor a tensile load and another one to monitor compressive load. For the tensile load, load cell has a hallow center cell which allows the passage of anchor through the cell and for the compressive load, the load cell is supplied with internal solid center platens mounted on the end faces of the load sensing element (Figure 4.11).

The load sensing element is a cylinder of high strength heat treated steel that survives rough handling and loading. The local compressive strains induced in the cell by the tension in the anchor are measured by one to six vibrating wire sensors. The average of the strain readings from the sensors represents the mean load on the anchor

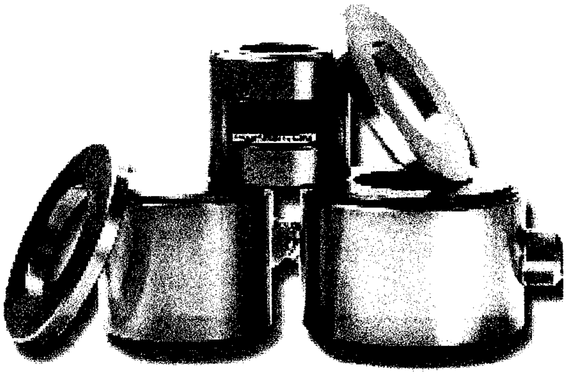


Figure 4.11 Anchor load cell

4.5.2 Tension Measuring Gage

Tension measuring gage contains a Teflon-sheathed resistance wire extending between two hard rubber end anchors and it is available in different length to suit all strand diameters which are more common like 12.7 mm and 15.2 mm.

It has a wide variety of application both in civil engineering and mines construction. In civil engineering it is utilized to measure load and strain in rock and soil anchors (stressing and bond zones) as well as measuring the load and strain in pre-stressed and post-tensioned concrete also to measure load and strain in cable bolts used for rock support. In Mines it would be applicable to load and strain measurement in cable bolts (underground and open pit mines) as well as construction of low cost, shear resistance extensometer also monitoring of special cable bolt applications (Figure4.12).

Figure 4.12 Tension measuring gage

4.5.3 Vibrating Wire Stress Meter (SM)

These are 1 meter long instrumented rebars which are welded to the existing rebar reinforcement pattern in the reinforced concrete in order to measure the compressive or tensile strain of the rebar (Figure 4.13) [29].

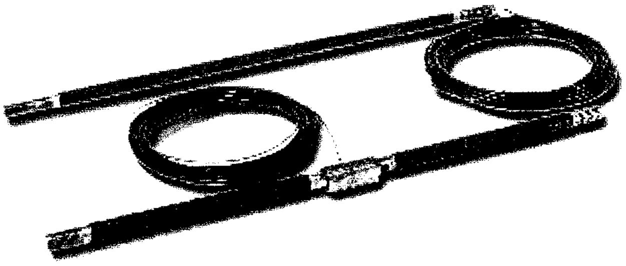


Figure 4.13 Vibrating Wire Stress Meter

4.6 Strain

4.6.1 Embedded Strain Gages

This type of strain gages are individually designed to measure strains caused by stress variations in concrete structure. The stress can also be determined while the concrete's modulus of elasticity is known, following compensation for temperature, creeping and concrete reaction effects. The mentioned strain gages can be embedded in a variety of structures such as tunnels, dams, bridges, nuclear power plants, tall buildings, harbors, foundations, walls, footings, piles.

The structure of embedded strain gage contains two end pieces joined by a tube that protects a length of steel wire and the wire is sealed in the tube by a set of o-rings on each end piece. Both end pieces have a flat circular flange to enable shift of concrete deformation to the wire. An electromagnet is fitting at the center of the gage which read the modified tension and its resonant frequency caused by strain developing in the concrete (Figure 4.14) [17].

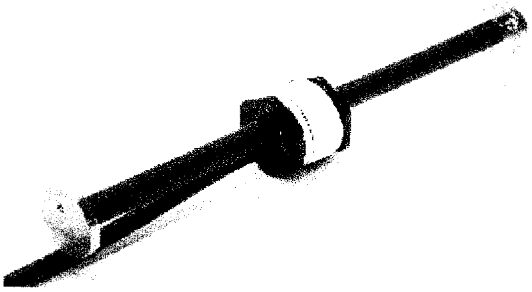


Figure 4.14 Embedded strain gage

4.6.2 Surface Mount Strain Gages

This type of strain gages consist of two end pieces joined by a tube that protects the length of steel wire. An electromagnet is located in a protective housing placed at the center of the tube. When the exterior forces applied on the strain gage modify the tension in the wire and consequently the wire's resonant frequency read by the electro magnet. Surface mount strain gage are designed to monitor variation in strain which enables stress evaluation when the material's modulus of elasticity is known and the gage is applicable in: Concrete structures such as retaining walls, bridges, hydraulic structures; metal structures such as piles, pipelines, pressure vessels; underground and underwater supports, linings, footings and piers (Figure 4.15) [17, 29].

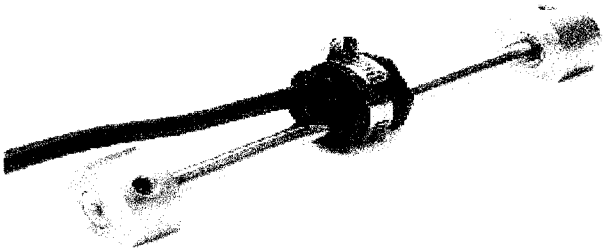


Figure 4.15 Surface mounted strain gage

4.7 Temperature

4.7.1 Temperature Sensors

These sensors are designed to measure and monitor the reliable temperature in rock, concrete, soil, grout or ground fill.

The vibrating wire transducers are more suitable and more welcomed compare to other types like thermistors or thermocouples but evidently more expensive (Figure 4.16) [2].

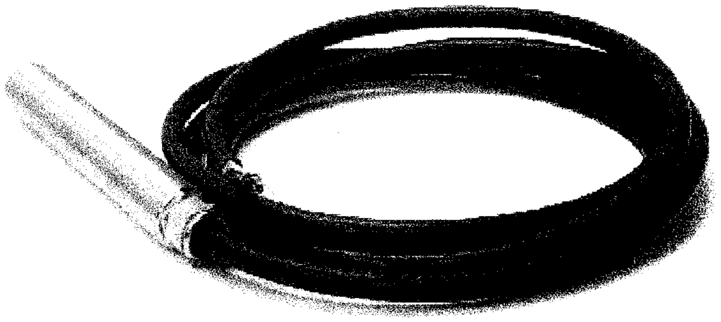


Figure 4.16 Temperature sensor

CHAPTER 5

Fiber Optic Transducers

5.1 History of fiber optic technology

In 1870, the British Royal Society in London (England) witnessed a thought-provoking demonstration given by natural philosopher, John Tyndall. He used a jet of water that flowed from one container to another and a beam of light to demonstrate that light used internal reflection to follow specific path. As water poured through the spout of the first container, Tyndall directed a beam of sunlight at the path of the water. The light as seen by the audience followed a zigzag path inside the curved path of the water. This was the first research on the transmission of light.

Fiber optic technology experienced more seriously in the second half of the twentieth century. In 1950 fiber scope has been developed. This image transmitting unit which used the first practical all-glass fiber was at the same time developed by Brian O'Brien at the American Optical Company and at the Imperial College of Science and Technology in London. Few decades after in 1980 optical fiber used in telecommunication as real application and later on in 1990 optical fiber used in instrumentation and computer networks and still it is considered as very new development in the field of geotechnical and structural engineering and it is obvious that this new technology will be replaced all other sensors in the instrumentation field [18].

5.2 Fiber optic sensors advantages

Fiber optic sensors depend on the ability of the fibers to carry light from a source to a photosensitive detector. Fiber optic sensors can be used to sense the relative position between an object and the end of a fiber or the distance between two points along a fiber; they can also indicate bending. They are unaffected by temperature or humidity extremes and are immune to electrical noise [2].

And the most valuable advantage is that they are safe against lightning strike (even directly) and need no protection [13]. The fiber optic instruments are more expensive compare to other type of instrument and in short time it could be as a disadvantage for fiber optic sensors but unfortunately they don’t take the lightning protection expenses of other of instruments into account while comparing fiber optic instruments with others in terms of price. Also this kind of instruments could be utilized in a Long length (over 1 km). The structure of fiber optic cable is illustrated in figure 5.1.

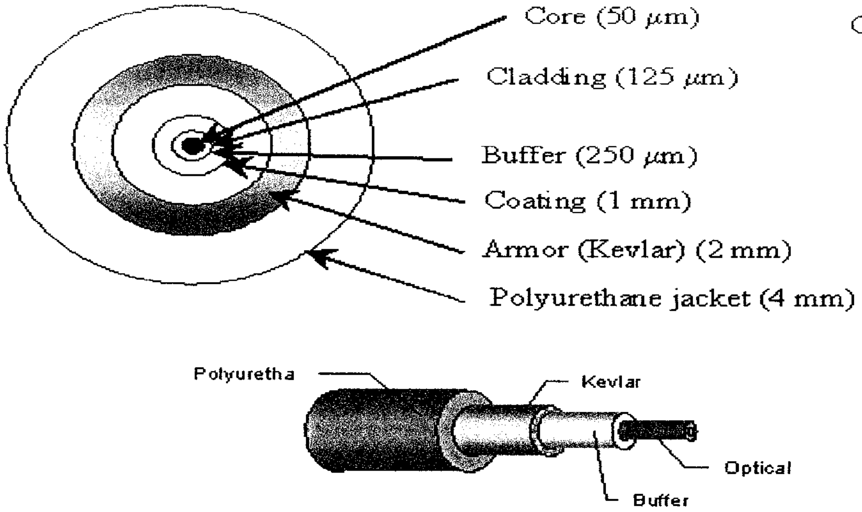


Figure 5.1.Optical Fiber Structure

5.3 Type of Fiber optic sensors

Fiber optic sensors are divided in two main categories, distributed and localized. Distributed fiber optic sensors have a interesting performance which enable them to used less sensors and take advantage of more effective use of optical fibers so that each element of fiber optic are used for both measurement and data transmission purposes. The biggest issue of distributed fiber optic sensor is that they don’t fulfill the need for high resolution, flexible sensing architecture and refined degradation [25].

Localized fiber optic sensors verify the measurement over a certain section of the optical fiber and have this in common to conventional strain or temperature gages. Localized fiber optic sensors are subdivided to Fabry-Perot and Bragg grating.

5.3.1 Bragg grating sensors

This fiber optic sensor relies on the narrow band reflection from a region of periodic variation in the core index of refraction of a single mode optical fiber. In this sensor the center (Bragg) wavelength of the reflected signal is linearly dependent upon the product of the scale length of the periodic index variation and the mean core index of refraction. Hence, changes in strain or temperature to which the optical fiber is subjected, will consequently shift this Bragg wavelength leading to a spectrally encoded optical measurement.

In the field of sensing, Bragg grating can be utilized as strain gage. When the fiber optic is bonded to a surface under strain or deformation, the periodic spacing “d_o” between gratings changes to modified value “d_1” and the resulting strain“ ε” can be calculated by the equation in below [2].

$\Delta\lambda/\lambda_o = (\lambda_1 - \lambda_o)/\lambda_o = GF.\ \varepsilon + \beta.\ \Delta T$, $\varepsilon = \Delta\, d/\ell_o = (d_1 - d_o)/\ell_o$

Where:

β= thermo- optic response of grating, usually in the range of 6.0 micro-strain/ °C

GF= gage factor, usually in the range of 0.75

ΔT=temperature change, in °C

5.3.2 Fabry-Perot sensors

Fabry-Perot sensors are kind of sensors that take advantage of the reflection of light on two nearby semi-reflective surfaces where these reflective surfaces can be included into the optical fiber or can be placed at one end of the fiber as illustrated in figure 5.2 [2, 10 and 12].

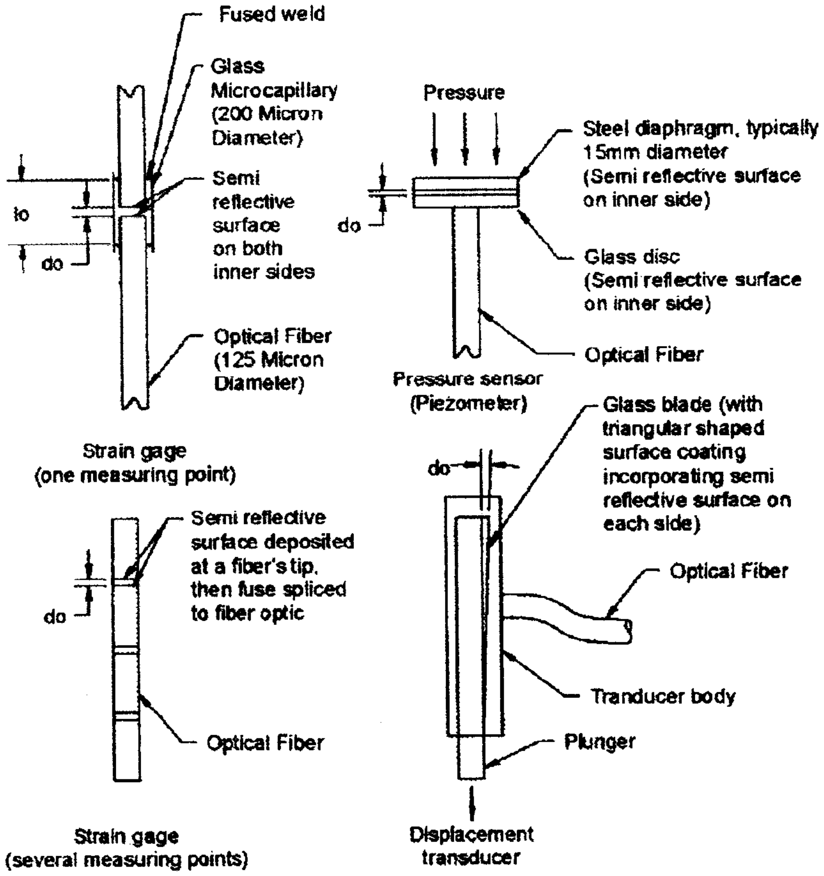


Figure 5.2 Working principles of some Fabry-Perot fiber optic sensors

The gap d_o between two adjacent reflective surfaces represents a Fabry-Perot cavity. The strain can be calculated by the following equation [2]:

$$\varepsilon = \Delta d/\ell_o = (d_1 - d_o)/\ell_o$$

Where: ℓ_o is the initial distance between the two-fused weld points on the microcapillary, which is used to set the initial distance d_o increases to a value d_1 between the two semi-reflective surfaces.

Also it is very important to make the unit cost of this sensing technology as low as possible for its implementation to be economically sound; one sensor should be capable of measuring of different parameters as much as possible in order to be used in a wide range of applications. Some of these parameters to be measured could be: strain, acceleration, vibration frequency, spatial vibrating mode, pressure, temperature and displacement (Figure 5.3) [25].

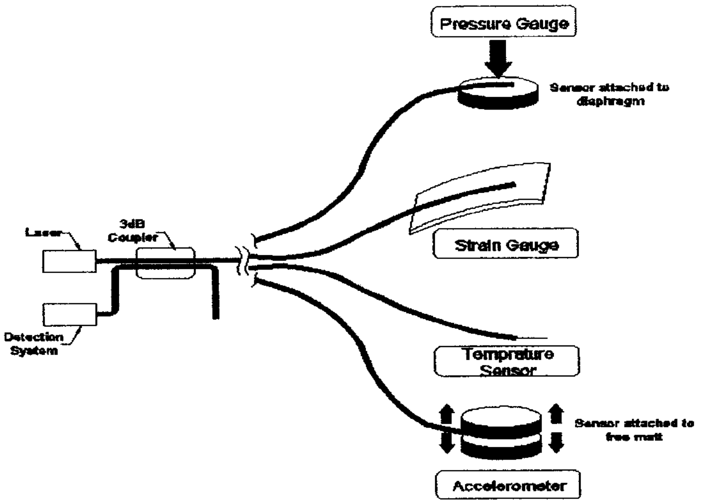


Figure 5.3 Schematic illustration of how a fiber optic sensor can be used as a: pressure gage, strain sensor, temperature sensor, and an accelerometer

5.4 Reading principle of Fabry-Perot fiber optic sensors

Several reading methods have been developed for Fabry-Perot sensors. One of the most accurate and repeatable methods makes use of white-light and Fizeau interferometer (Figure 5.4. and 5.5 and 5.6) (Guidelines for Instrumentation by ASCE) [2, 6].

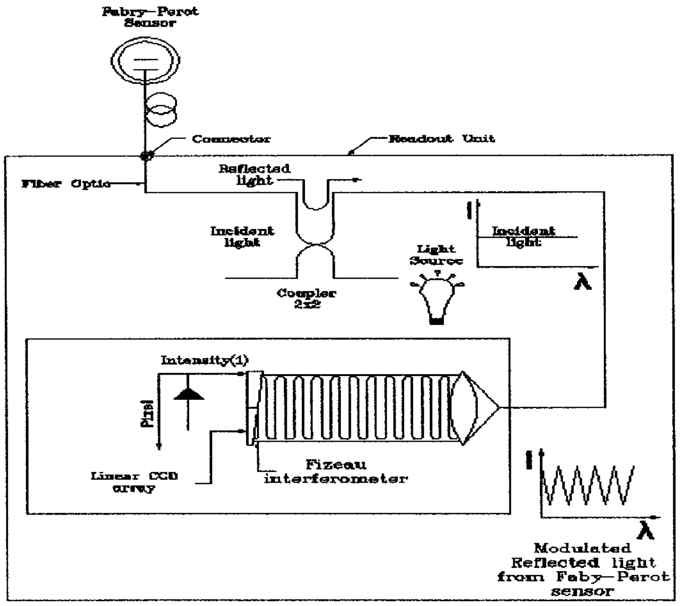


Figure 5.4 Reading principle of Fabry-Perot fiber optic sensor

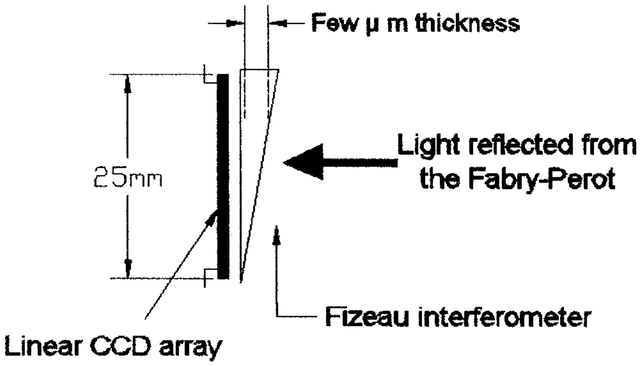


Figure 5.5 Fizeau operating principle

Incident white light is launched into one arm of 2x2 coupler and direct toward the Fabry-Perot sensor (Figure 5.4). The light signal is wavelength modulated by the sensor and is reflected back toward the readout instrument where it is diffracted through a lens and thrown onto the so-called Fizeau interferometer (Figure 5.5). This latter interferometer is essentially a glass blade on which a triangular shaped surface coating is deposited. A linear CCD array is then located on the other side of the Fizeau interferometer. Now the interesting optical property of a Fizeau interferometer is that maximum light is transmitted at the location along it where the thickness of the coating is exactly equal to the cavity length in the Fabry-Perot sensor. The pixels of the CCD array are used to locate this position [6, 10].

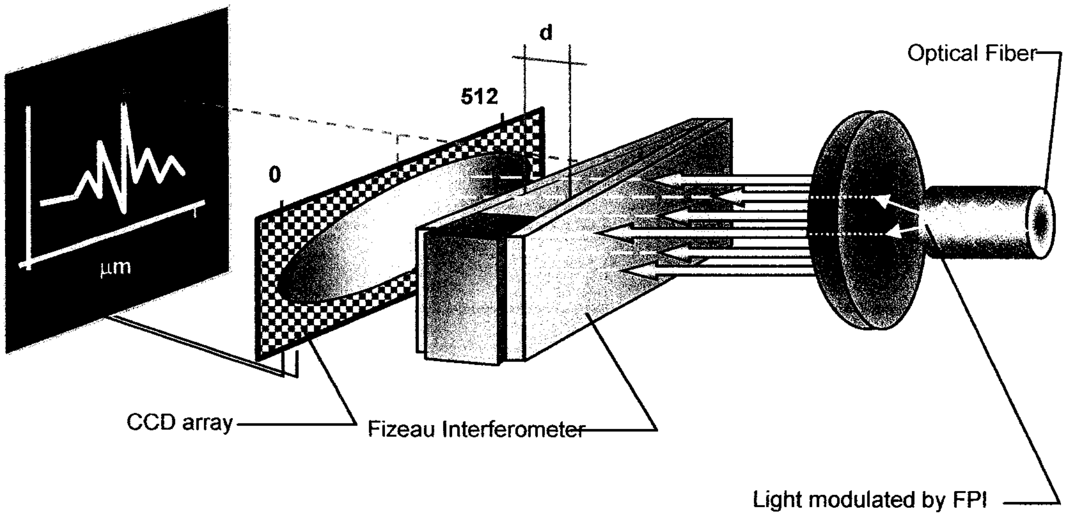


Figure 5.6 Readout Operating Principle

5.5 Fiber Optic Instruments

Embedment Strain Gage

These gages are designed to be embedded in the concrete to measure the compressive or tensile strain in the concrete (Figure 5.7). It should be noted that usually in order to get the true strain in the concrete, some no-stress gages can also be installed in the concrete, so that the true strain is equal to the measured strain minus the strain measured by the no-stress gage (dummy) installed in the nearest proximity to the strain gage. Strain gages are installed either single, to measure strain in one direction, or in rosettes of two or more gages to obtain the complete state of strain in two or three directions[2, 10].

Figure 5.7 Dynamic (FO) Embedment Strain Gage

Spot-weldable Strain Gage

These are spot-welded to the existing rebar reinforcement pattern in the reinforced concrete in order to measure the compressive or tensile strain of the rebar (Figure 5.8) [2, 7 and 10].

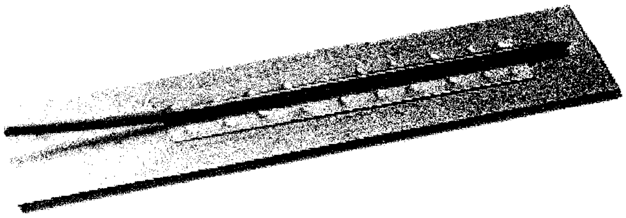


Figure 5.8 Dynamic (FO) Rebar Stress Meter

Piezometers

Fiber optic piezometer is designed to measure pore water or other fluid pressure and it is based on a non-contact measurement of the deflection of a stainless steel diaphragm, as opposed to more conventional measurement of diaphragm deformation.

When the gage is under pressure, there is a variation of the Fabry-Perot cavity length made by the inner surface of the stainless steel diaphragm on one side and the tip of an optical fiber on the other side (Figure 5.9) [10].

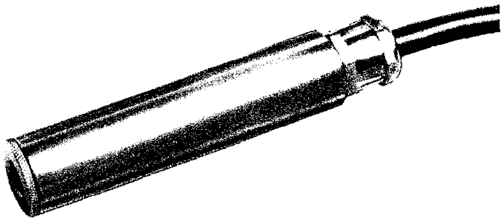


Figure 5.9 Fiber optic piezometer

Displacement Transducer

Fiber optic displacement sensor is based on a spatially-distributed Fabry-Perot interferometer. The maximum non-linearity error observed is lower than 0.1% full scale. The resolution of the sensor is 0.002 mm. This sensor is illustrated in Figure 5.10. [10].

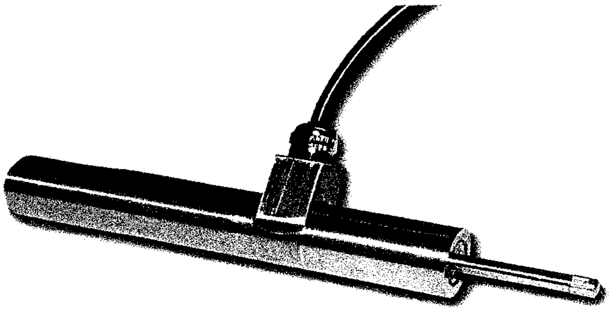


Figure 5.10 Fiber optic displacement transducer

Temperature Sensor

Fiber optic temperature sensor is based on the thermal expansion of highly stable glass, allowing precise, stable and repeatable measurements. Their compact size, immunity to lightning, resistance to corrosive environments, high accuracy and reliability make them the best choice for temperature measurement s in harsh environments (Figure 5.11) [10].

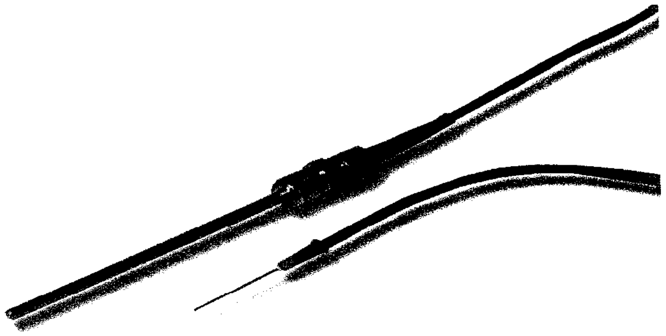


Figure 5.11 Fiber optic temperature sensor

CHAPTER 6

Analysis of the structural instrumentation of concrete and steel in Tehran Tower

6.1 Introduction

Tehran Tower is a concrete and steel structure with 435m height. The construction of the tower began in the mid 90's in Tehran (Iran) on an area of 14 hectares between Sheikh Fazlollah Nouri, Shahid Hemmat, Shahid Chamran and Resalaat highways. After the Toronto tower with 553.3m height, the Moscow tower with 533.3.m height and the Shanghai tower with 460m height, the Tehran Tower has been assessed as the tallest tower in the world and it is the first existing tower which is instrumented by fiber optic sensors and conventional instruments. The project calls for establishment of a Tehran International Communication Center and a telecommunication/TV tower over it, a center for international seminars, and a center for international trade and a 5-star hotel beside it. A number of structural monitoring instruments, both vibrating wire and fiber optic have been installed in the Tehran tower during its construction (Table 6.1). This provides a unique opportunity to compare the behavior of these two types of instruments. The owner of the tower is Yadman Sazeh Co. and the contractor is Boland Payeh Co. who installed the instruments and performed the readings. The Canadian consulting firm Nicolet, Chartrand, Knoll who has had also experience in the construction of the CN tower was appointed as an expert by the owner.

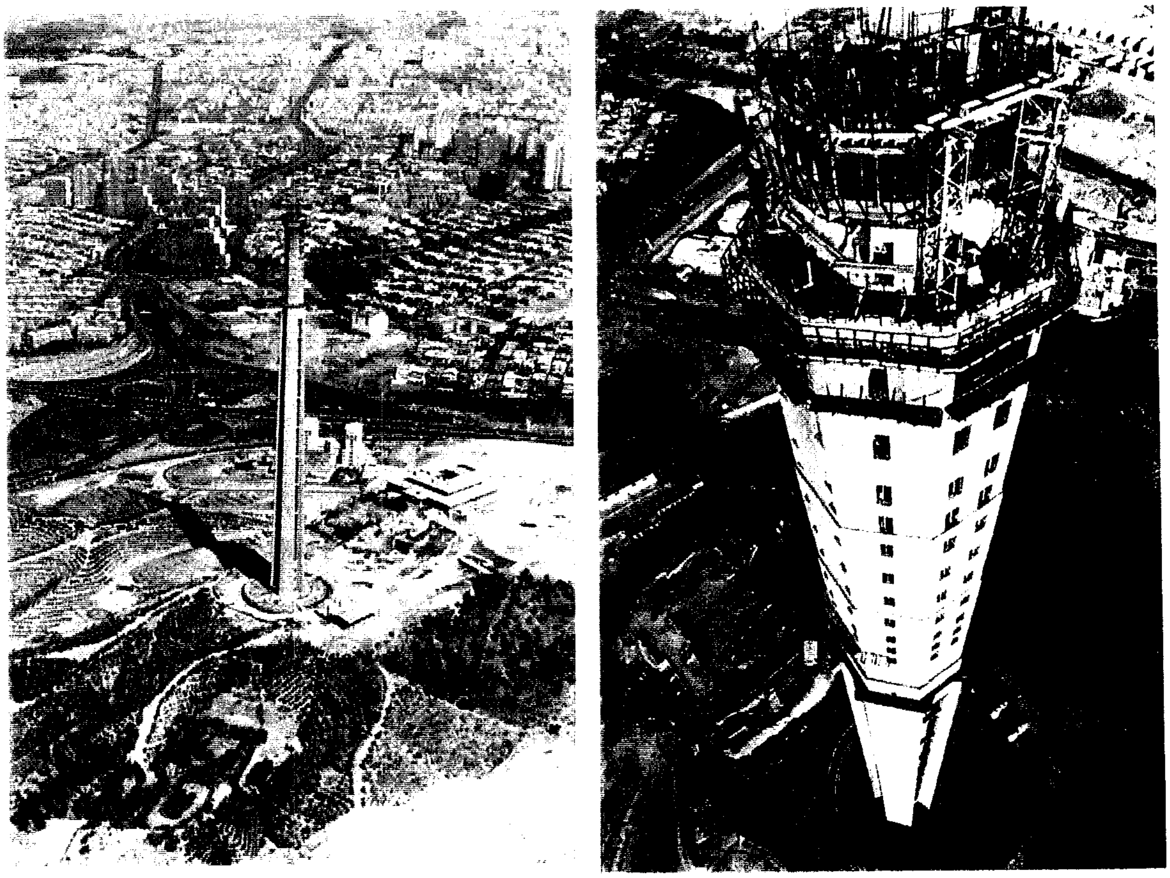


Figure 6.1 View of Tehran tower

a) Vibrating wire instruments

Tehran Tower was instrumented by the following types of vibrating wire (VW), (Table 6.1):

- **Vibrating Wire Rebar Stress Meter (SM)**
- **Vibrating Wire Strain Gage (SG), (concrete embedment type)**

It should be noted that in order to get the true strain in the concrete based on the readings of the SG gages, some no-stress gages were also installed in the concrete, so that the true strain is equal to the measured strain minus the strain measured by the no-stress gage installed in the nearest proximity to the strain gage. This procedure allows correcting the thermal effects in the concrete. It should be noted that the VW Strain Gage (SG) measures the same strain as the Dynamic Embedment Strain Gage (DSG) described below.

- **Vibrating Wire Total Pressure Cell (TPC)**

These have been installed at the base of the Mat in order to measure the total vertical pressure on the foundation rock due to the weight of the tower. It should be noted that a long re-pressurization tube was connected to each total pressure cell in order to re-pressurize the cell after the curing of the concrete in order to re-establish the pressure which could have been lost due to concrete shrinkage. The long re-pressurization tube was needed so that the end of the tube could protrude from the concrete at the top of the mat and allow re-pressurization after the concrete had cured.

b) Fiber optic instruments

The following types of fiber optic (FO) instruments were installed (Table 6.1):

- **Dynamic (FO) Embedment Strain Gage (DSG)**

It should be noted that some no-stress gages were also installed in the concrete, in a similar way as for the vibrating wire embedment strain gages, in order to do the temperature effect corrections.

- **Dynamic (FO) Rebar Stress Meter (DSM)**

Instruments are installed in the “Mat and Wall”, the “Shaft” and “Solid”. In the sections 6.2, 6.3 and 6.4 below, a discussion has been prepared on the quality of the measurement results. Also a summary in table 7.2 at the end of this chapter has been prepared to show the performance of each type of instruments. Section 6.5 shows a favorable comparison between strain readings by vibrating wire instruments and fiber optic instruments in the shaft of the tower at all elevations (115, 228, 247 and 303) and in the "Solid". Measurement results have been studied and plotted in the Excel graphs which are provided for all instruments in the section 6.2 to 6.4. Also the ambiance temperature in as well as time table of the construction are provided in figures 6.3 and 6.4.

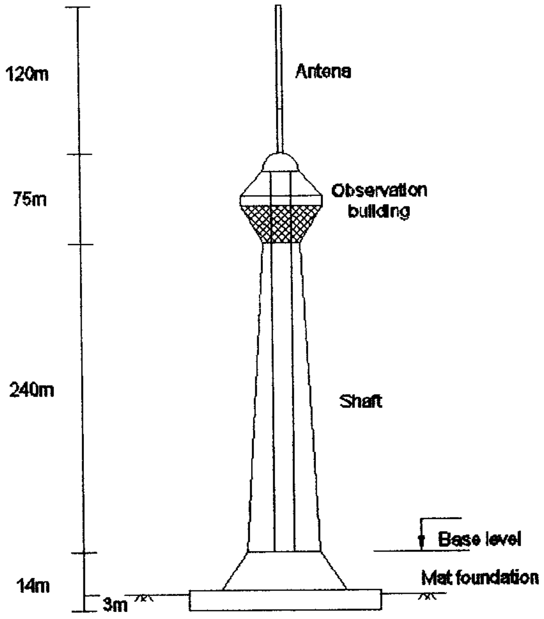


Figure 6.2 Tehran Tower Elevation View

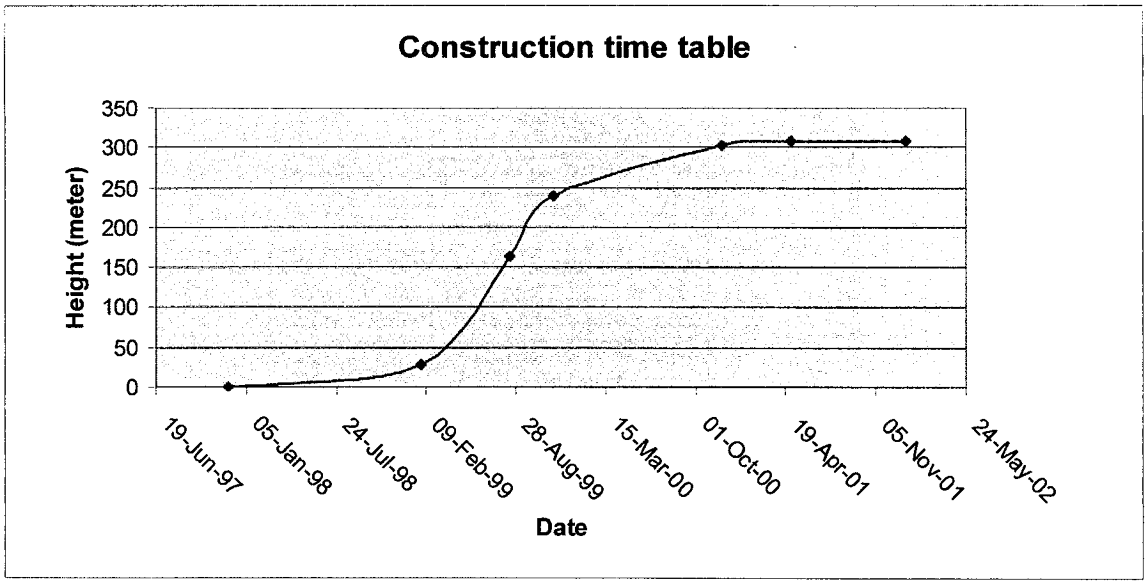


Figure 6.3 Construction time table

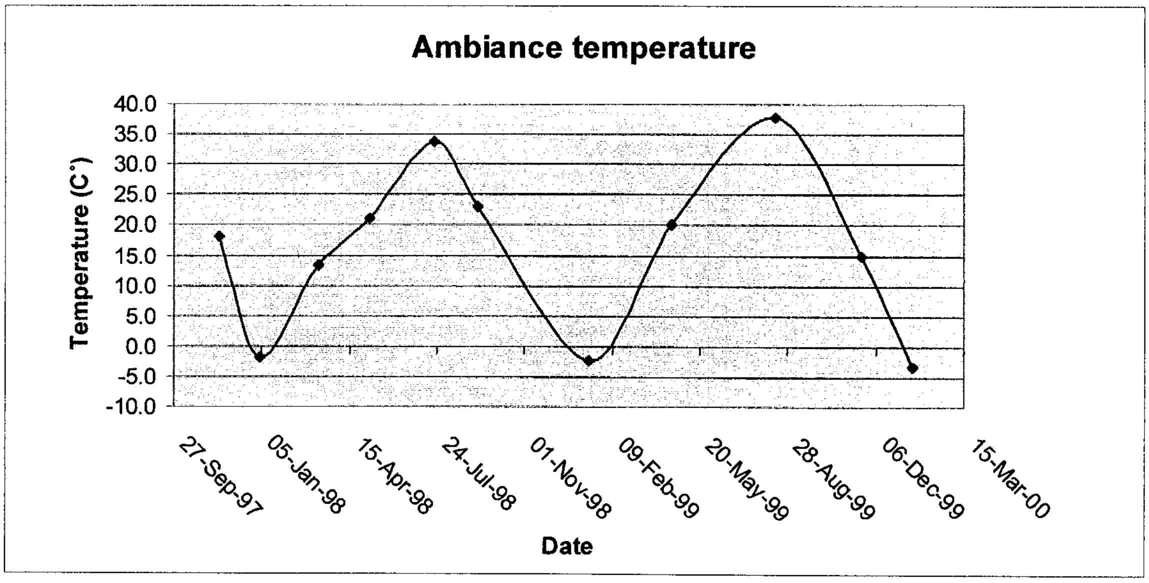


Figure 6.4 Ambiance temperature during construction

Location	Direction	Instrument Name	Instrument Type
Mat & Wall	Northeast	VW Strain Gage	SG3,SG4,SG9
		VW Stress Meter	SM3,SM7
		VW Total Pressure Cell	TPC3,TPC7
	Northwest	VW Strain Gage	SG5,SG6,SG10
		VW Stress Meter	SM4,SM8
		VW Total Pressure Cell	TPC4,TPC8
	Southeast	VW Strain Gage	SG2,SG8
		VW Stress Meter	SM2,SM6
		VW Total Pressure Cell	TPC2,TPC6
	Southwest	VW Strain Gage	SG1,SG7
		VW Stress Meter	SM1,SM5
		VW Total Pressure Cell	TPC1,TPC5
Shaft, ELV 000	Northeast	VW Strain Gage	SG17
		Dynamic Embedment Strain Gage	DSG7
		Dynamic Rebar Stress Meter	DSM11
	Northwest	VW Strain Gage	SG18
		Dynamic Embedment Strain Gage	DSG8
		Dynamic Rebar Stress Meter	DSM12
	Southeast	VW Strain Gage	SG16
		Dynamic Embedment Strain Gage	DSG6
		Dynamic Rebar Stress Meter	DSM10
	Southwest	VW Strain Gage	SG15
		Dynamic Embedment Strain Gage	DSG5
		Dynamic Rebar Stress Meter	DSM9
Shaft, ELV 115	Northeast	VW Strain Gage	SG21
		Dynamic Embedment Strain Gage	DSG11
		Dynamic Rebar Stress Meter	DSM15
	Northwest	VW Strain Gage	SG22
		Dynamic Embedment Strain Gage	DSG12
		Dynamic Rebar Stress Meter	DSM16
	Southeast	VW Strain Gage	SG20
		Dynamic Embedment Strain Gage	DSG10
		Dynamic Rebar Stress Meter	DSM14
	Southwest	VW Strain Gage	SG19
		Dynamic Embedment Strain Gage	DSG9
		Dynamic Rebar Stress Meter	DSM13
Shaft, ELV 228	Northeast	VW Strain Gage	SG25
		Dynamic Embedment Strain Gage	DSG15
		Dynamic Rebar Stress Meter	DSM20
	Northwest	VW Strain Gage	SG26
		Dynamic Embedment Strain Gage	DSG16
		Dynamic Rebar Stress Meter	DSM19
	Southeast	VW Strain Gage	SG24
		Dynamic Embedment Strain Gage	DSG14
		Dynamic Rebar Stress Meter	DSM18
	Southwest	VW Strain Gage	SG23
		Dynamic Embedment Strain Gage	DSG13
		Dynamic Rebar Stress Meter	DSM17

Table 6.1 Instruments Quantity (Continued)

Shaft, ELV 247	Northeast	VW Strain Gage	SG29
		Dynamic Embedment Strain Gage	DSG19
		Dynamic Rebar Stress Meter	DSM23
	Northwest	VW Strain Gage	SG30
		Dynamic Embedment Strain Gage	DSG20
		Dynamic Rebar Stress Meter	DSM24
	Southeast	VW Strain Gage	SG28
		Dynamic Embedment Strain Gage	DSG18
		Dynamic Rebar Stress Meter	DSM22
	Southwest	VW Strain Gage	SG27
		Dynamic Embedment Strain Gage	DSG17
		Dynamic Rebar Stress Meter	DSM21
Shaft, ELV 303	Northeast	VW Strain Gage	SG33
		Dynamic Embedment Strain Gage	DSG23
		Dynamic Rebar Stress Meter	DSM26
	Northwest	VW Strain Gage	SG34
		Dynamic Embedment Strain Gage	DSG24
		Dynamic Rebar Stress Meter	DSM27
	Southeast	VW Strain Gage	SG32
		Dynamic Embedment Strain Gage	DSG22
		Dynamic Rebar Stress Meter	DSM25
	Southwest	VW Strain Gage	SG31
		Dynamic Embedment Strain Gage	DSG21
		Dynamic Rebar Stress Meter	DSM28
Solid	Northeast	VW Strain Gage	SG13
		VW Stress Meter	SM11
		Dynamic Embedment Strain Gage	DSG3
		Dynamic Rebar Stress Meter	DSM7
	Northwest	VW Strain Gage	SG14
		VW Stress Meter	SM12
		Dynamic Embedment Strain Gage	DSG4
		Dynamic Rebar Stress Meter	DSM8
	Southeast	VW Strain Gage	SG12
		VW Stress Meter	SM10
		Dynamic Embedment Strain Gage	DSG2
		Dynamic Rebar Stress Meter	DSM6
	Southwest	VW Strain Gage	SG11
		VW Stress Meter	SM9
		Dynamic Embedment Strain Gage	DSG1
		Dynamic Rebar Stress Meter	DSM5

6.2 Instrumentation Results in the Mat and Wall

- **VW Rebar Stress Meter (SM) (Figure 6.5)**

As it is shown in the figure below, readings of VW rebar stress meters (SM1 to SM4) in mat and wall at the latest date are very close and vary from -8.2 kN to -12.2 kN in compression, while readings for VW rebar stress meters SM5, SM7 and SM8 are close to each other and vary from -28.5 kN to -33.4 kN, also in compression (mostly 3 times more than SM1 to SM4). SM6 appears to be not working or cannot be read for whatever reason (Appendix 1, Figures A4, A5, A6, A21 and A22).

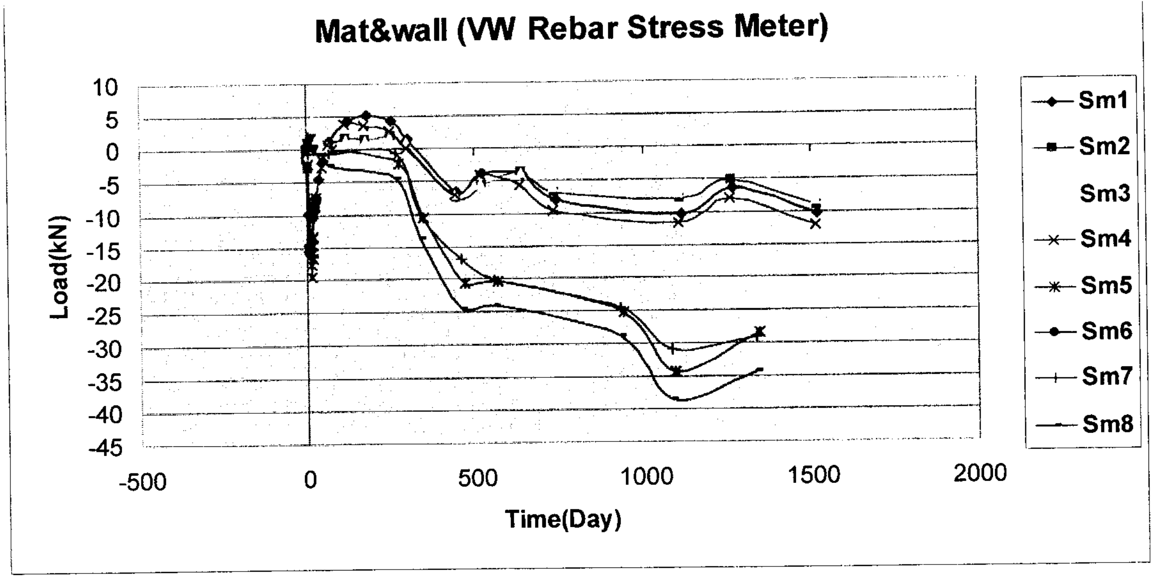


Figure 6.5 VW Rebar Stress Meter (SM) in the Mat and Wall

- **VW Strain Gage (SG) (Figure 6.6)**

Except SG 8 which has no reading, the other strain gages (SG1 to SG7 & SG9 to SG 10) appear to be repeatable and the readings vary from 131 to -463 micro-strain. Actually all strain gages indicate compressive values, except one (SG6) (Appendix 1, Figures A2, A3, A7 and A8).

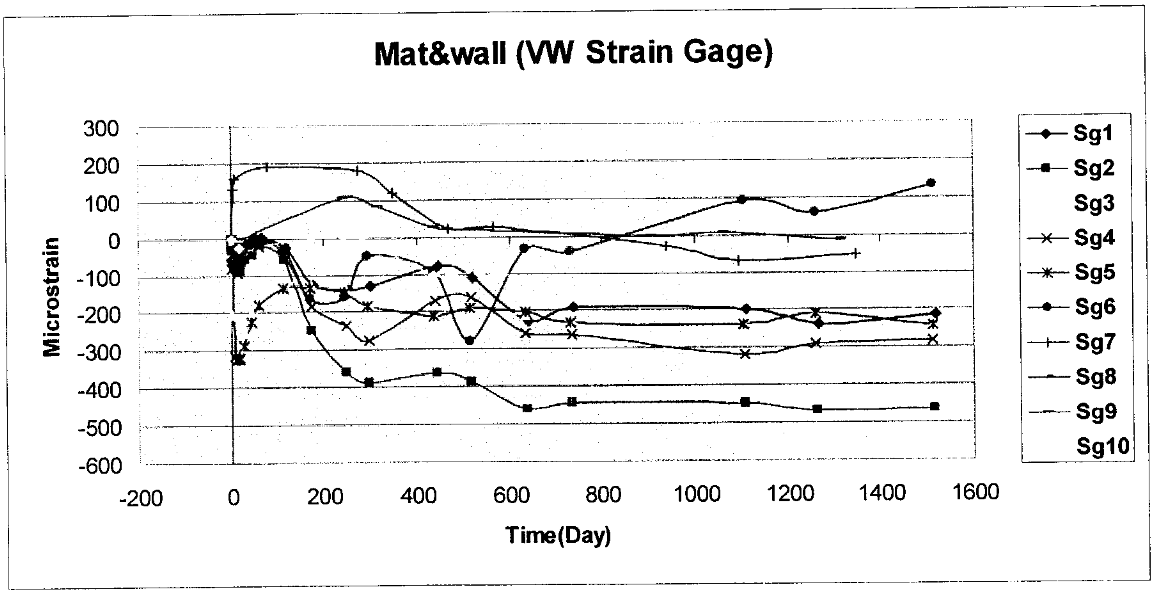


Figure 6.6VW Strain Gage (SG) in the Mat and Wall

- **VW Total Pressure Cell (TPC) (Figure 6.7)**

Except TPC 5 which has no reading, the other Total Pressure Cells (TPC1 to TPC 4 & TPC6 to TPC 8) have very low readings, in the range of –20.4 to 117 kPa. Actually, all the readings are positive but low, except TPC 6 which indicates –20.4 kPa.

It is believed that the theoretical value for the pressure on the foundation should be in the range of 500 kPa [20], and then Total Pressure Cell readings are actually very low. This may be due to the long re-pressurization tube of the cell which introduces some reading error. However, it is not believed that there is a leak in the cells since the readings show a reasonable continuity, and therefore it is still useful to continue to read them. In addition, some of the cells have also indicated a higher pressure before reducing to a lower value, which may have been due to some specific steps in the construction sequence (Appendix 1, Figures A9, A10, A11 and A12).

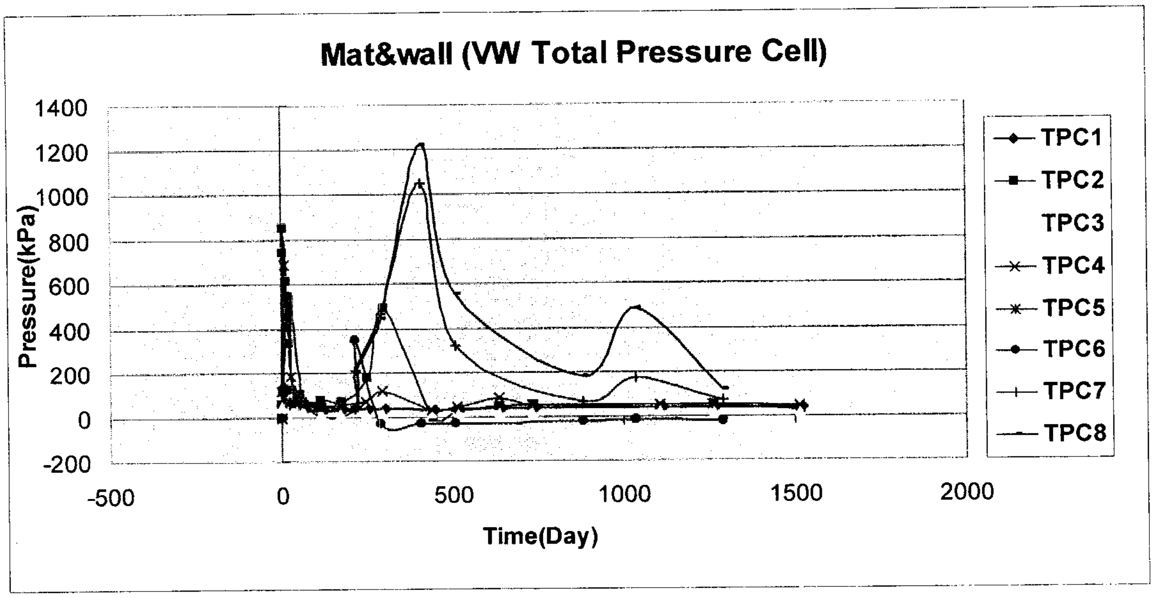


Figure 6.7 VW Total Pressure Cell (TPC) in the Mat and Wall

6.3 Instrumentation Results in the Shaft

ELEVATION 000

- **Dynamic (FO) Embedment Strain Gage (DSG) (Figure 6.8)**

According to the method described earlier for correction of temperature effects in the concrete, the reading of NDSG1 (reading of the No-stress gage) is subtracted from each one of the DSG reading in order to obtain the real strain. As can be seen, the readings vary in compression from -178.5 to – 309 micro-strain at the latest date and they appear to be very repeatable. The reading of + 646 micro-strain of DSG8 is out of the range of the other readings and it is certainly a wrong reading which should be discarded (Appendix 1, Figure A16).

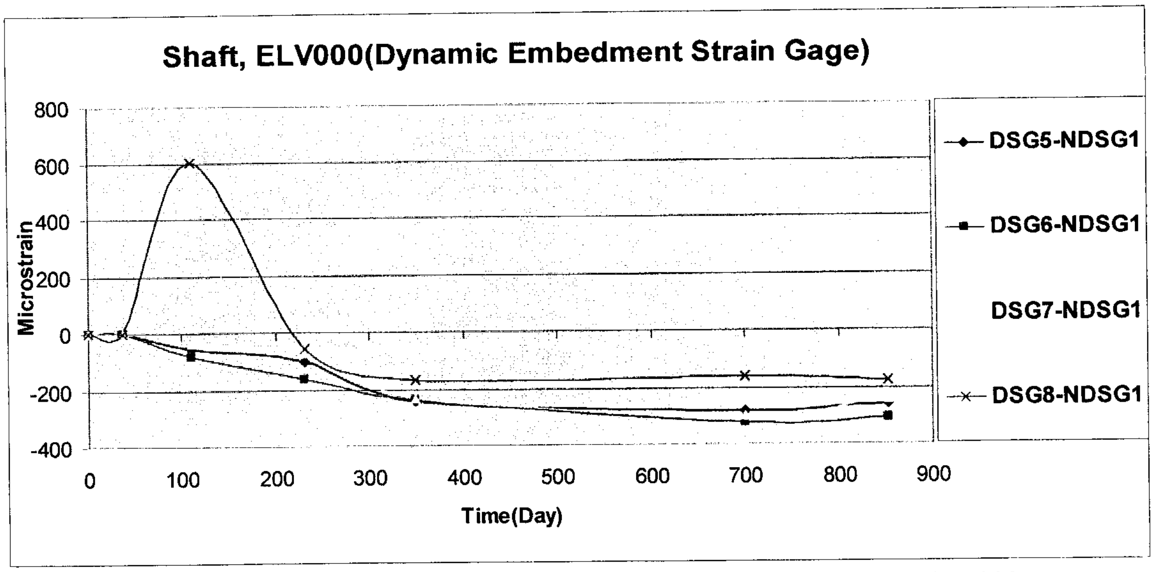


Figure 6.8 Dynamic (FO) Embedment Strain Gage (DSG) at elevation 000

- **Dynamic (FO) Rebar Stress Meter (DSM) (Figure 6.9)**

The readings of DSM9 and DSM11 at the latest date vary in the range of -12 to 117 micro-strain and for DSM 10 there is no reading and for DSM 12, -845 micro-strain. The readings of DSM9, DSM11 and DSM12 appear to be good quality readings, although they indicate different strain values (Appendix 1, Figures A16 and A17).

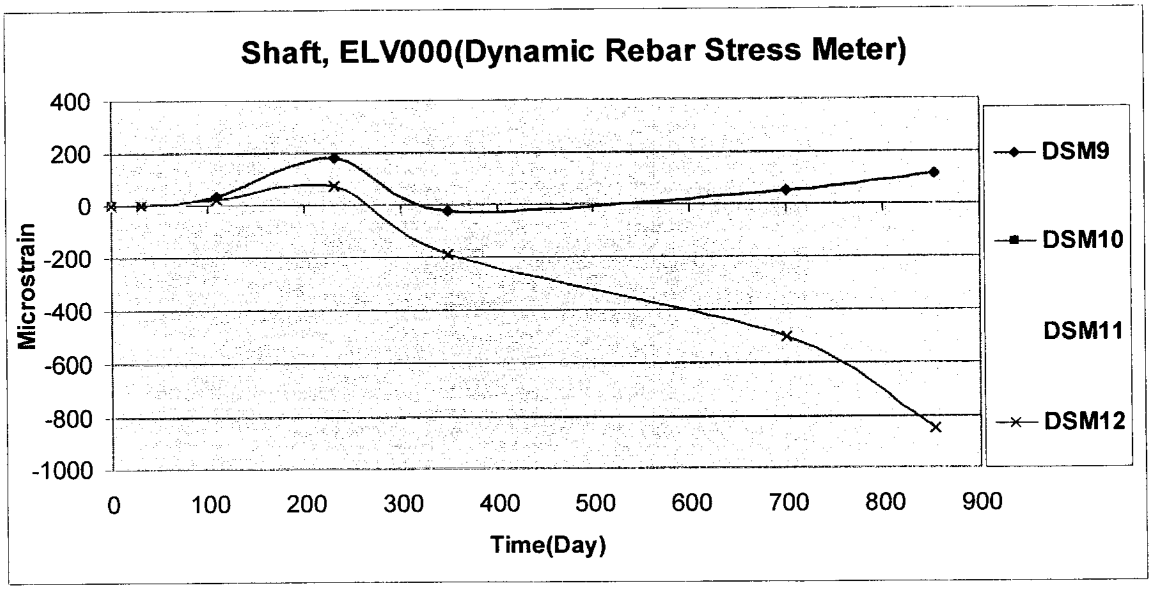


Figure 6.9 Dynamic (FO) Rebar Stress Meter (DSM) at elevation 000

- **VW Strain Gage (SG) (Figure 6.10)**

For correcting of temperature effects, the reading of NDSG1 (reading of the No-stress gage) are subtracted from each one of the SG reading in order to obtain the real strain. For VW Strain Gages after subtraction of the reading of NSG1 (No-stress Gage) there are similar and repeatable readings in the range of -426.7 to -507.9 micro-strain at the latest date. The reading of -429.8 micro-strain of SG15 is out of the range of the other strain gages at the day no.110 and it is considered as a wrong reading (Appendix 1, Figure A16).

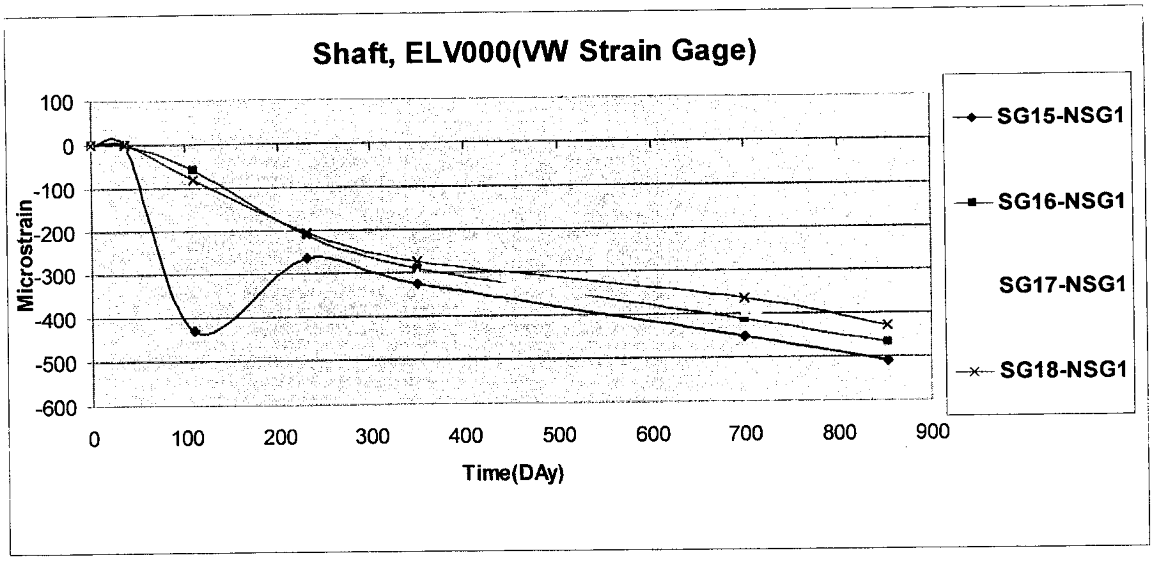


Figure 6.10 VW Strain Gage (SG) at elevation 000

ELEVATION 115

- **Dynamic (FO) Embedment Strain Gage (DSG)(Figure 6.11)**

The reading of NDSG2 (reading of the No-stress gage) is subtracted from each one of the DSG in order to obtain the real strain for Dynamic (FO) embedment strain gage. As can be seen in Figure 6.11, the values vary from - 277 to – 331 micro-strain and they appear to be repeatable.

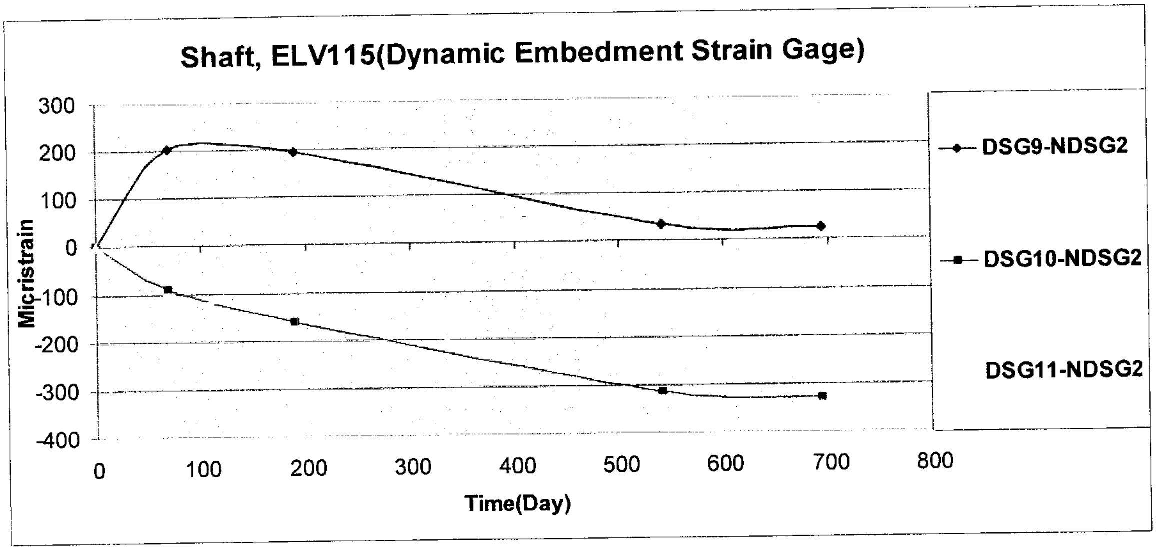


Figure 6.11 Dynamic (FO) Embedment Strain Gage (DSG) at elevation 115

Indeed, in Figure 6.9 the reading of DSG9, DSG 10 and DSG 11 follow the same trend (Appendix 1, Figure A15).

- **Dynamic (FO) Rebar Stress Meter (DSM) (Figure 6.12)**

The readings are in compression and vary from -20 to – 224.5 micro-strain at day no. 541 and considering their repeatability. They represent good quality readings although they indicate different values (Appendix 1, Figure A15).

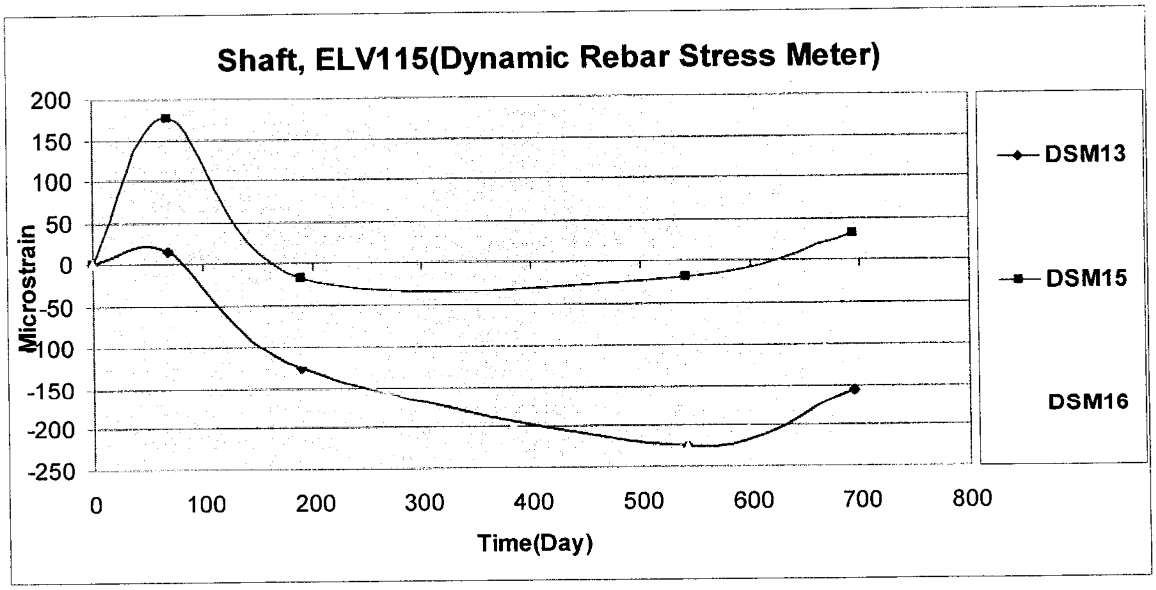


Figure 6.12 Dynamic (FO) Rebar Stress Meter (DSM) at elevation 115

- **VW Strain Gage (SG) (Figure 6.13)**

Based on the method for correcting of temperature effects, the reading of NSG 2 (reading of the No-stress gage) is subtracted from each one of the SG19 to SG22 in order to obtain the real strain for VW Strain Gages. The values are pretty similar and repeatable and vary in compression from -319.8 to -366 micro-strain (Appendix 1, Figure A15).

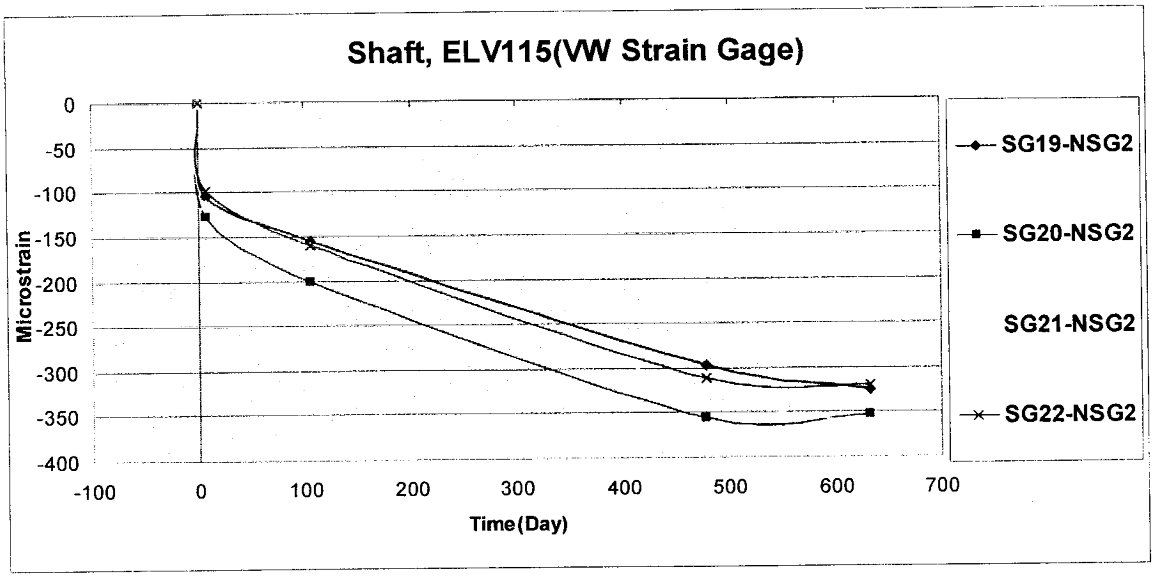


Figure 6.13 VW Strain Gage (SG) at elevation 115

ELEVATION 228

- **Dynamic (FO) Embedment Strain Gage (DSG) (Figure 6.14)**

The reading of NDSG3 (reading of the No-stress gage) is subtracted from each one of the DSG 13 to DSG16 to correct the temperature effects. As it can be observed in Figure 6.12, on the day no. 414 the values are very similar and vary in compression from -202 to -218 micro-strain. Afterwards, at the latest date, the readings are still very repeatable, although they have reduced to values from -161 to -249 micro-strain (Appendix 1, Figure A14).

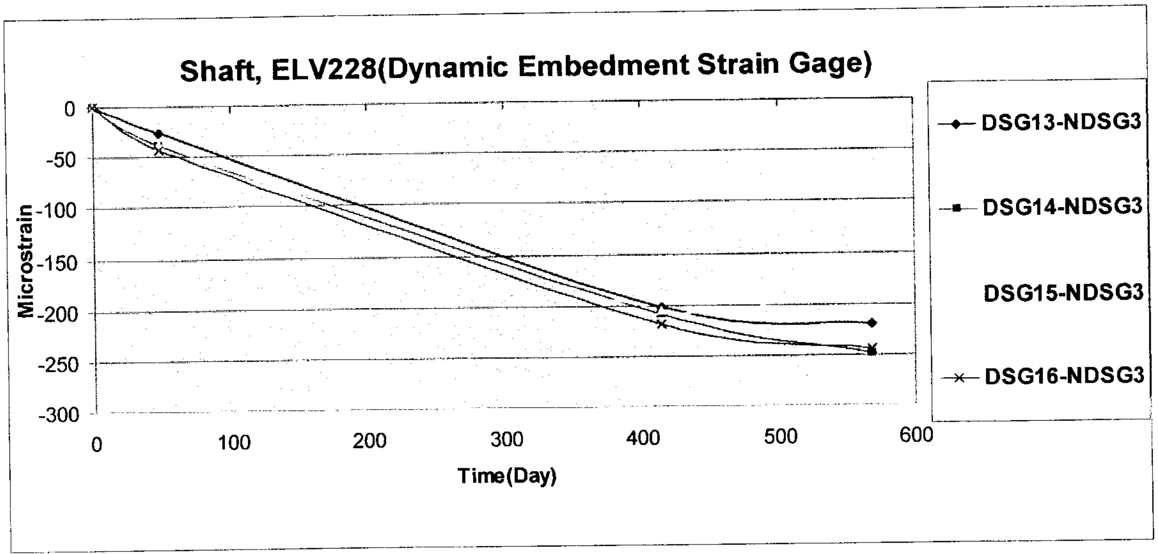


Figure 6.14 Dynamic (FO) Embedment Strain Gage (DSG) at elevation 228

- **Dynamic (FO) Rebar Stress Meter (DSM) (Figure 6.15)**

Referring to figure 6.15, it shows that the readings of Dynamic Rebar Stress Meters (DSM17, DSM19, and DSM20) vary from 4 to -311 micro-strain at day no.414. Later on, at day 568, they vary from 96 to -224 micro-strain and they appear to be repeatable. The reading of –1180 micro-strain for DSM18 appears to be a wrong reading for whatever reason (Appendix 1, Figure A14).

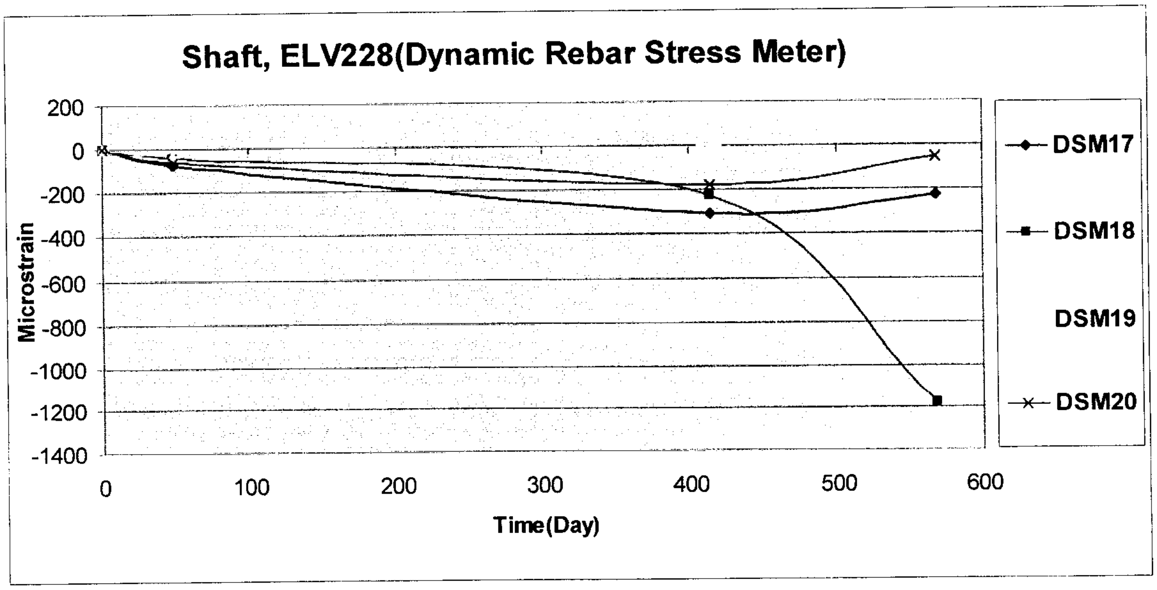


Figure 6.15 Dynamic (FO) Rebar Stress Meter (DSM) at elevation 228

- **VW Strain Gage (SG) (Figure 6.16)**

For correcting of temperature effects, the reading of the No-stress gage is subtracted from each one of the SG in order to find out the real strain. Therefore, as can be seen on the Excel chart, the readings vary all in compression in the range of - 162.1 to -217.4 micro-strain which are very close to each other. At the same time, this implies that all the gages are working properly (Appendix 1, Figure A14).

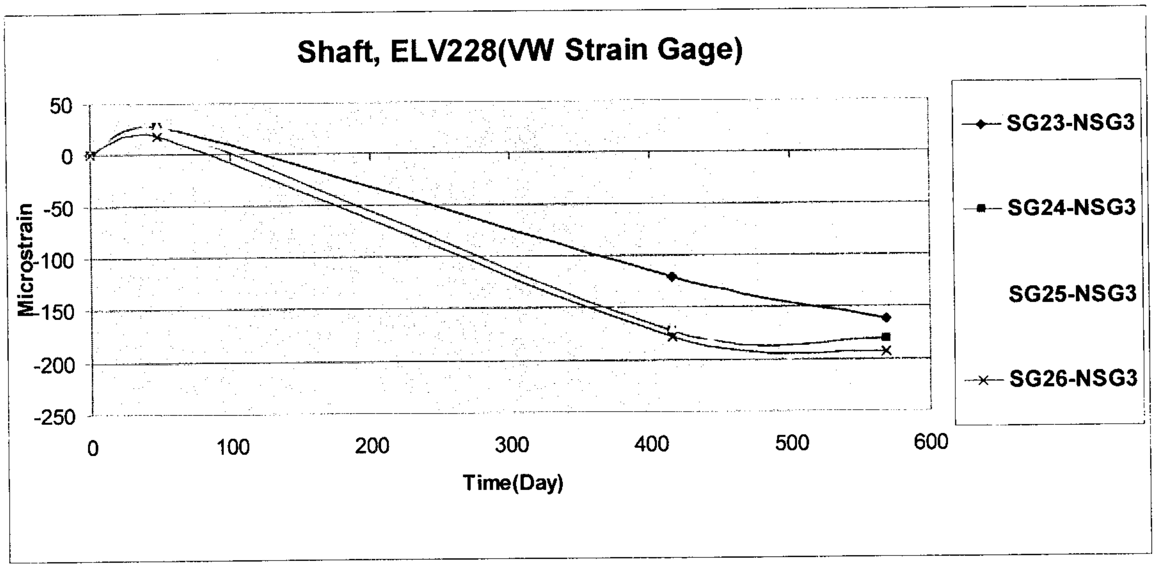


Figure 6.16 VW Strain Gage (SG) at elevation 228

ELEVATION 247

- **Dynamic (FO) Embedment Strain Gage (DSG) (Figure 6.17)**

There is only one reading for each one of the DSG and they apparently work properly. The reading of the No-stress gage NDSG4 is a wrong reading, therefore, it is not possible to calculate the corrected readings. There was also no initial reading for the gage DSG18; however, it is recommended continuing reading it. It could be possible to assign later an initial reading to that gage which would be similar to the initial readings of the two other gages, since they appear to be indicating the same magnitude of strain (Appendix 1, Figure A13).

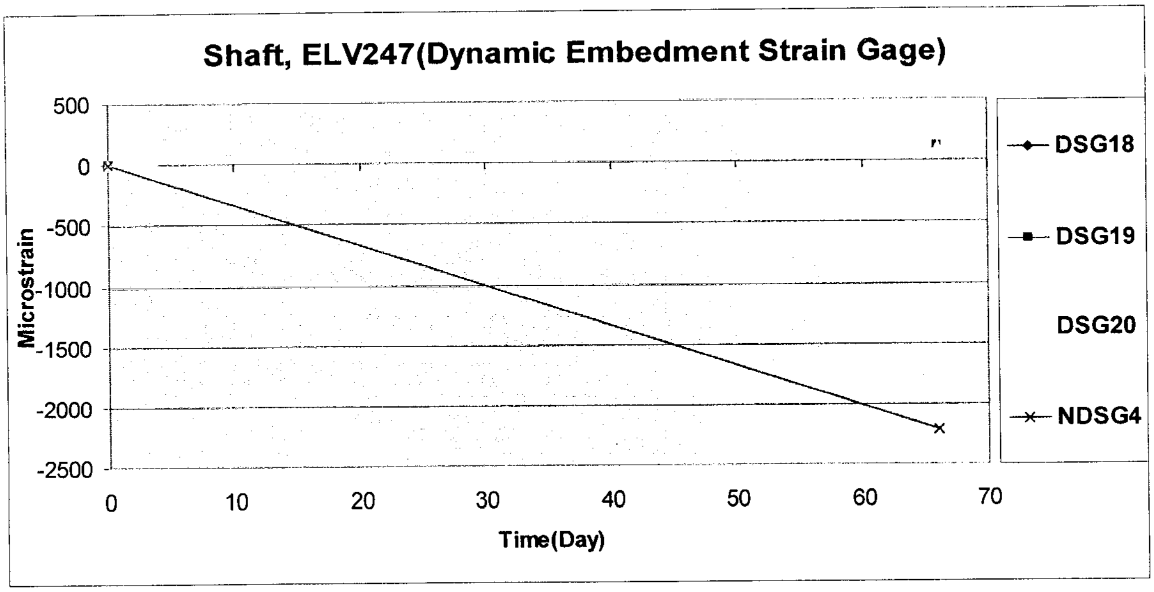


Figure 6.17 Dynamic (FO) Embedment Strain Gage (DSG) at elevation 247

- **Dynamic (FO) Rebar Stress Meter (DSM) (Figure 6.18)**

Except DSM24 which had no reading and may not work, the rest (DSM21 to DSM 23) vary at the latest date in the range of 104 to 132 micro-strain which are close to each other and they seem to be working properly (Appendix 1, Figure A13).

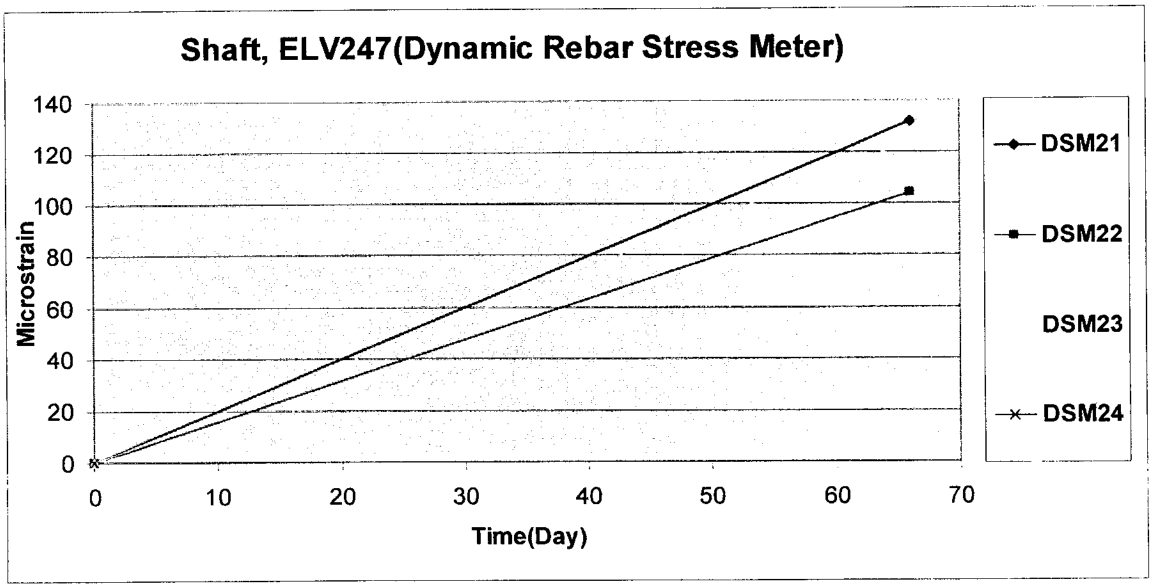


Figure 6.18 Dynamic (FO) Rebar Stress Meter (DSM) at elevation 247

- **VW Strain Gage (SG) (Figure 6.19)**

According to the method for correcting of temperature effects, the reading of NDSG4 (reading of the No-stress gage) is subtracted from each one of the SG 27 to SG30 in order to obtain the real strain values. These values vary in compression in the range of -40.5 to -56.2 micro-strain and they are very close to each other so it is considered that the gages are working properly (Appendix 1, Figure A13).

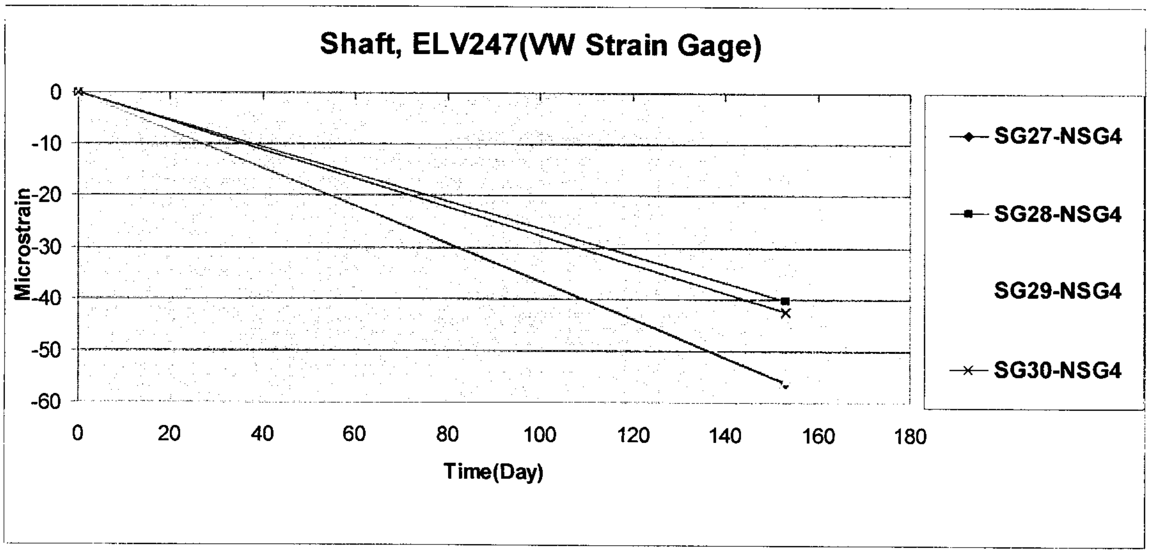


Figure 6.19 VW Strain Gage (SG) at elevation 247

ELEVATION 303

- **Dynamic (FO) Embedment Strain Gage (DSG) (Figure 6.20)**

The reading of NDSG5 (reading of the No-stress gage) is subtracted from each one of the DSG 21 to DSG24 in order to obtain the real strain values. As it can be seen in below, they vary in the range of 89 to 299 micro-strain which are all positive, therefore indicating tensile strains. It is considered that these gages are working properly, although it is unusual that the strain readings are tensile instead of compressive. As there are only two sets of readings, the initial values and the values at day no. 67, it is not possible to determine if there was an error in the initial readings or some other reason to justify the tensile values (Appendix 1, Figure A1).

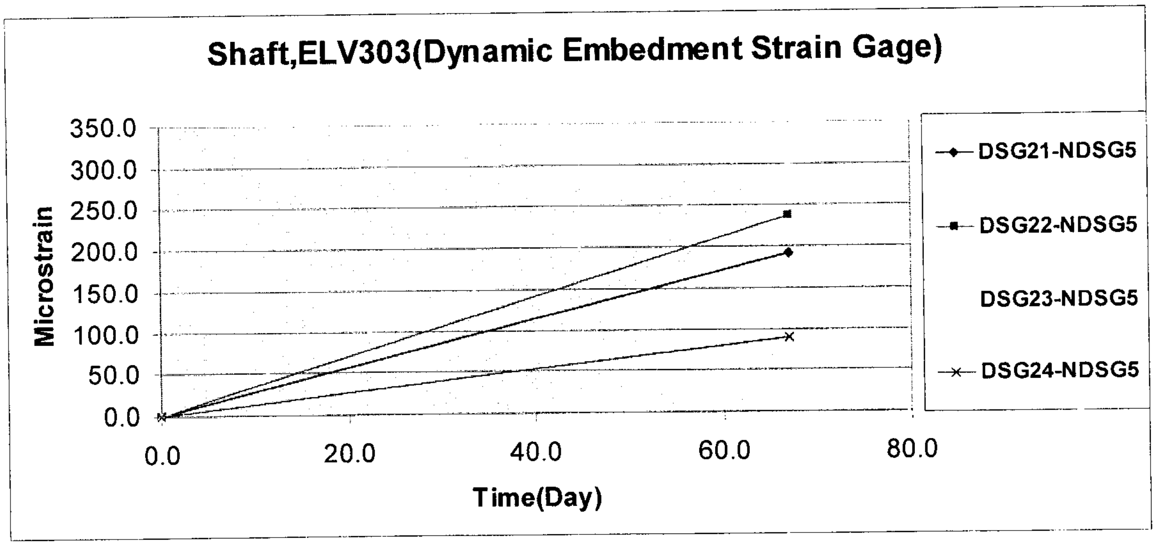


Figure 6.20 Dynamic (FO) Embedment Strain Gage (DSG) at elevation 303

- **Dynamic (FO) Rebar Stress Meter (DSM) (Figure 6.21)**

Although there is only one reading at day 67, the readings of Dynamic Rebar Stress Meters (DSM25, DSM27andDSM29) are indicating tensile strains and they are similar and vary in the range of 89 to 124 micro-strain. The DSM 26 shows a wrong reading and apparently it is not working (Appendix 1, Figure A1).

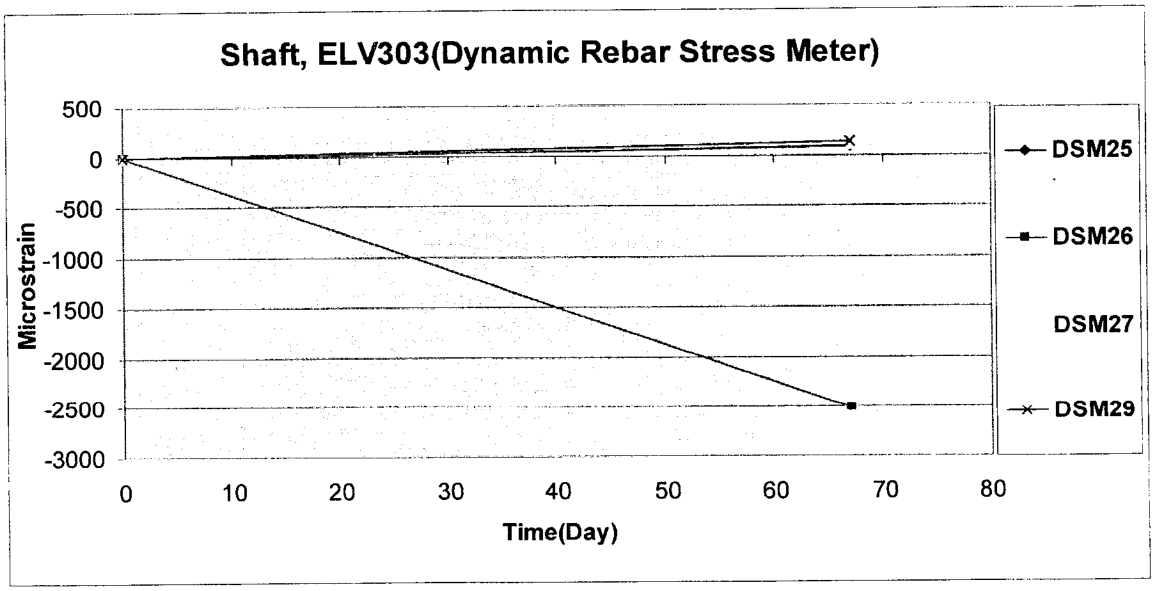


Figure 6.21 Dynamic (FO) Rebar Stress Meter (DSM) at elevation 303

- **VW Strain Gage (SG) (Figure 6.22)**

Due to the method for correcting of temperature effects, the reading of NSG5 (reading of the No-stress gage) is subtracted from each one of the SG in order to approach the real strain for VW Strain Gage and it is showing that the readings are quite close and they vary in compression in the range of -6.4 to -21.6 micro-strain (Appendix 1, Figure A1).

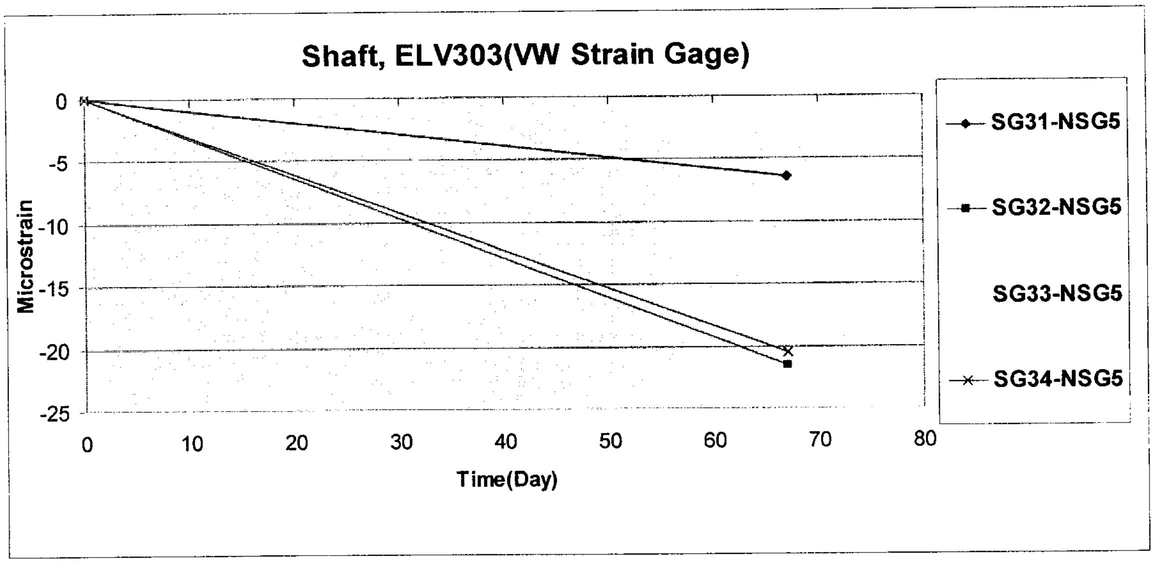


Figure 6.22 VW Strain Gage (SG) at elevation 303

6.4 Instrumentation Results in the Solid

- **Dynamic (FO) Embedment Strain Gage (DSG) (Figure 6.23)**

Only DSG1 has been read and the values are all in compression and appear to make sense. For the other gages DSG2, DSG3 and DSG4 there is no reading but it is not clear if they are out of order or if they were not read because of some field problems (Appendix 1, Figures A19 and A20).

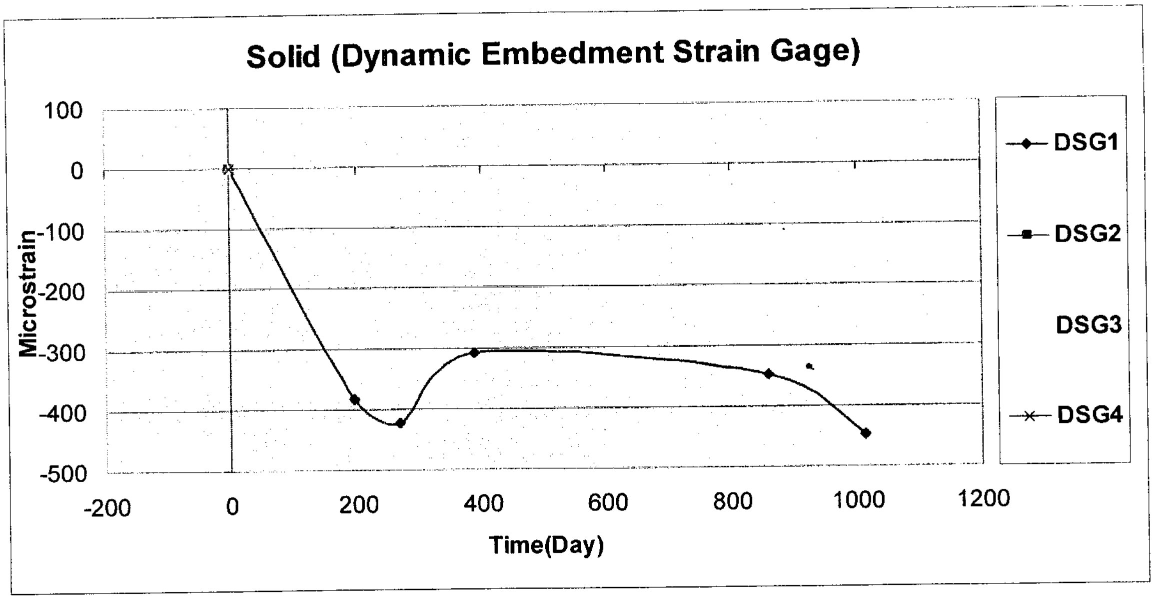


Figure 6.23 Dynamic (FO) Embedment Strain Gage (DSG) in the Solid

- **Dynamic (FO) Rebar Stress Meter (DSM) (Figure 6.24)**

Only DSM5 has been read and the values are all in compression and appear to make sense. For the other gages DSM6, DSM7 and DSM8 there is no reading but again it is not clear if they are out of order or if they were not read because of some field problems (Appendix 1, Figures A17 and A18).

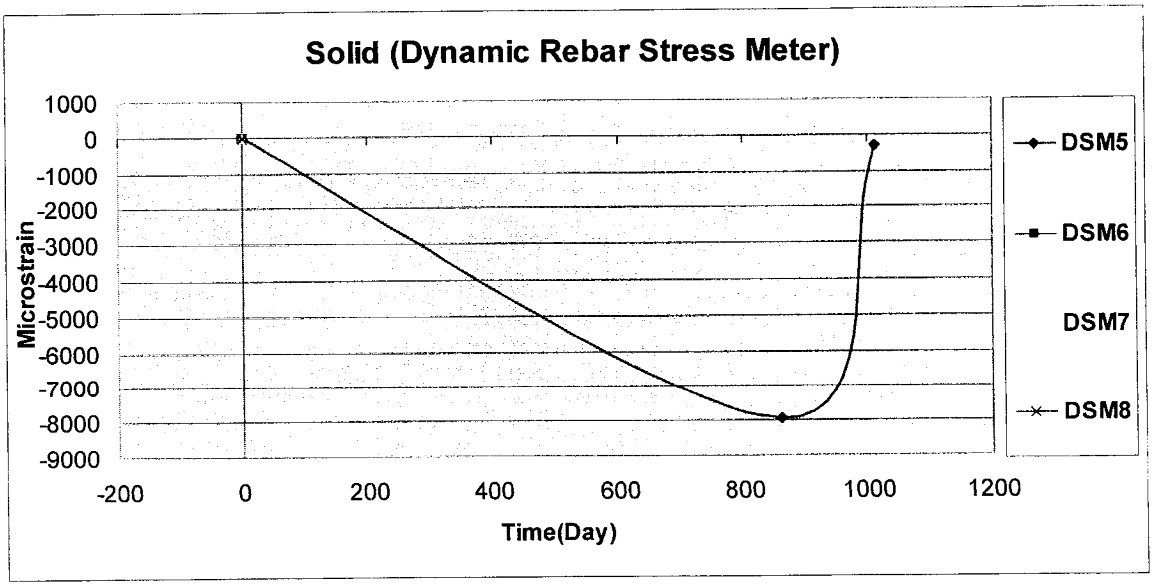


Figure 6.24 Dynamic (FO) Rebar Stress Meter (DSM) in the Solid

- **VW Rebar Stress Meter (SM) (Figure 6.25)**

On the day no. 9, all VW Rebar Stress Meter(SM) are very close to each other and they vary in compression from -10.1 to -12 kN. After that date there are only readings for SM9. The other gages SM10, SM11 and SM 12 were not read because they were not accessible (Appendix 1, Figures A17 and A18).

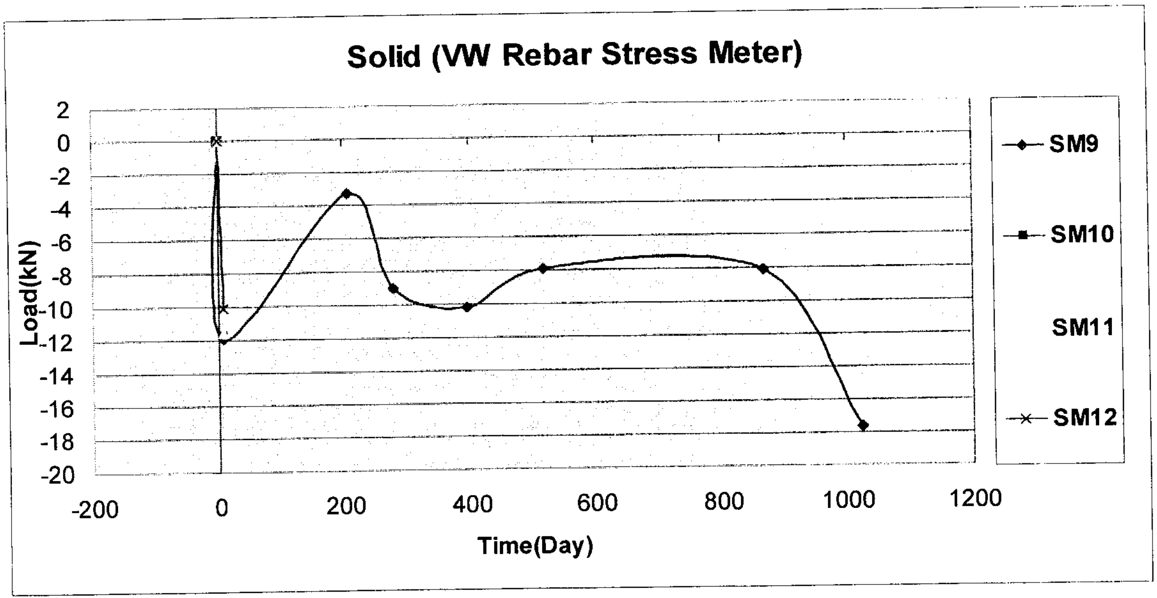


Figure 6.25 VW Rebar Stress Meter (SM) in the Solid

- **VW Strain Gage (SG)** ***(Figure 6.26)***

At day 4, the related chart shows that all VW Strain Gages are very close to each other in compression from -53.1 to -92.3 micro-strain. After that date there are only readings for SG11. The other gages SG12, SG13 and SG14 were not read because they were not accessible (Appendix 1, Figures A19 and A20).

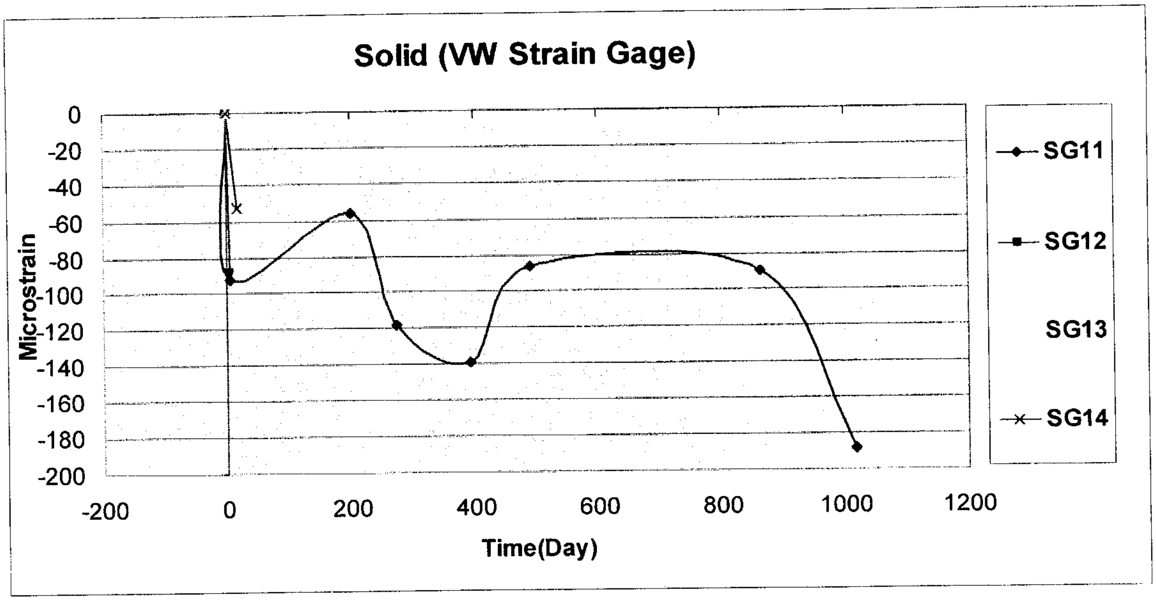


Figure 6.26 VW Strain Gage (SG) in the Solid

6.5 Discussion on strain readings in the shaft

An interesting comparison can be made between the readings of the Dynamic Embedment Strain Gage (DSG) and the VW Strain Gage (SG) in the Shaft at the different elevations, as these gages were installed adjacent to each other. The comparison is therefore between the two types of gages: fiber optic in the first case and vibrating wire in the second case. This comparison is presented in Table 6.2.

Elevation (m)	DSG (EFO) (micro-strain)	SG (EM-5) (micro-strain)
0	-178.5 to -309.0	-426.7 to -507.9
115	-277 to -331.0	-319.8 to -366.0
228	-161.0 to -249.0	-162.1 to -217.4
247	0 to 116.0 (Without correction of the No-stress gage value)	-40.5 to -56.2
303	89.0 to 299.0 (Possibly an error in the initial reading of the gages)	-6.4 to -20.5

Table 6.2 Comparison of Fiber optic and vibrating wire readings

As can be seen on the Table 6.2, the comparison between the vibrating wire and the fiber optic instruments shows the same tendency, especially for the elevations 0, 115 and 228 where it can be observed that all the measured strains are in compression (negative values) although somewhat higher for the vibrating wire values than for the fiber optic values. Nevertheless, they are in the same range of magnitude and it is also obvious that the compression is higher at elevation 0 where the weight of the tower is higher than on the higher elevations.

For the elevations 247 and 303, there are actually not enough readings to make a comparison and also the readings for the fiber optic instrument DSG are without correction at elevation 247, as there is no reading available for the No-stress gage.

6.6 Comparison of theoretical strains and measured strains in the shaft

The objective is to calculate some theoretical vertical strain values in the concrete and the steel reinforcement at different elevations in the shaft of the tower due to the own weight of the tower and to compare these theoretical values to the measured strain readings at the same elevations, considering the assumption that the strains tend to equilibrate between the steel reinforcement and the concrete. This latter situation, if verified, would correspond to the plane strain situation.

The theoretical weight of the tower at different elevations was provided by the designer [20].

The cross-section area at the different elevations was roughly calculated based on the cross-section drawings provided by designer. Some of these drawings can be found in Appendix 2.

The elasticity modulus for the concrete and steel were provided by the designer as well as the percentage of reinforcement steel at each elevation of interest.

The elasticity modulus for the concrete was actually assumed to be the static modulus as recommended by ACI (American Concrete Institute), e.g. 3,160,000 ton/ m^2. For the steel, the modulus of elasticity is assumed to be 21,000,000 ton/ m^2.

The theoretical strain at each elevation is calculated based on the Hooke's law and incorporates an equivalent modulus for the concrete and steel, taking into account the percentage of steel with respect to concrete.

The stress is calculated by the equation in below:

$\sigma = L / A$ Where:

σ = Stress (ton / m^2)

L = Load (ton)
A = Cross-section Area (m^2)

According to the Hooke's law:

$\varepsilon = \sigma / E$; $\varepsilon = L / (A \times Eeq)$
Where:

ε = Strain
Eeq = Equivalent elasticity modulus (ton / m^2)

Ec = Elasticity modulus of concrete= 3,160,000 ton/ m^2 or 4,500,000 psi
Es = Elasticity modulus of steel= 21,100,000 ton/ m^2v or 30,000,000 psi

Elevation 000

L = -76,000 ton (compressive)
Percentage of steel = 0.6 %
A = 204.8 m^2

$\varepsilon = -76{,}000 / [204.8 \times ((21{,}100{,}000 \times 0.6\%) + (3{,}160{,}000 \times 99.4\%))] = -0.0001135$
$\varepsilon = -113.5$ micro-strain

Elevation 115

L = -29,000 ton (compressive)
Percentage of steel = 0.7 %
A = 96.8 m^2

$\varepsilon = -29{,}000 / [96.8 \times ((21{,}100{,}000 \times 0.7\%) + (3{,}160{,}000 \times 99.3\%))] = -0.00009118$
$\varepsilon = -91.18$ micro-strain

Elevation 228

L = -9,000 ton (compressive)
Percentage of steel = 1.05 %
A = 66.4 m^2

$\varepsilon = -9{,}000 / [66.4 \times ((21{,}100{,}000 \times 1.05\%) + (3{,}160{,}000 \times 98.95\%))] = -0.00004$
$\varepsilon = -40$ micro-strain

Elevation 247

L = -7,400 ton (compressive)
Percentage of steel = 0.65 %

$A = 58.08\ m^2$

$\varepsilon = -7{,}400 / [66.4 \times ((21{,}100{,}000 \times 0.65\%) + (3{,}160{,}000 \times 99.35\%))] = -0.0000388$
$\varepsilon = -38.8$ micro-strain

The following tables (Table 6.3 to 6.26) show the comparison between the measured strains (vibrating wire and fiber optic) to the theoretical strains. Actually, in the Solid (Table 6.3 to 6.6) it was not possible to calculate the theoretical strain value, so the comparison is only between the measured strains of the two types. In the other Tables 6.7 to 6.26 which correspond to the Shaft at different elevations, the theoretical and measured strains can be compared. The result of these comparisons is discussed in Chapter 7.

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Solid Northeast	Vibrating Wire	SM11	-11.5	kN
		SG13	-87.3	micro-strain
	Fiber Optic	DSG3	No reading	micro-strain
		DSM7	No reading	micro-strain

Table 6.3 Comparison of Fiber optic and VW readings in solid (N.E.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Solid Northwest	Vibrating Wire	SM12	-10.1	kN
		SG14	-53.1	micro-strain
	Fiber Optic	DSG4	No reading	micro-strain
		DSM8	No reading	micro-strain

Table 6.4 Comparison of Fiber optic and VW readings in solid (N.W.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Solid Southeast	Vibrating Wire	SM10	-11.7	kN
		SG12	-87.7	micro-strain
	Fiber Optic	DSG2	No reading	micro-strain
		DSM6	No reading	micro-strain

Table 6.5 Comparison of Fiber optic and VW readings in solid (S.E.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Solid Southwest	Vibrating Wire	SM9	-17.6	kN
		SG11	-188.5	micro-strain
	Fiber Optic	DSG1	-447.5	micro-strain
		DSM5	-294.0	micro-strain

Table 6.6 Comparison of Fiber optic and VW readings in solid (S.W.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Shaft ELV 000 Northeast	Vibrating Wire	SG17	-442.8	micro-strain
	Fiber Optic	DSG7	-244.5	micro-strain
Theoretical Value			-113.5	micro-strain

Table 6.7 Comparison of theoretical and measured strains in shaft, elv.000 (N.E.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Shaft ELV 000 Northwest	Vibrating Wire	SG18	-426.7	micro-strain
	Fiber Optic	DSG8	-178.5	micro-strain
Theoretical Value			-113.5	micro-strain

Table 6.8 Comparison of theoretical and measured strains in shaft, elv.000 (N.W.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Shaft ELV 000 Southeast	Vibrating Wire	SG16	-468.2	micro-strain
	Fiber Optic	DSG6	-309.0	micro-strain
Theoretical Value			-113.5	micro-strain

Table 6.9 Comparison of theoretical and measured strains in shaft, elv.000 (S.E.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Shaft ELV 000 Southwest	Vibrating Wire	SG15	-507.9	micro-strain
	Fiber Optic	DSG5	-260.5	micro-strain
Theoretical Value			-113.5	micro-strain

Table 6.10 Comparison of theoretical and measured strains in shaft, elv.000 (S.W.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Shaft ELV 115 Northeast	Vibrating Wire	SG21	-366.0	micro-strain
	Fiber Optic	DSG11	-277.0	micro-strain
Theoretical Value			-91.18	micro-strain

Table 6.11 Comparison of theoretical and measured strains in shaft, elv.115 (N.E.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Shaft ELV 115 Northwest	Vibrating Wire	SG22	-319.8	micro-strain
	Fiber Optic	DSG12	No reading	micro-strain
Theoretical Value			-91.18	micro-strain

Table 6.12 Comparison of theoretical and measured strains in shaft, elv.115 (N.W.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Shaft ELV 115 Southeast	Vibrating Wire	SG20	-351.9	micro-strain
	Fiber Optic	DSG10	-331.0	micro-strain
Theoretical Value			-91.18	micro-strain

Table 6.13 Comparison of theoretical and measured strains in shaft, elv.115 (S.E.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 115 Southwest	Vibrating Wire	SG19	-324.7	micro-strain
	Fiber Optic	DSG9	23.5	micro-strain
Theoretical Value			-91.18	micro-strain

Table 6.14 Comparison of theoretical and measured strains in shaft, elv.115 (S.W.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 228 Northeast	Vibrating Wire	SG25	-217.4	micro-strain
	Fiber Optic	DSG15	-161.0	micro-strain
Theoretical Value			-40	micro-strain

Table 6.15 Comparison of theoretical and measured strains in shaft, elv.228 (N.E.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 228 Northwest	Vibrating Wire	SG26	-194.1	micro-strain
	Fiber Optic	DSG16	-245.0	micro-strain
Theoretical Value			-40	micro-strain

Table 6.16 Comparison of theoretical and measured strains in shaft, elv.228 (N.W.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 228 Southeast	Vibrating Wire	SG24	-181.4	micro-strain
	Fiber Optic	DSG14	-249.0	micro-strain
Theoretical Value			-40	micro-strain

Table 6.17 Comparison of theoretical and measured strains in shaft, elv.228 (S.E.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 228 Southwest	Vibrating Wire	SG23	-162.1	micro-strain
	Fiber Optic	DSG13	-220.0	micro-strain
Theoretical Value			-40	micro-strain

Table 6.18 Comparison of theoretical and measured strains in shaft, elv.228 (S.W.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 247 Northeast	Vibrating Wire	SG29	-55.5	micro-strain
	Fiber Optic	DSG19	116.0 (without correction)	micro-strain
Theoretical Value			-38.8	micro-strain

Table 6.19 Comparison of theoretical and measured strains in shaft, elv.247 (N.E.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 247 Northwest	Vibrating Wire	SG30	-42.7	micro-strain
	Fiber Optic	DSG20	116 (without correction)	micro-strain
Theoretical Value			-38.8	micro-strain

Table 6.20 Comparison of theoretical and measured strains in shaft, elv.247 (N.W.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 247 Southeast	Vibrating Wire	SG28	-40.5	micro-strain
	Fiber Optic	DSG18	0.0 (without correction)	micro-strain
Theoretical Value			-38.8	micro-strain

Table 6.21 Comparison of theoretical and measured strains in shaft, elv.247 (S.E.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 247 Southwest	Vibrating Wire	SG27	-56.2	micro-strain
	Fiber Optic	DSG17	No reading	micro-strain
Theoretical Value			-38.8	micro-strain

Table 6.22 Comparison of theoretical and measured strains in shaft, elv.247 (S.W.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 303 Northeast	Vibrating Wire	SG33	-10.5	micro-strain
	Fiber Optic	DSG23	299.0	micro-strain

Table 6.23 Comparison of Fiber optic and VW readings in shaft, elv.303 (N.E.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 303 Northwest	Vibrating Wire	SG34	-20.5	micro-strain
	Fiber Optic	DSG24	89.0	micro-strain

Table 6.24 Comparison of Fiber optic and VW readings in shaft, elv.303 (N.W.)

Location	Instrument Type	Instrument Name	Last Reading(Corrected with No-Stress Gage value if applicable)	Unit
Shaft ELV 303 Southeast	Vibrating Wire	SG32	-21.6	micro-strain
	Fiber Optic	DSG22	237.0	micro-strain

Table 6.25 Comparison of Fiber optic and VW readings in shaft, elv.303 (S.E.)

Location	**Instrument Type**	**Instrument Name**	**Last Reading(Corrected with No-Stress Gage value if applicable)**	**Unit**
Shaft ELV 303 Southwest	Vibrating Wire	SG31	-6.4	micro-strain
	Fiber Optic	DSG21	192.0	micro-strain

Table 6.26 Comparison of Fiber optic and VW readings in shaft, elv.303 (S.W.)

CHAPTER 7

Conclusion and recommendation

7.1 Conclusion

Table 7.1 is a summary according to the different types of instruments and Table 7.2 is a detailed table showing all the instruments and the judgment on the performance. In Table 7.1 two more columns are added with question marks (?), meaning that there is not enough data to confirm the status of the instrument, but it has been put the best evaluation on its working status. Also the values highlighted in yellow are wrong readings.

Comparison of theoretical to measured strain values presented in Chapter 6 remarkably implies that the theoretical and measured values are in the same range of magnitude, although it should be noted that the two types of embedment strain gages (fiber optic and vibrating wire) have higher strain values than the calculated theoretical values.

In the steel, it could be seen the same observation, namely that the measured values are higher than the calculated strain. These observations are very noticeable at the three elevations 000, 115, 228 m. For higher elevations, the measured strains are probably less representative as there were very few readings made.

According to the designer [20], it can be expected that the strain values should become more equal in the steel and concrete, meaning that the plane strain situation should become more true with time. It is certainly a strong recommendation to continue reading of all the instruments that are noted as working in Table 7.1 in order to confirm this redistribution of strain between the steel and the concrete.

It was the first real attempt, in the case of a tower, for comparing conventional instruments with fiber optic sensors and certainly some difficulties exist, for example, the lack of reading at higher elevations in the shaft. Therefore, the future observations would definitely give more information.

Instrument Type	**Working**	**Not Working**	**Working (?)**	**Not Working (?)**
VW Rebar Stress Meter (SM)	8 (66%)	1 (9%)	3 (25%)	0
VW Strain Gage (SG)	30 (88%)	1 (3%)	3 (9%)	0 (0%)
No Stress Gage (NSG)	5 (100%)	0	0	0
Dynamic Embedment Strain Gage (DSG)	18 (75%)	2 (8%)	4 (17%)	0
No Stress Gage (NDSG)	4 (75%)	0	1 (25%)	0
VW Total Pressure Cell (TPC)	7 (87%)	1(13%)	0	0
Dynamic Rebar Stress Meter (DSM)	15 (63%)	2 (8%)	3 (13%)	4 (16%)
Total	**87 (78 %)**	**7 (6 %)**	**14 (13%)**	**4 (3 %)**

Table 7.1 Performance of Instruments

Fig. No	Instrument Type	Instrument Name	Working?	Last Reading (Corrected with No-Stressed Gage value if applicable)	Unit
6.5	VW Rebar Stress Meter(SM)	SM1	Yes	-10.3	kN
		SM2	Yes	-9.1	kN
		SM3	Yes	-8.2	kN
		SM4	Yes	-12.2	kN
		SM5	Yes	-28.5	kN
		SM6	No	No reading	kN
		SM7	Yes	-29.1	kN
		SM8	Yes	-34.4	kN
6.6	VW Strain Gage (SG)	SG1	Yes	-216.1	micro-strain
		SG2	Yes	-463.0	micro-strain
		SG3	Yes	-243.2	micro-strain
		SG4	Yes	-281.9	micro-strain
		SG5	Yes	-241.8	micro-strain
		SG6	Yes	131.0	micro-strain
		SG7	Yes	-53.5	micro-strain
		SG8	No	No reading	micro-strain
		SG9	Yes	-14.4	micro-strain
		SG10	Yes	-157.3	micro-strain
6.7	VW Total Pressure Cell (TPC)	TPC1	Yes	37.6	kPa
		TPC2	Yes	21.8	kPa
		TPC3	Yes	17.3	kPa
		TPC4	Yes	46.0	kPa
		TPC5	No	No reading	kPa
		TPC6	Yes	-20.4	kPa
		TPC7	Yes	69.6	kPa
		TPC8	Yes	117.0	kPa
68	Dynamic (FO) Embedment Strain Gage (DSG)	NDSG1	Yes	134.5	micro-strain
		DSG5	Yes	-260.5	micro-strain
		DSG6	Yes	-309.0	micro-strain
		DSG7	Yes	-244.5	micro-strain
		DSG8	Yes	-178.5	micro-strain
6.9	Dynamic (FO) Rebar Stress Meter (DSM)	DSM9	Yes	117.0	micro-strain
		DSM10	No	No reading	micro-strain
		DSM11	Yes	-12.0	micro-strain
		DSM12	No?	-845.0	micro-strain

Table 7.2 Summary (continued)

Fig. No	Instrument Type	Instrument Name	Working?	Last Reading (Corrected with No-Stressed Gage value if applicable)	Unit
6.10	VW Strain Gage (SG)	NSG1	Yes	73.1	micro-strain
		SG15	Yes	-507.9	micro-strain
		SG16	Yes	-468.2	micro-strain
		SG17	Yes	-442.8	micro-strain
		SG18	Yes	-426.7	micro-strain
6.11	Dynamic(FO)Embedment Strain Gage(DSG)	NDSG2	Yes	117.5	micro-strain
		DSG9	Yes	23.5	micro-strain
		DSG10	Yes	-331.0	micro-strain
		DSG11	Yes	-277.0	micro-strain
		DSG12	No	No reading	micro-strain
6.12	Dynamic (FO) Rebar Stress Meter(DSM)	DSM13	Yes	-155.5	micro-strain
		DSM14	No	No reading	micro-strain
		DSM15	Yes	31.0	micro-strain
		DSM16	Yes	-61.5	micro-strain
6.13	VW Strain Gage(SG)	NSG2	Yes	50.6	micro-strain
		SG19	Yes	-324.7	micro-strain
		SG20	Yes	-351.9	micro-strain
		SG21	Yes	-366.0	micro-strain
		SG22	Yes	-319.8	micro-strain
6.14	Dynamic (FO) Embedment strain Gage(DSG)	NDSG3	Yes	-26.0	micro-strain
		DSG13	Yes	-220.0	micro-strain
		DSG14	Yes	-249.0	micro-strain
		DSG15	Yes	-161.0	micro-strain
		DSG16	Yes	-245.0	micro-strain
6.15	Dynamic (FO) Rebar Stress Meter(DSM)	DSM17	Yes	-224.0	micro-strain
		DSM18	No?	**-1180.0**	micro-strain
		DSM19	Yes	96.0	micro-strain
		DSM20	Yes	-53.0	micro-strain
6.16	VW Strain Gage(SG)	NSG3	Yes	-156.1	micro-strain
		SG23	Yes	-162.1	micro-strain
		SG24	Yes	-181.4	micro-strain
		SG25	Yes	-217.4	micro-strain
		SG26	Yes	-194.1	micro-strain
6.17	Dynamic(FO)Embedment Strain Gage(DSG)	NDSG4	Yes?	**-2208.0**	micro-strain
		DSG17	No	No reading	micro-strain
		DSG18	Yes?	0.0	micro-strain (without correction)
		DSG19	Yes	116.0	micro-strain (without correction)
		DSG20	Yes	116.0	micro-strain (without correction)

Fig. No	Instrument Type	Instrument Name	Working?	Last Reading (Corrected with No-Stressed Gage value if applicable)	Unit
6.18	Dynamic(FO)Rebar Stress Meter(DSM)	DSM21	Yes	132.0	micro-strain
		DSM22	Yes	104.0	micro-strain
		DSM23	Yes	124.0	micro-strain
		DSM24	No?	No reading	micro-strain
6.19	VW Strain Gage(SG)	NSG4	Yes	-14.2	micro-strain
		SG27	Yes	-56.2	micro-strain
		SG28	Yes	-40.5	mcrostrain
		SG29	Yes	-55.5	micro-strain
		SG30	Yes	-42.7	micro-strain
6.20	Dynamic(FO) Embedment Strain Gage(DSG)	NDSG5	Yes	86.0	micro-strain
		DSG21	Yes	192.0	micro-strain
		DSG22	Yes	237.0	micro-strain
		DSG23	Yes	299.0	micro-strain
		DSG24	Yes	89.0	micro-strain
6.21	Dynamic(FO)Rebar Stress Meter(DSM)	DSM25	Yes	89.0	micro-strain
		DSM26	No?	**-2504.0**	micro-strain
		DSM27	Yes	91.0	micro-strain
		DSM29	Yes	124.0	micro-strain
6.22	VW Strain Gage(SG)	NSG5	Yes	-66.6	micro-strain
		SG31	Yes	-6.4	micro-strain
		SG32	Yes	-21.6	micro-strain
		SG33	Yes	-10.5	micro-strain
		SG34	Yes	-20.5	micro-strain
6.23	Dynamic(FO)Embedment Strain Gage(DSG)	DSG1	Yes	-447.5	micro-strain
		DSG2	Yes?	No reading	micro-strain
		DSG3	Yes?	No reading	micro-strain
		DSG4	Yes?	No reading	micro-strain
6.24	Dynamic(FO)Rebar Stress Meter(DSM)	DSM5	Yes	-294.0	micro-strain
		DSM6	Yes?	No reading	micro-strain
		DSM7	Yes?	No reading	micro-strain
		DSM8	Yes?	No reading	micro-strain
6.25	VW Stress Meter(SM)	SM9	Yes	-17.6	kN
		SM10	Yes?	-11.7	kN
		SM11	Yes?	-11.5	kN
		SM12	Yes?	-10.1	kN
6.26	VW Strain Gage(SG)	SG11	Yes	-188.5	micro-strain
		SG12	Yes?	-87.7	micro-strain
		SG13	Yes?	-87.3	micro-strain
		SG14	Yes?	-53.1	micro-strain

7.2 Recommendation

It is recommended for further future research to automate the readings with data acquisition systems so that automatic readings could be made for the long term behavior study of the tower and the possibility of reading of instruments during extreme events such as an earthquake.

Automating readings would also help to collect more points in order to observe gradual transfer of strain from concrete to steel.

It would also be a good recommendation to measure temperature at different elevations in order to correlate the fluctuation of strain values between different seasons and time of the day to the actual temperature.

Normally these changes of temperature are accounted for use of the no-stress gages but recording of temperature would give additional useful information on the structural behavior of the tower.

As there was a limitation of variety for fiber optic sensors in Tehran Tower, it is recommended that in the future, more variety of fiber optic sensors undergo comparison.

REFERENCES

1. **Arthur, J.R.F.** (1974), "Principles of measurement," Symposium on Field Instrumentation, Field Instrumentation in Geotechnical Engineering, London, pp. 510-516.
2. **ASCE TASK Committee** (2000), "Guidelines for instrumentation and measurements for monitoring dam performance," American Society of Civil Engineering
3. **Ballivy, G., Bois, A.P., Ghorbal, A., Hajiabdolmajid, R. and Saleh, K.** (2003), "Measurements of deformation and stress variations in mine pillars," CIM Bulletin, Vol. 96, No. 1071, pp. 49-53.
4. **Ballivy, G., Saleh, K. and Bois, A.P.** (1991), "Monitoring of a mine pillar by CIUS," 3rd International Symposium on Field Measurements in Geomechanics, Oslo, Norway, pp.13-21.
5. **Ballivy, G., Saleh, K., Bois, A.P., Ghorbal, A. and Hajiabdolmajid, V.** (1995), "Measurements of deformations and stress variations in mine pillars under static and dynamic conditions," Proceedings of Rock Mechanics and Strata Control Session , 97th CIM Annual Meeting, Halifax, Canada, pp. 267-276.
6. **Belleville, C. and Duplain, G.** (1993), "White-light interferometric multimode fiber-optic strain sensors, " Optics Letters, Vol. 18, No. 1, pp. 78-80.

7. **Benmokrane, B., Rahman, H., Mukhopadhyaya, P., Masmoudi, R., Chekired, M., Nicole, J.F. and El-Safty, A.** (2000) , "Use of fiber reinforced polymer reinforcement integrated with fiber optic sensors for concrete bridge deck slab construction," Canadian Journal of Civil Engineering, Vol. 27, No. 5, pp. 928-940.
8. **Bois, A.P., Ballivy, G. and Saleh, K.** (1994) , "Monitoring stress changes in three dimensions using cylindrical cell," international journal of Rock Mechanics and Mining Science & Geomechanics ISRM, Vol.31, No. 6, pp. 707-718.
9. **Bordes, J.L. and Debreuille, P.J.** (1985), "Some facts about long-term reliability of vibrating wire instruments," Transportation Research Record, No. 1004, pp. 20-26.
10. **Choquet, P., Juneau, F. and Besseette, J.** (2000), "New generation of Fabry-Perot fiber optic sensors for monitoring of structures," Proceedings of SPIE, the International Society for Optical Engineering, Vol. 3986, pp. 418-426.
11. **Choquet, P., Juneau, F., Debreuille, P.J. and Bessette, J.** (1999), "Reliability, long-term stability and gage performance of vibrating wire sensors with reference to case histories," Proceedings of the 5th International Symposium on Field Measurements in Geomechanics, Singapore.
12. **Choquet, P., Leroux, R. and Juneau, F.** (1997), "New Fabry-Perot fiber optic sensors for structural and geotechnical monitoring applications," Transportations Research Record, No. 1596, pp. 39-44.

13. **Choquet, P., Quirion, M. and Juneau, F.** (2000), “Advances in Fabry-Perot fiber optic sensors and instruments for geotechnical monitoring,” Geotechnical News, Vol. 18, No. 1, pp. 35-40.

14. **Desai, H.** (1982), “Construction practices and instrumentation in geotechnical engineering,” Proceedings of the Conference Practices and Instrumentation in Geotechnical Engineering, Surat, India, 20-30 Dec. 1982 / edited by Mahesh Desai.

15. **Dibiagio, E.** (1988), “More information, reduced costs, better design and improved safety through instrumentation,” Norwegian Geotechnical Inst., Publikasion-Norges Geotekniske Institutt, No. 175, 1988, 16p.

16. **Dibiagio, E. and Myrvoll, F.** (1986), “Instrumentation and Instrumentation techniques used to monitor the performance of Norwegian embankment dams,” Norwegian Geotechnical Inst., Publikasion-Norges Geotekniske Institutt, No. 165, 1986, 14p.

17. **Dunnicliff, J.** (1988), “Geotechnical Instrumentation for Monitoring Field Performance,” John Wiley and Sons.

18. **Goff, D.R.** (1999), “Fiber optic reference guide: a practical guide to the technology,” Edited by Kimberly S. Hansen.

19. **Hanna, T.H.** (1989), “Field Instrumentation in Geotechnical Engineering,” Trans Tech Publications, Clausthal-Zellerfeld, F.R. Germany.

20. **Knoll, F.** (2003), Personal Communication, Nicolet Chartrand Knoll Ltd. Structural Engineer, Montréal, Québec, Canada.

21. **Kulhawy, F.H.** (1981), "Recent development in geotechnical engineering for hydro projects: embedment dam instrument performance, Engineering geology aspect, Rock mechanics studies," Proceedings of three Sessions Sponsored by the Geotechnical Engineering Division at the ASCE International Convention, New York City.

22. **Larive, C., Joly, M., Dubois, J.P. and Choquet, P.** (1995), "Theoretical and experimental validation of the vibrating wire principle. Application to a low stiffness strainmeter for embedment in concrete," Proceedings of the 4th International symposium on Field Measurements in Geomechanics, Bergano, pp. 341-348.

23. **Londe, p.** (1982), "Concepts and instrumentation for improved monitoring," American Society of Civil Engineering, Journal of the Geotechnical Engineering Division, Vol. 108, No. GT6, pp. 820-834.

24. **McRae, J.B. and Simmonds, T.** (1991), "Long-term stability of vibrating wire instruments: one manufacturer's perspective," 3rd Proceedings of the International Symposium on Field Measurements in Geomechanics, Vol. 1, pp.283-293.

25. **Measures, R.M.** (1993), "Smart structure technology and its potential for civil engineering," Application of Fiber Optic Sensors in Engineering Mechanics, ASCE, New York, pp. 17-39.

26. **O'Rourke, T.D. and Cording, E.J.** (1975), "Measurement of strut loads by means of vibrating wire strain gages," Performance Monitoring for Geotechnical Construction, ASTM STP 584, American Society for Testing and Materials, pp. 58-77.

27. **Petrovsky, Mayron B.** (1989), "Instrumentation monitoring of small hydroelectric dams," Proceedings of the 51st American Power Conference, Vol. 51, pp. 1015-1020.

28. **Tunbridge, L.W. and Qien, K.** (1988), "The advantages of vibrating wire instruments in geomechanics," 2nd International Symposium on Field Measurements in Geomechanics, Balkema, Rotterdam, Vol. I, pp.3-16.

29. **U.S. Army Corps of Engineers** (1980), "Instrumentation for concrete structures," EM 1110-2-4300.

30. **U.S. Army Corps of Engineers** (1995), "Instrumentation of Embankment dams and Levees concrete structures," EM 1110-2-190800.

APPENDIX 1

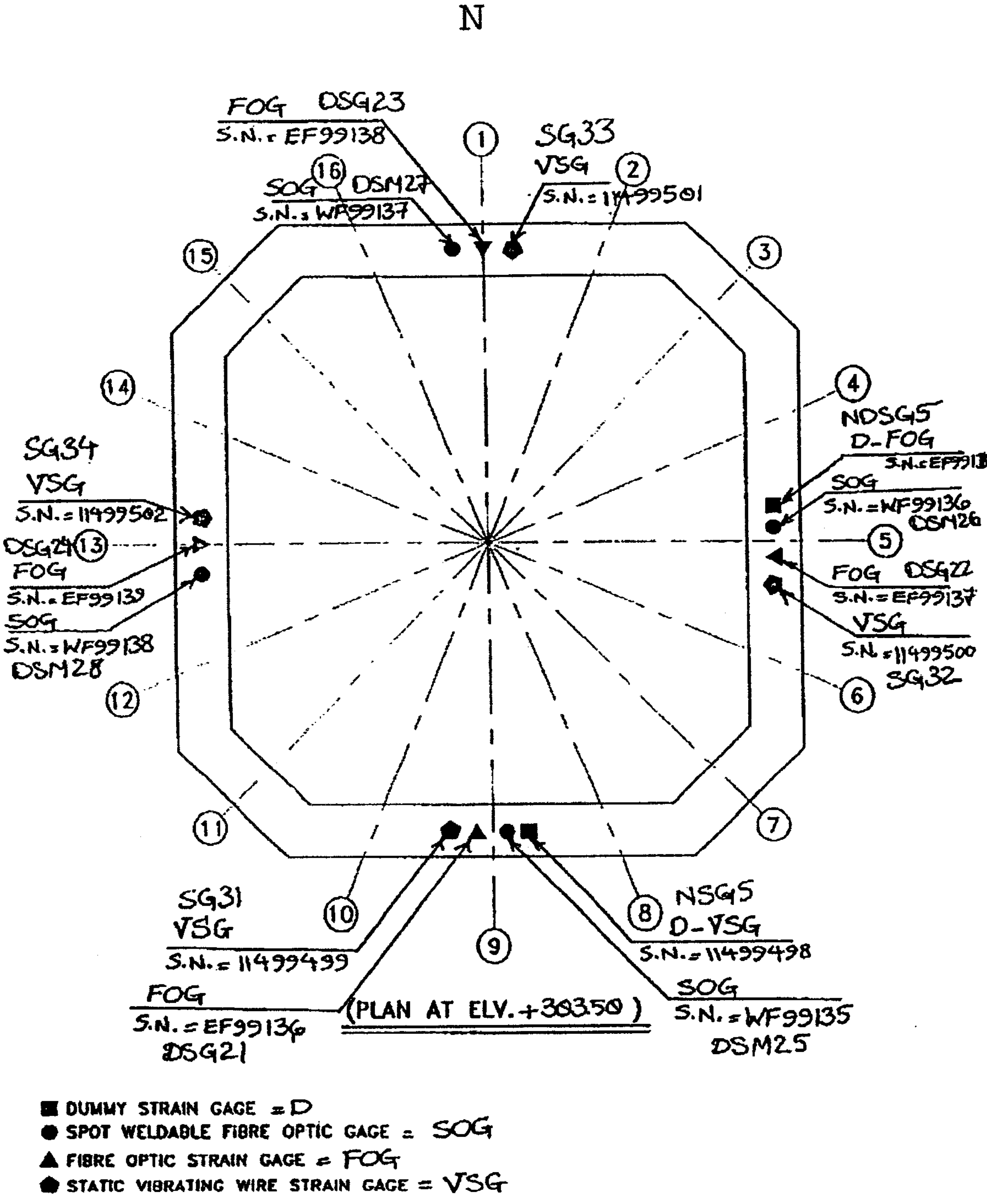
N
FOG DSG23
S.N. = EF99138
①
SG33
VSG
②
S.N. = 11499501
⑯
SOG DSM27
S.N. = WF99137
⑮
③
⑭
④
NDSG5
D-FOG
S.N. = EF99135
SOG
S.N. = WF99136
DSM26
⑤
FOG DSG22
S.N. = EF99137
VSG
S.N. = 11499500
SG32
⑥
SG34
VSG
S.N. = 11499502
DSG24 ⑬
FOG
S.N. = EF99139
SOG
S.N. = WF99138
DSM28
⑫
⑪
⑦
SG31
VSG
S.N. = 11499499
⑩
⑨
⑧
NSG5
D-VSG
S.N. = 11499498
FOG
S.N. = EF99136
DSG21
(PLAN AT ELV. +30350)
SOG
S.N. = WF99135
DSM25
■ DUMMY STRAIN GAGE = D
● SPOT WELDABLE FIBRE OPTIC GAGE = SOG
▲ FIBRE OPTIC STRAIN GAGE = FOG
⬟ STATIC VIBRATING WIRE STRAIN GAGE = VSG

Figure A1

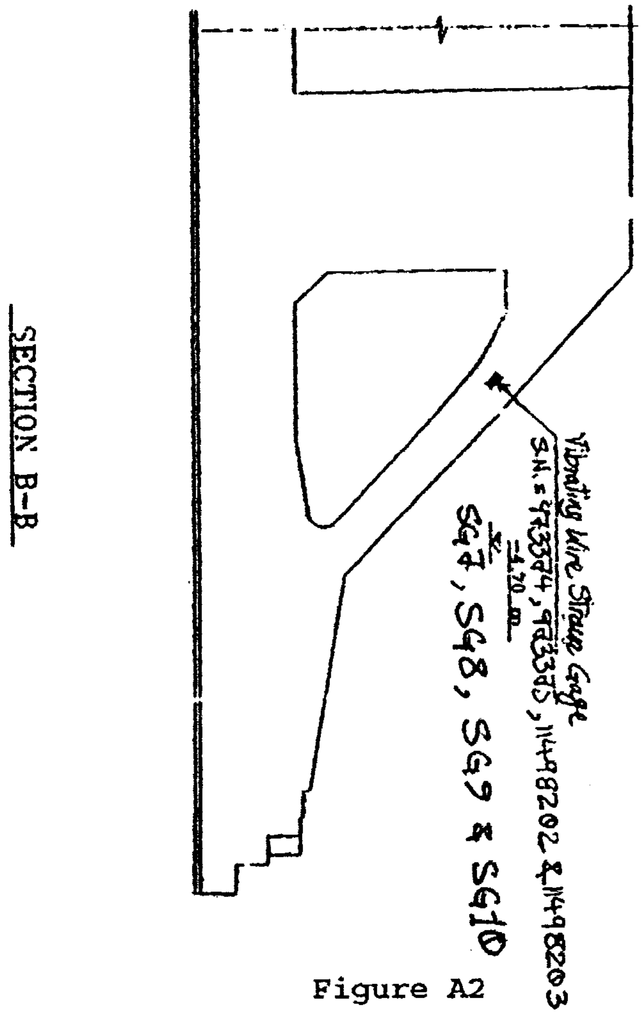

SECTION B-B
Vibrating Wire Strain Gage
S.N. = 973374, 973375, 11498202 & 11498203
x
= 4.70 m
SG7, SG8, SG9 & SG10

Figure A2

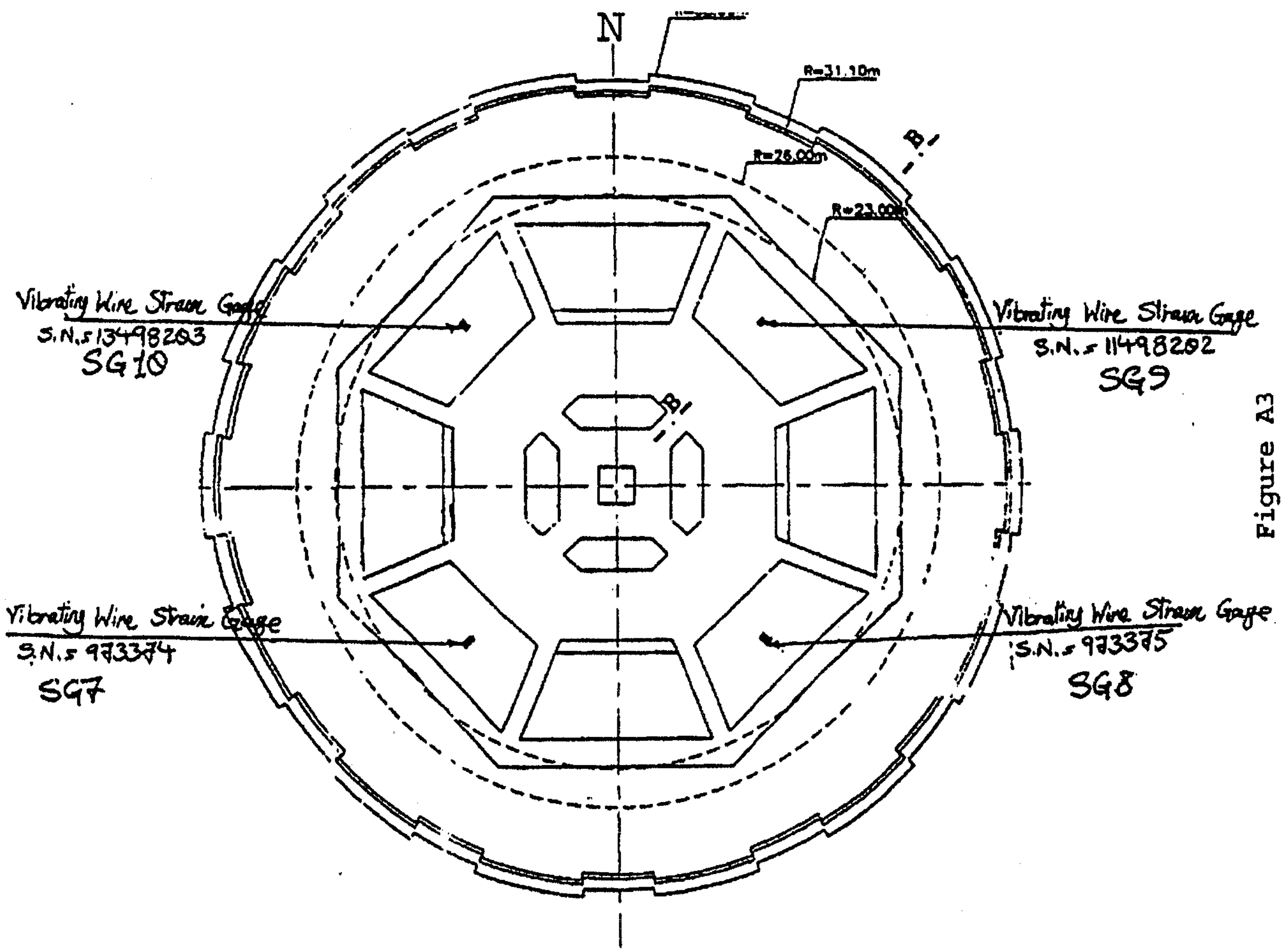


Figure A3

LOCATION OF STRAIN GAGE FOR MEASURING CONCRETE STRAIN
[illegible] FOUNDATION AND TRANSITION WALLS

Figure A3

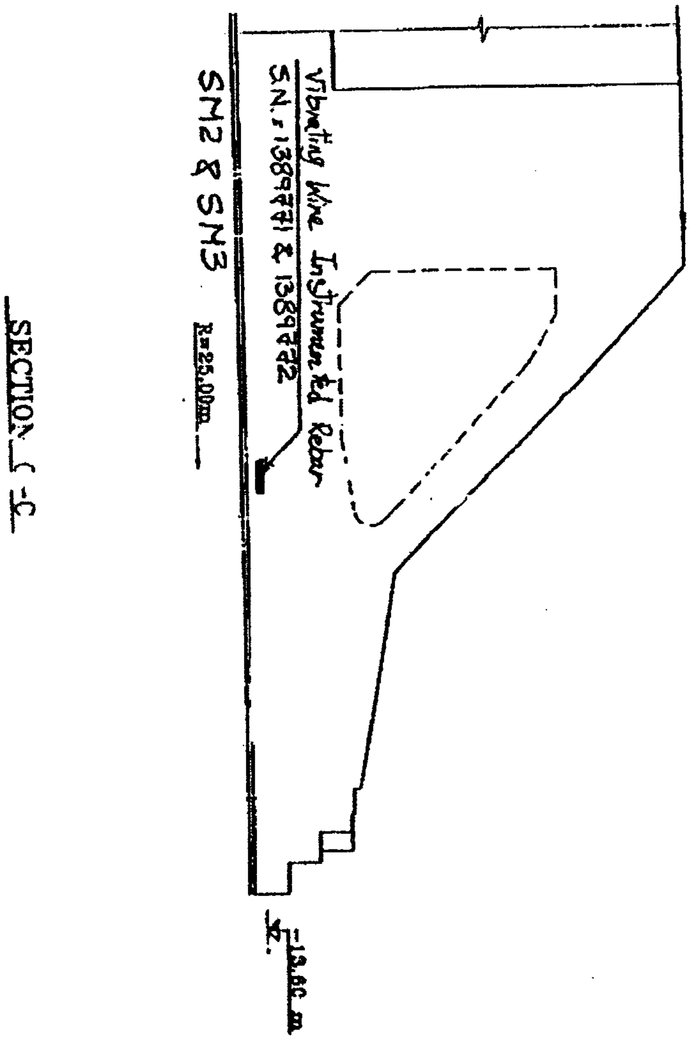

Vibrating Wire Instrumented Rebar
S.N.: 1389771 & 1389772
SM2 & SM3
R=25.00m
SECTION C-C
-13.60 m

Figure A4

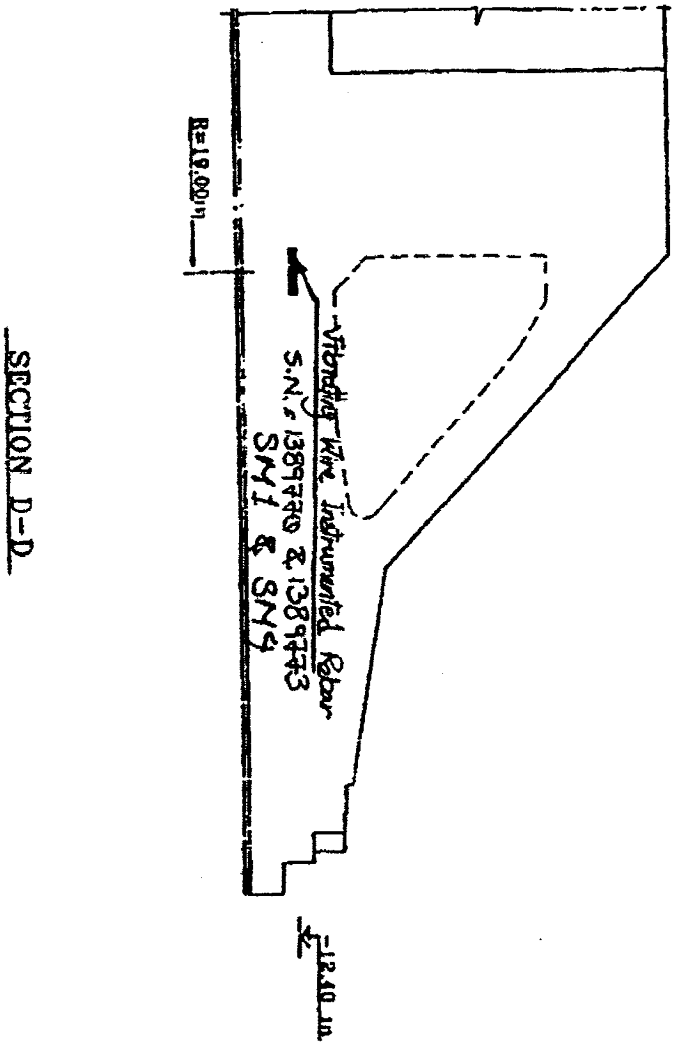
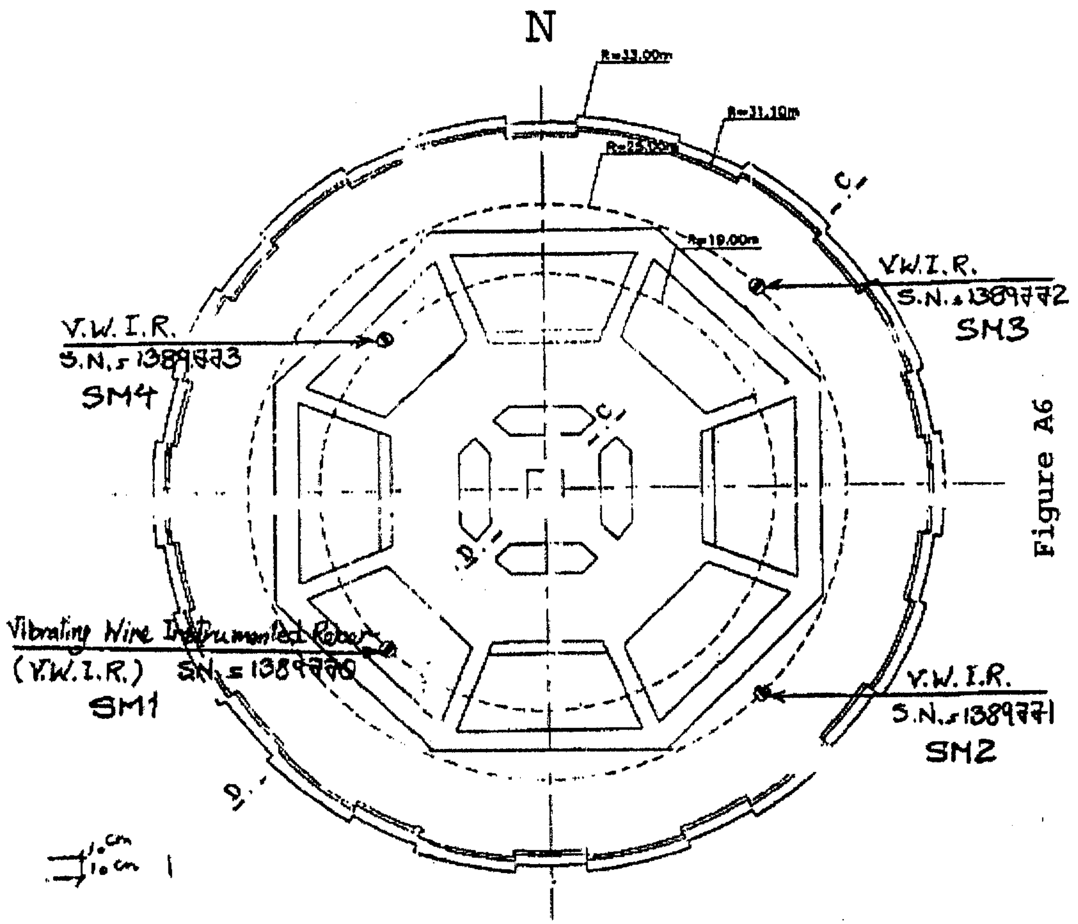

SECTION D-D
R=19.00 in
Vibrating Wire Instrumented Rebar
S.N.s 1389770 & 1389773
SM1 & SM4
℄ 12.40 in

Figure A5



LOCATION OF REBOR STRESSMETER FOR MEASURING STRESS IN REBORS
IN MAT FOUNDATION AND TRANSITION WALLS

Figure A6

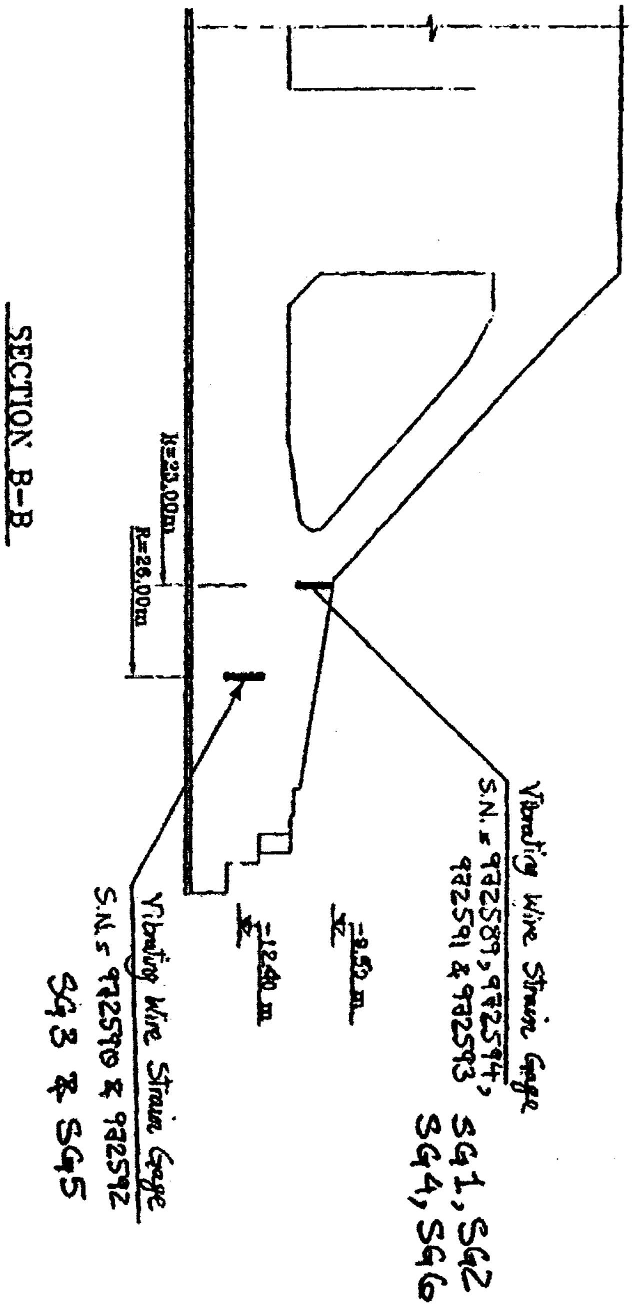

SECTION B-B
R=23.00m
R=26.00m
-9.50 m
-12.40 m
Vibrating Wire Strain Gage
S.N. = 972589, 972594, 972591 & 972593
SG1, SG2
SG4, SG6
Vibrating Wire Strain Gage
S.N. = 972590 & 972592
SG3 & SG5

Figure A7

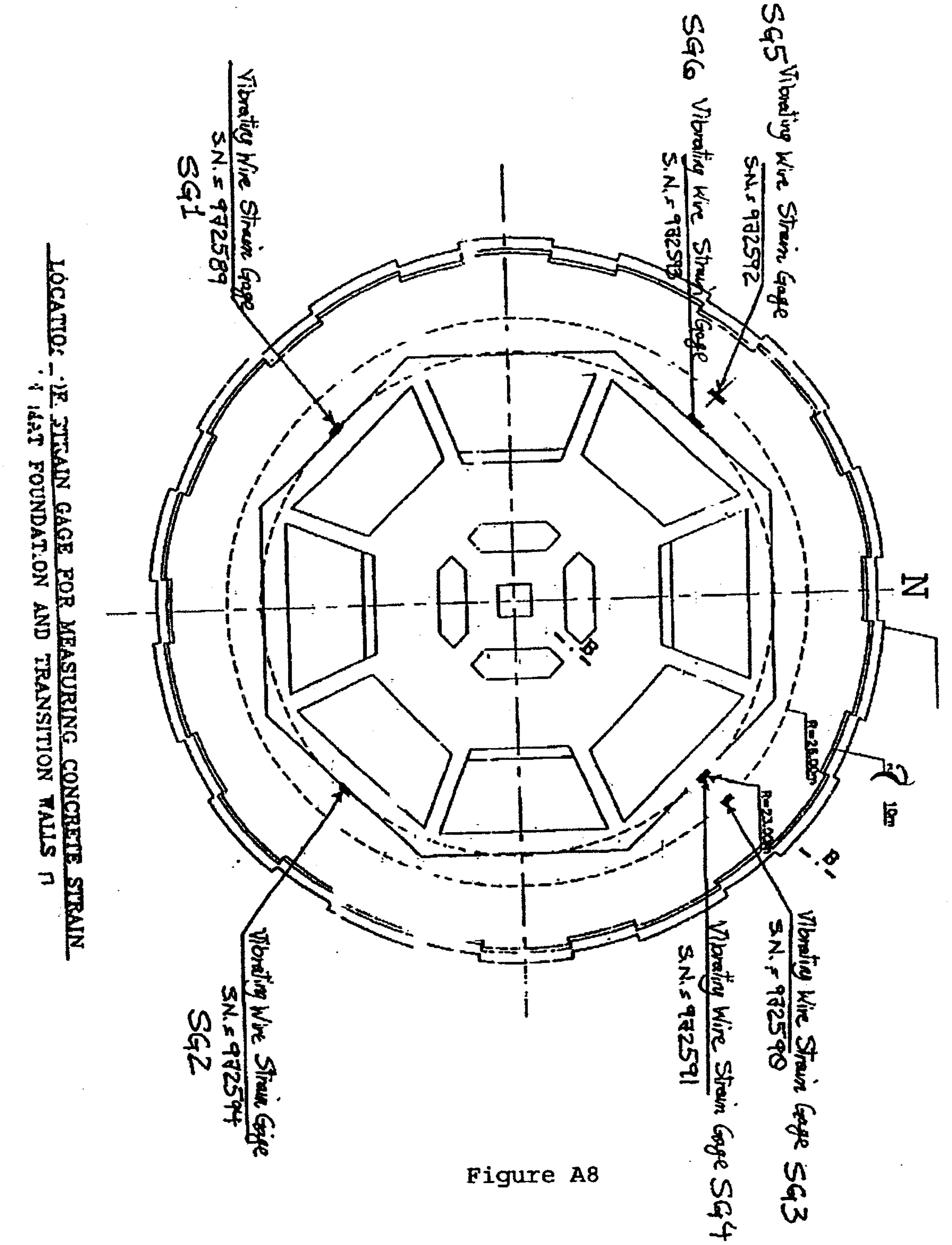

SG5 Vibrating Wire Strain Gage
S.N.= 972592
SG6 Vibrating Wire Strain Gage
S.N.= 972593
Vibrating Wire Strain Gage
S.N.= 972589
SG1
N
R=28.00m
R=23.00m
10m
B
B
Vibrating Wire Strain Gage SG3
S.N.= 972590
Vibrating Wire Strain Gage SG4
S.N.= 972591
Vibrating Wire Strain Gage
S.N.= 972594
SG2
LOCATION OF STRAIN GAGE FOR MEASURING CONCRETE STRAIN
IN MAT FOUNDATION AND TRANSITION WALLS

Figure A8

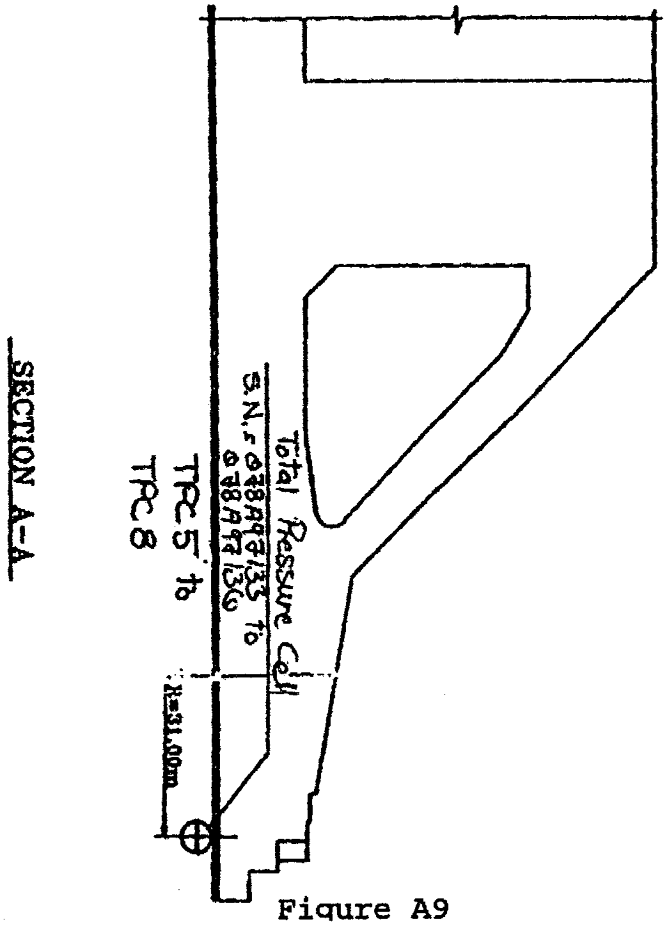

SECTION A-A
TPC 5 to
TPC 8
Total Pressure Cell
S.N. 078A97133 to
078A97136
H=31.00m

Figure A9

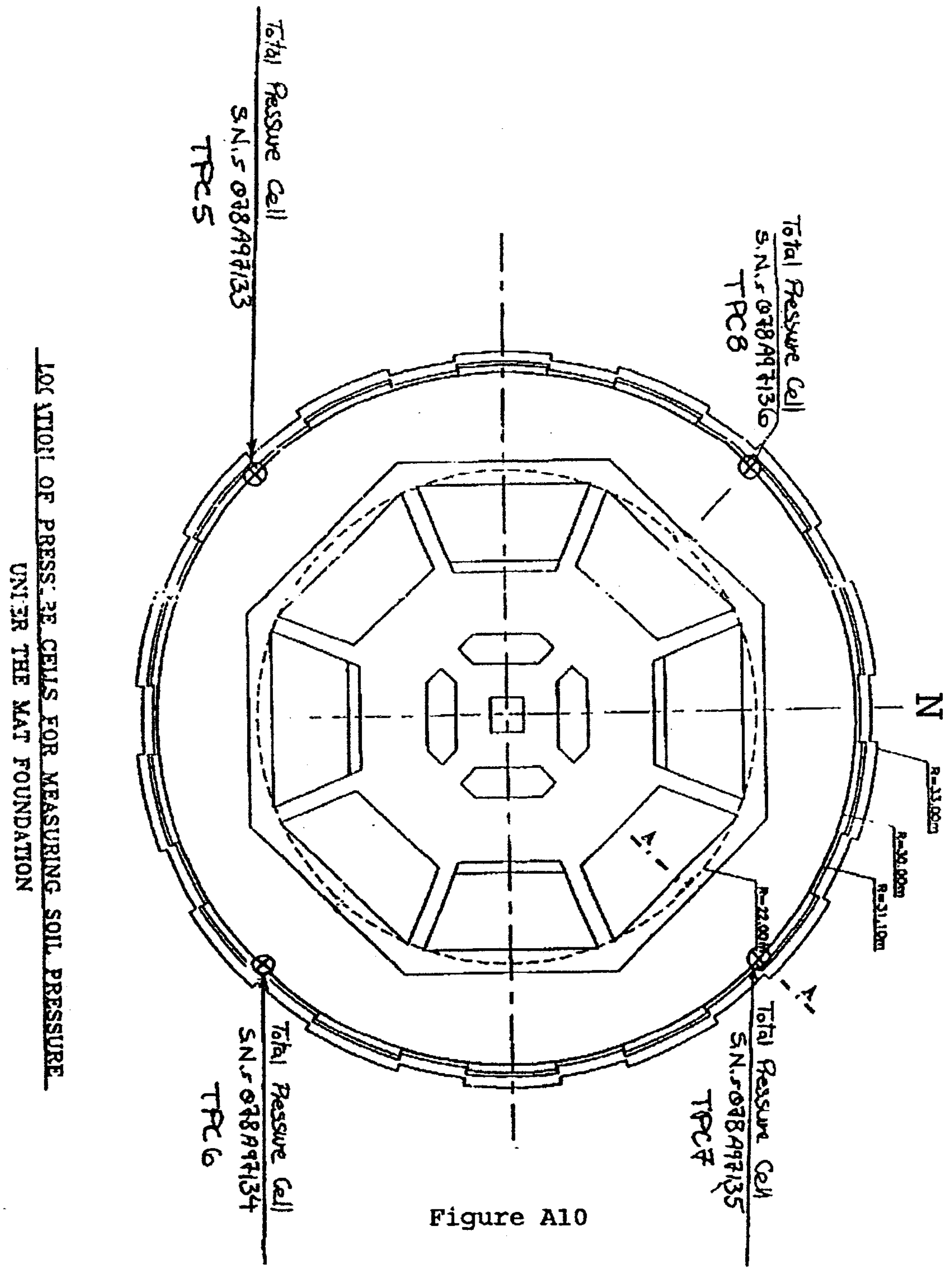

LOCATION OF PRESSURE CELLS FOR MEASURING SOIL PRESSURE
UNDER THE MAT FOUNDATION
N
R=33.00m
R=30.00m
R=31.10m
R=22.00m
A
A
Total Pressure Cell
S.N.s 078A97133
TPC5
Total Pressure Cell
S.N.s 078A97136
TPC8
Total Pressure Cell
S.N.s 078A97134
TPC6
Total Pressure Cell
S.N.s 078A97135
TPC7

Figure A10

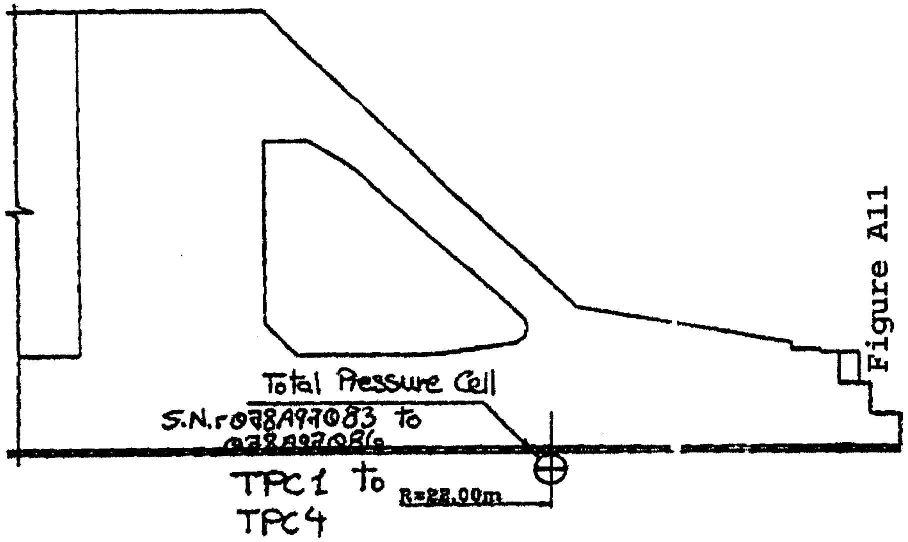
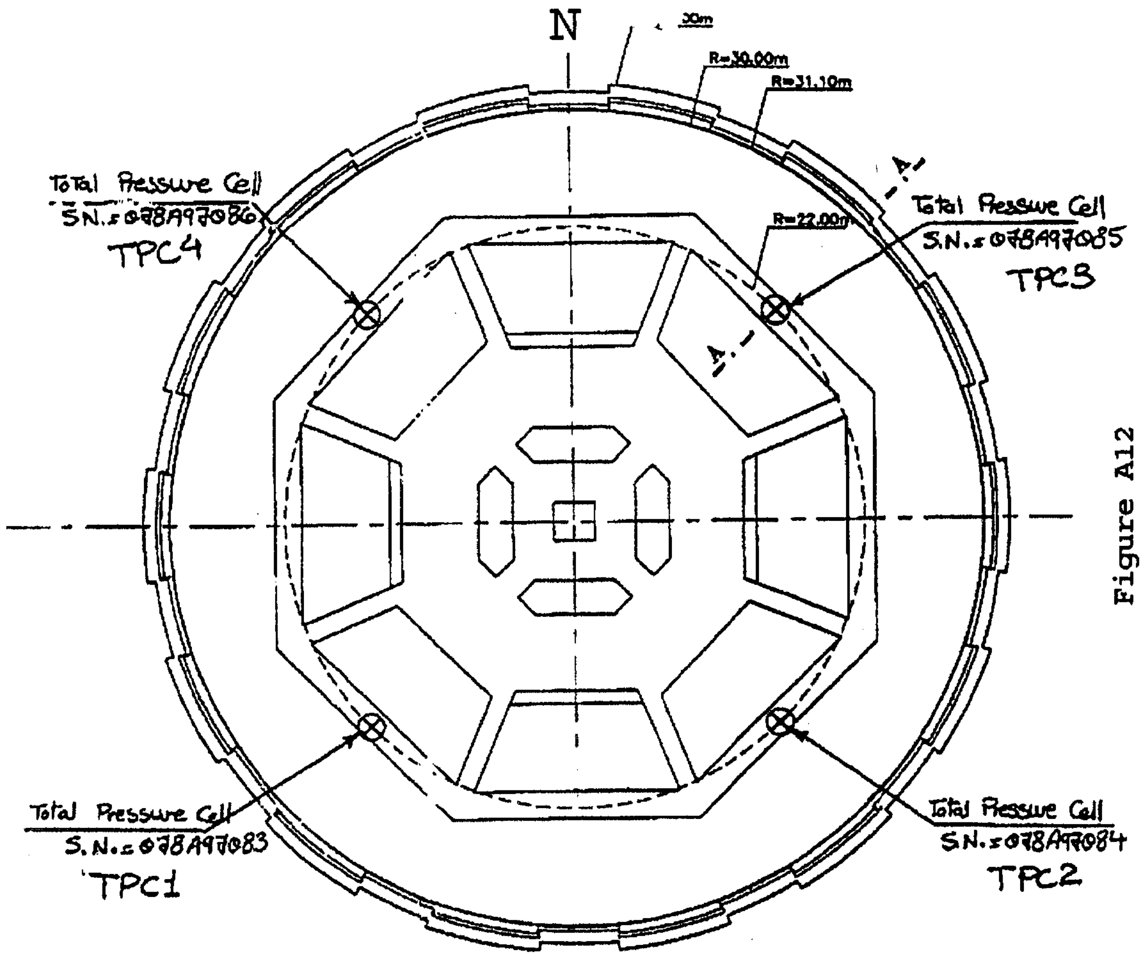


Figure A11

SECTION A-A



LOCATION OF PRESSURE CELLS FOR MEASURING SOIL PRESSURE
UNDER THE MAT FOUNDATION

Figure A12

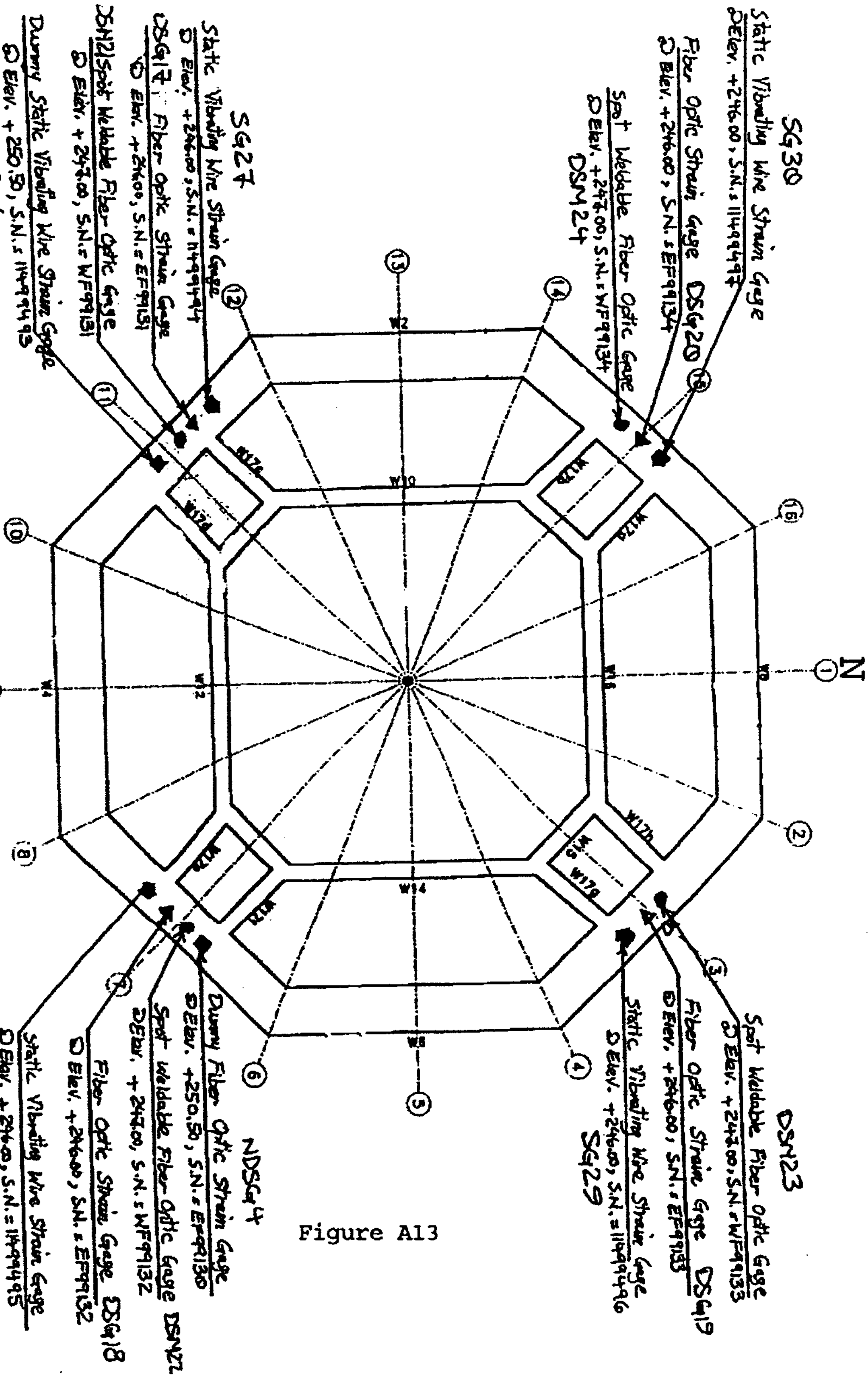

N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
W0
W2
W4
W6
W10
W12
W14
W16
W17a
W17b
W17c
W17d
W17e
W17f
W17g
W17h
SG30
Static Vibrating Wire Strain Gage
① Elev. +246.00, S.N.=11499497
Fiber Optic Strain Gage DSG20
① Elev. +246.00, S.N.=EF99134
Spot Weldable Fiber Optic Gage
① Elev. +247.00, S.N.=WF99134
DSM24
SG27
Static Vibrating Wire Strain Gage
① Elev. +246.00, S.N.=11499494
DSG17 Fiber Optic Strain Gage
① Elev. +246.00, S.N.=EF99131
DSM21 Spot Weldable Fiber Optic Gage
① Elev. +247.00, S.N.=WF99131
Dummy Static Vibrating Wire Strain Gage
① Elev. +250.50, S.N.=11499493
NSG4
DSM23
Spot Weldable Fiber Optic Gage
① Elev. +247.00, S.N.=WF99133
Fiber Optic Strain Gage DSG19
① Elev. +246.00, S.N.=EF99133
Static Vibrating Wire Strain Gage
① Elev. +246.00, S.N.=11499496
SG29
NDSG4
Dummy Fiber Optic Strain Gage
① Elev. +250.50, S.N.=EF99130
Spot Weldable Fiber Optic Gage DSM22
① Elev. +247.00, S.N.=WF99132
Fiber Optic Strain Gage DSG18
① Elev. +246.00, S.N.=EF99132
Static Vibrating Wire Strain Gage
① Elev. +246.00, S.N.=11499495
SG28

Figure A13

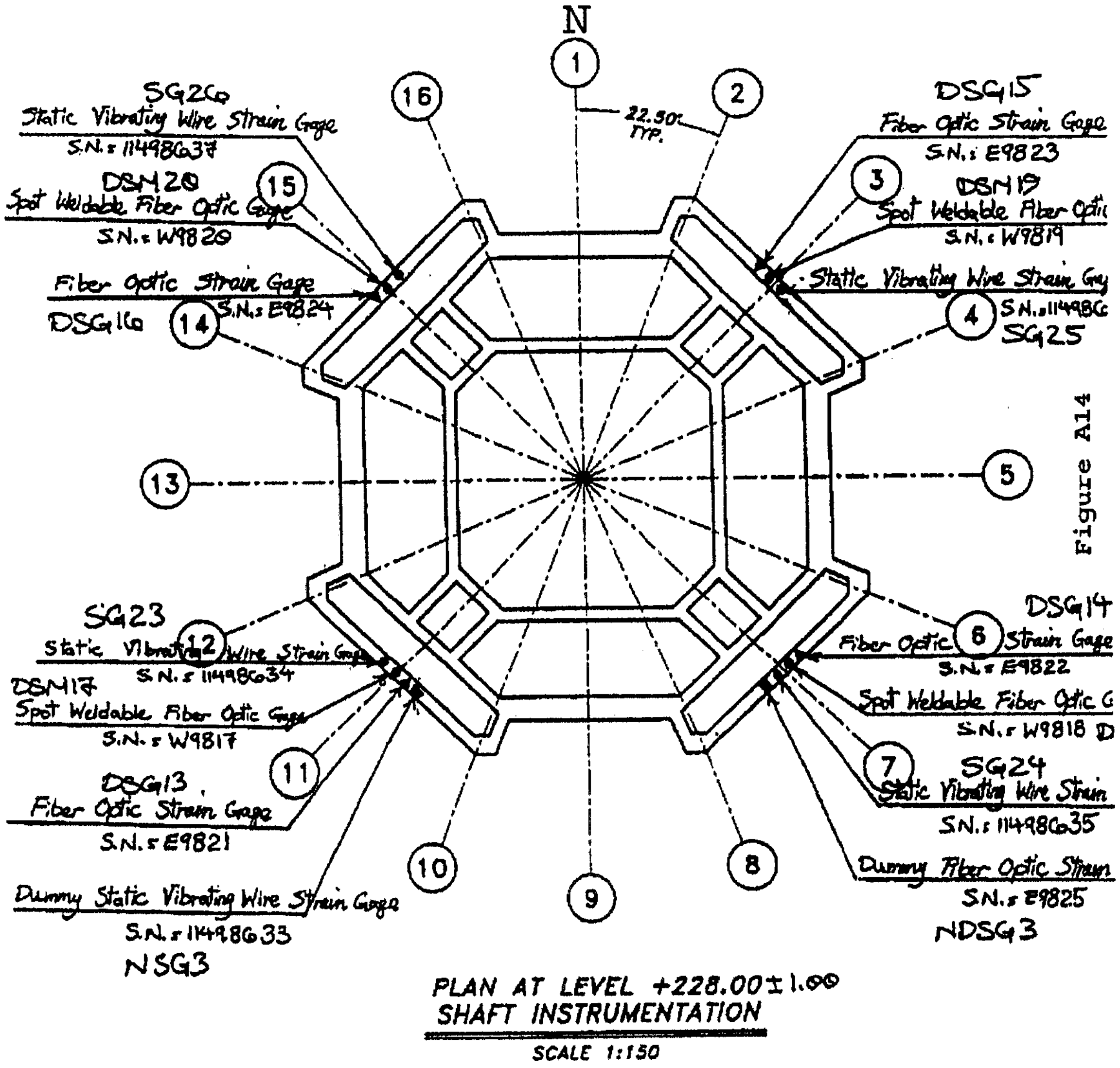
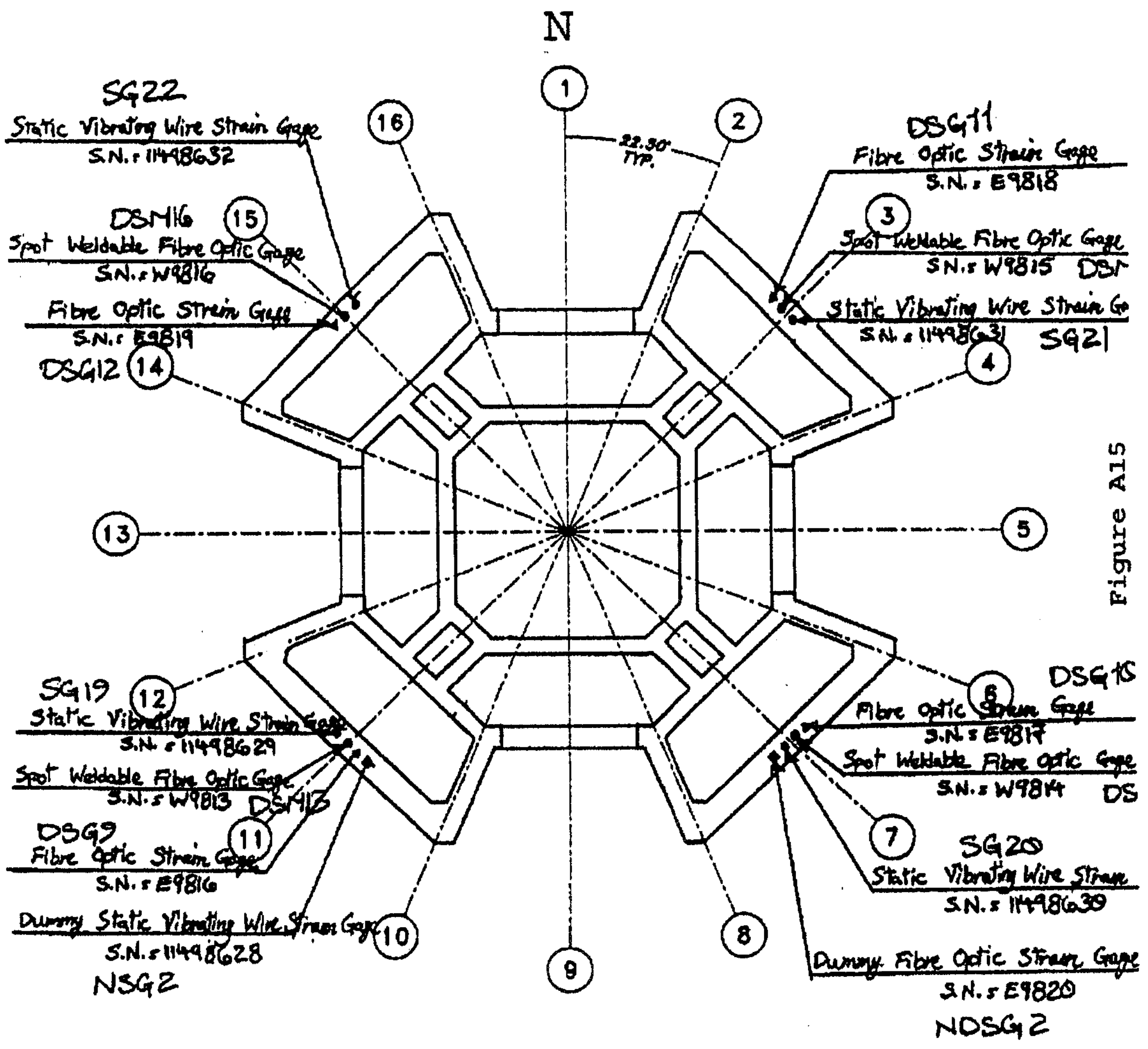
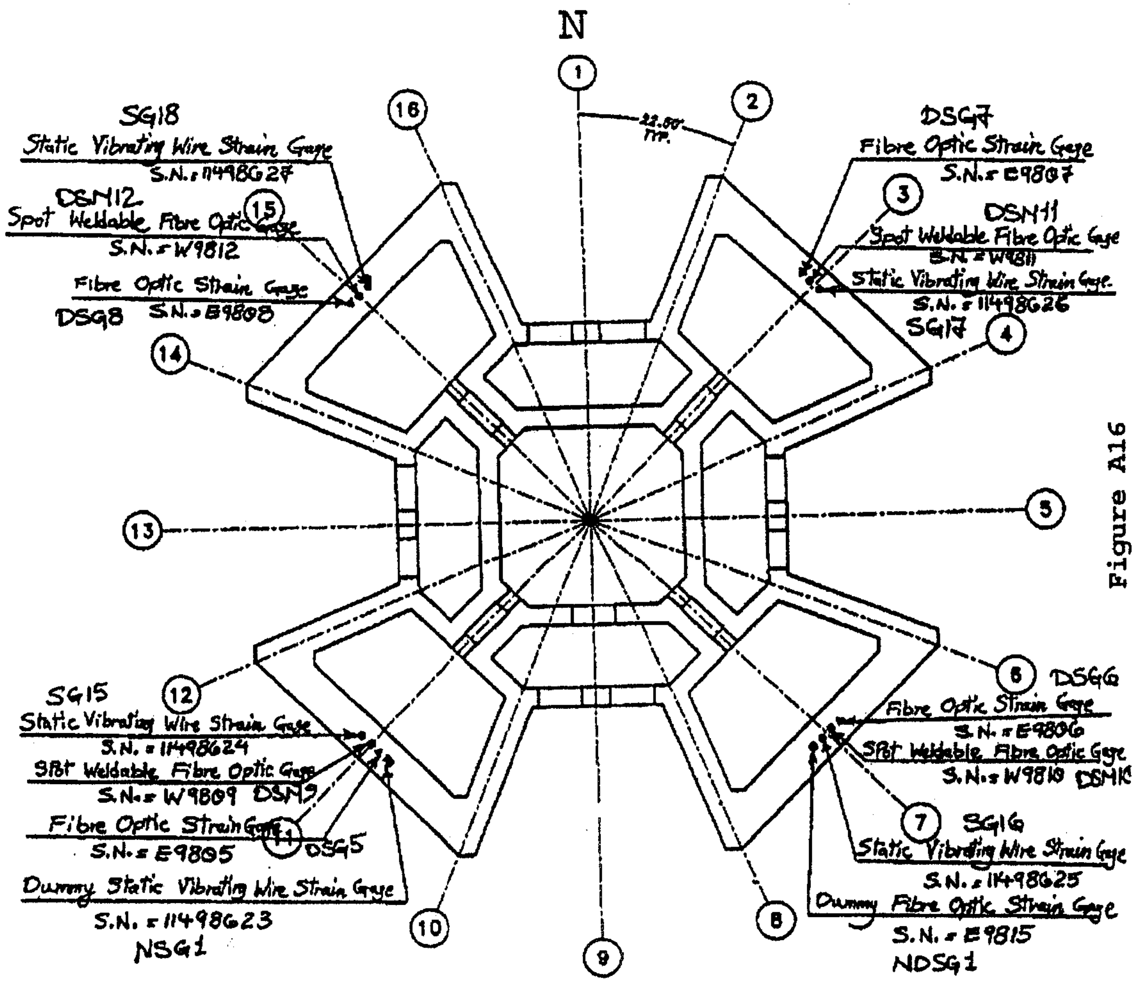

N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
22.50° TYP.
SG26
Static Vibrating Wire Strain Gage
S.N.: 11498637
DSM20
Spot Weldable Fiber Optic Gage
S.N.: W9820
Fiber Optic Strain Gage
S.N.: E9824
DSG16
DSG15
Fiber Optic Strain Gage
S.N.: E9823
DSM19
Spot Weldable Fiber Optic
S.N.: W9819
Static Vibrating Wire Strain Gag
S.N.: 11498G
SG25
SG23
Static Vibrating Wire Strain Gage
S.N.: 11498634
DSM17
Spot Weldable Fiber Optic Gage
S.N.: W9817
DSG13
Fiber Optic Strain Gage
S.N.: E9821
Dummy Static Vibrating Wire Strain Gage
S.N.: 11498633
NSG3
DSG14
Fiber Optic Strain Gage
S.N.: E9822
Spot Weldable Fiber Optic G
S.N.: W9818 D
SG24
Static Vibrating Wire Strain
S.N.: 11498635
Dummy Fiber Optic Strain
S.N.: E9825
NDSG3
PLAN AT LEVEL +228.00±1.00
SHAFT INSTRUMENTATION
SCALE 1:150

Figure A14



PLAN AT LEVEL +115.00
SHAFT INSTRUMENTATION
SCALE 1:150

Figure A15



PLAN AT LEVEL ±0.00
SHAFT INSTRUMENTATION
SCALE 1:150

Figure A16

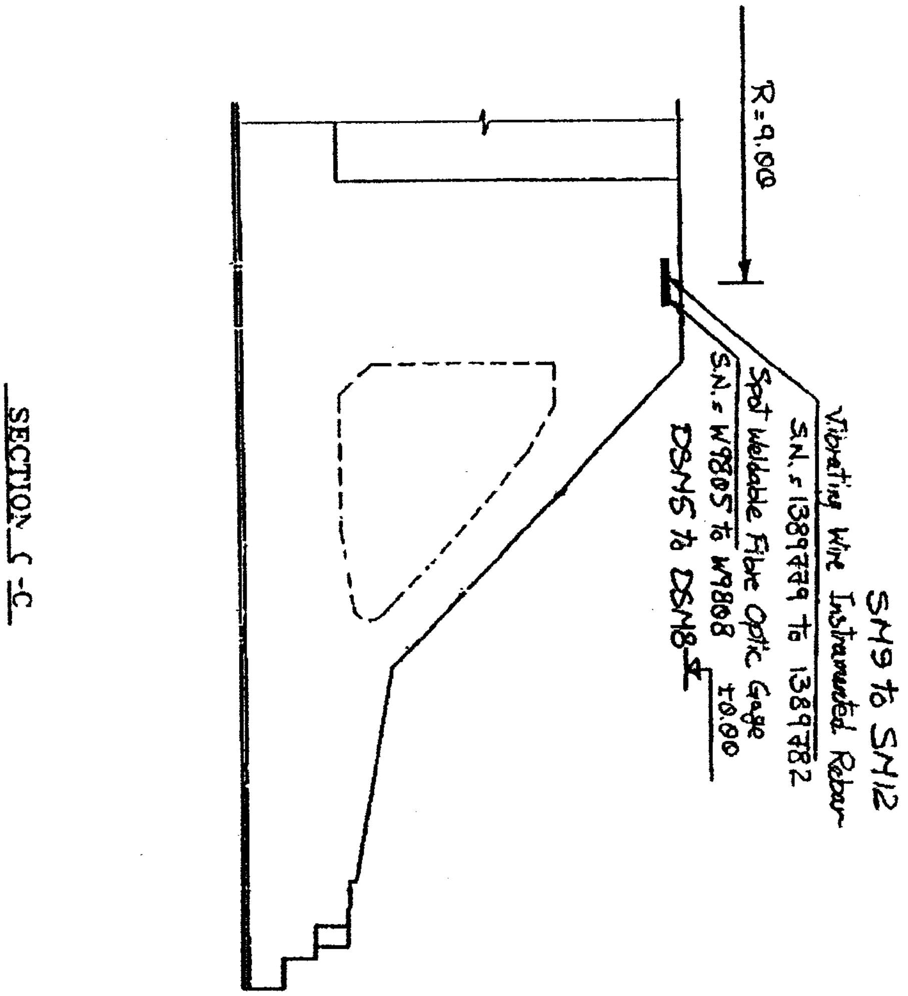
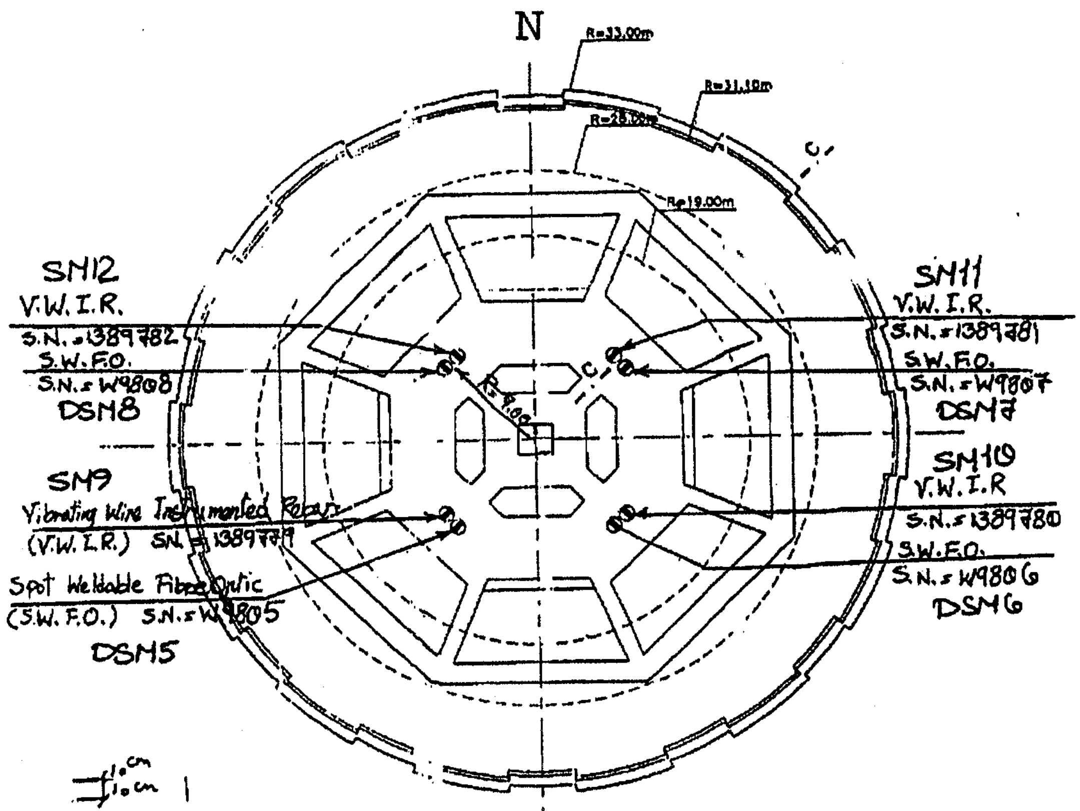
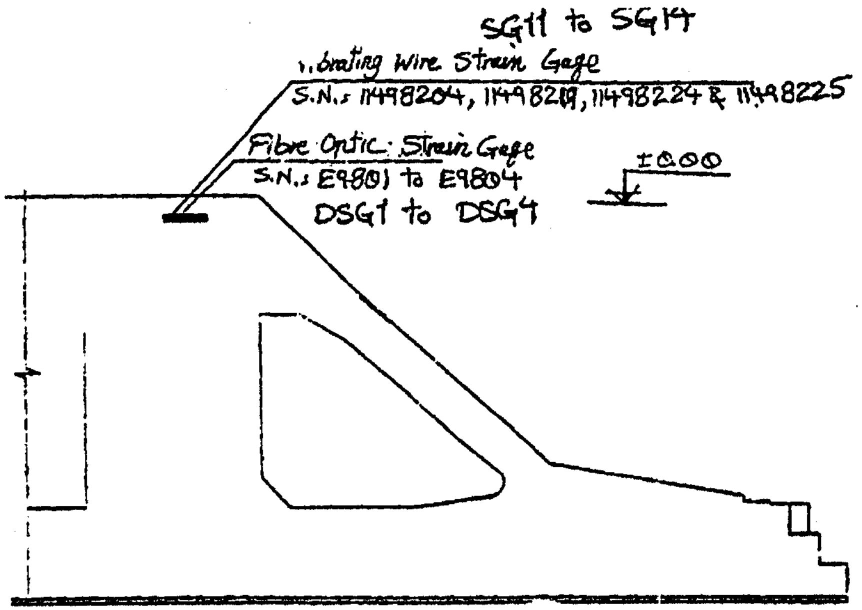

SM9 to SM12
Vibrating Wire Instrumented Rebar
S.N. = 1389779 to 1389782
Spot Weldable Fibre Optic Gage
S.N. = W9805 to W9808
DSM5 to DSM8
±0.00
R=9.00
SECTION C-C

Figure A17



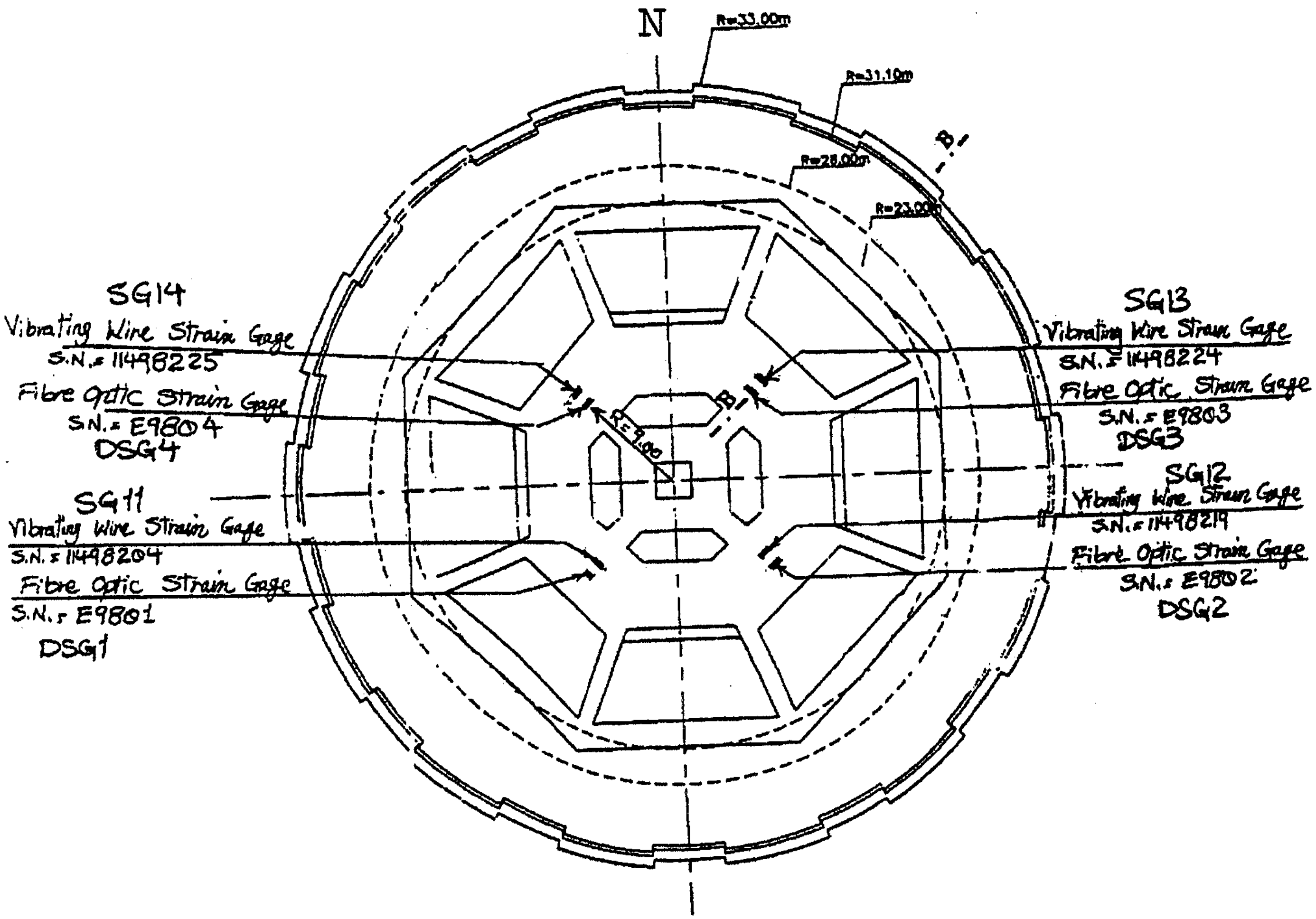
LOCATION OF REBOR STRESSMETER FOR MEASURING STRESS IN REBORS
IN MAT FOUNDATION AND TRANSITION WALLS

Figure A18



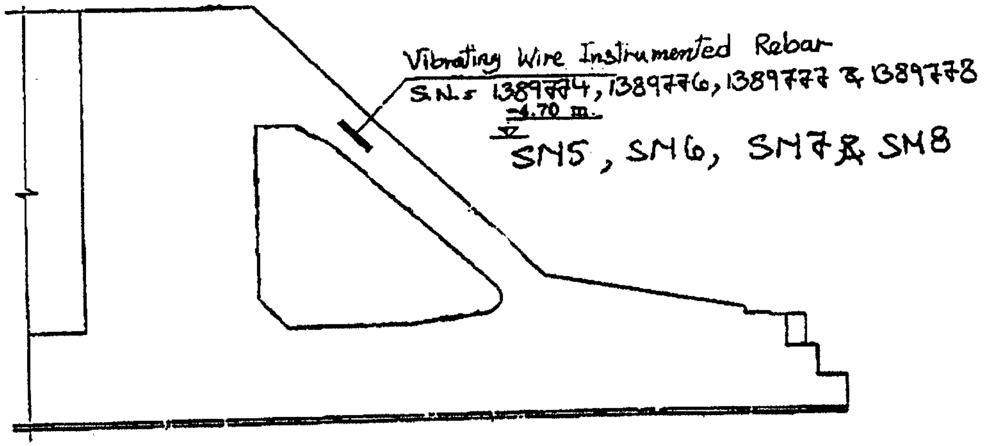
SECTION B-B

Figure A19



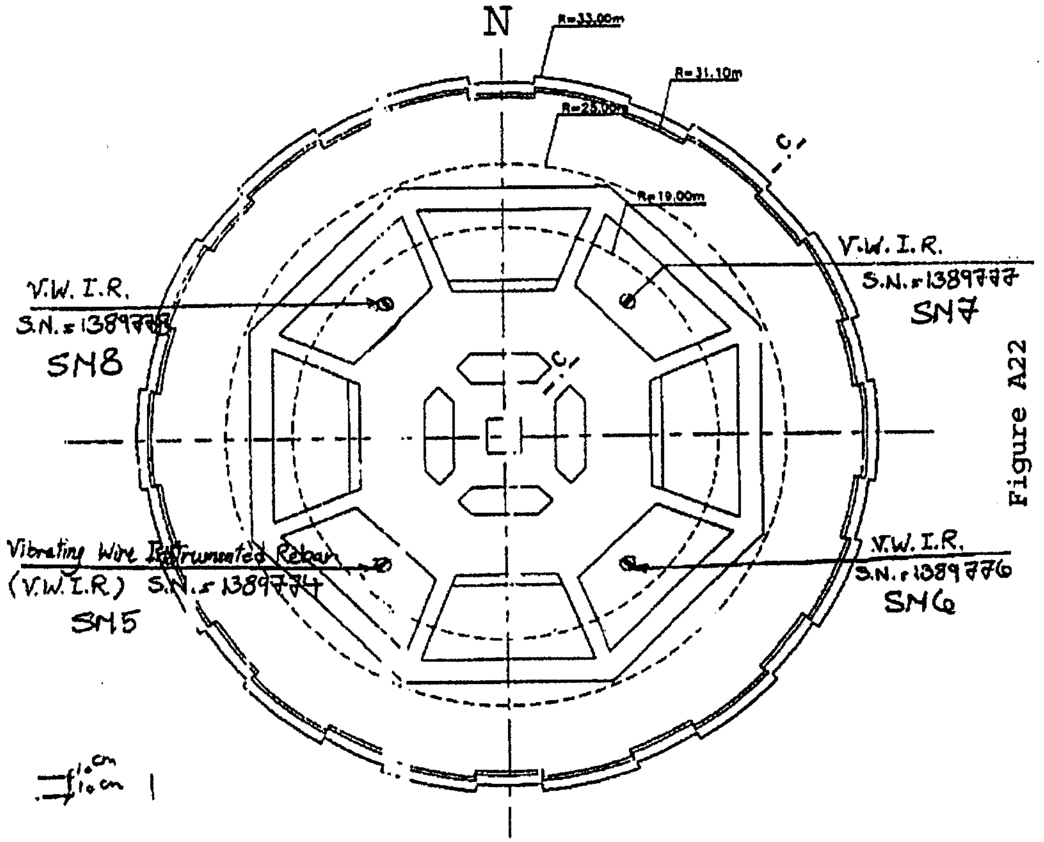
LOCATION OF STRAIN GAGE FOR MEASURING CONCRETE STRAIN IN MAT FOUNDATION AND TRANSITION WALLS

Figure A20



SECTION C-C

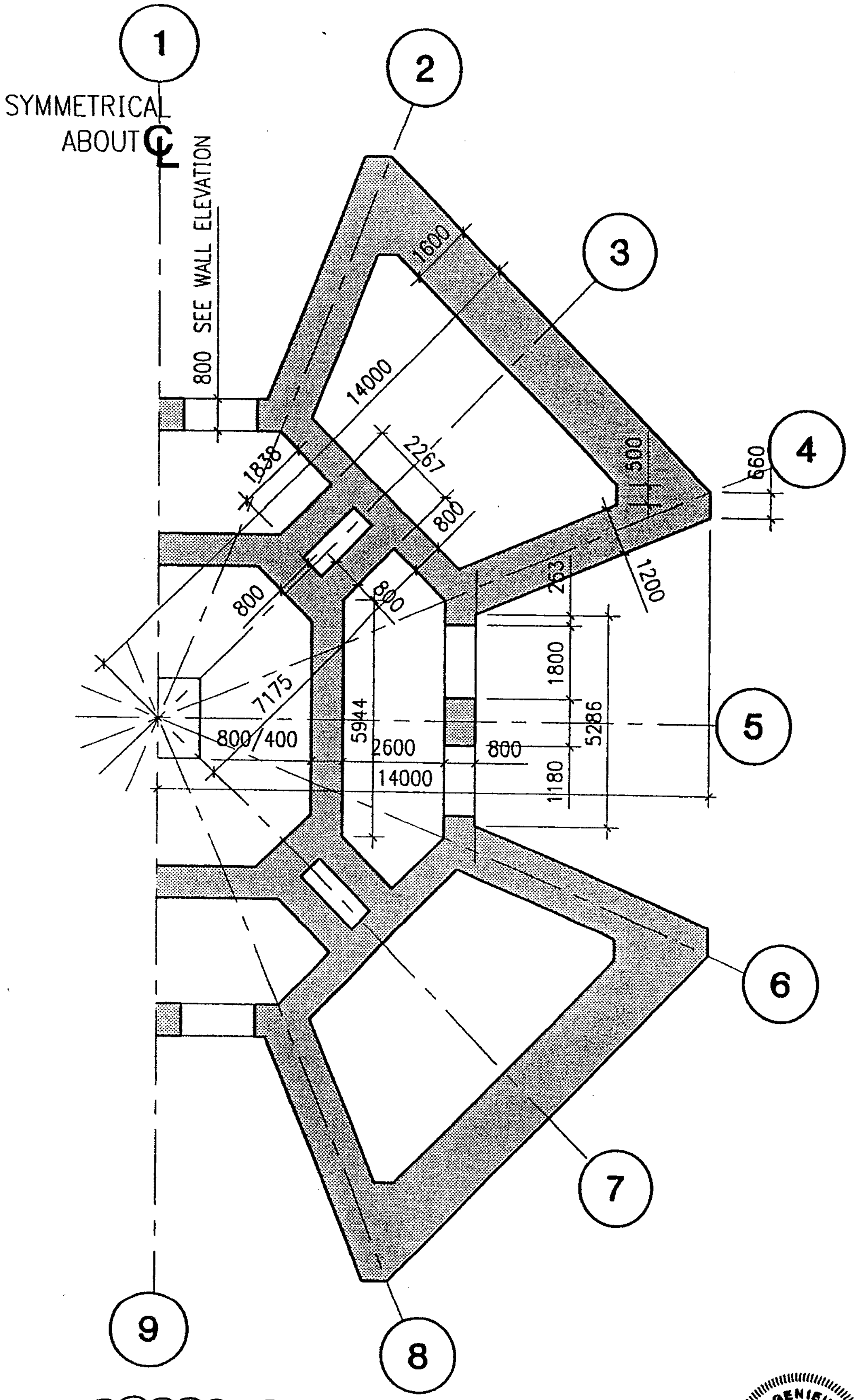
Figure A21



LOCATION OF REBOR STRESSMETER FOR MEASURING STRESS IN REBORS IN MAT FOUNDATION AND TRANSITION WALLS

Figure A22

APPENDIX 2



FOR INFORMATION ONLY
NOT TO BE USED FOR CONSTRUCTION.

4

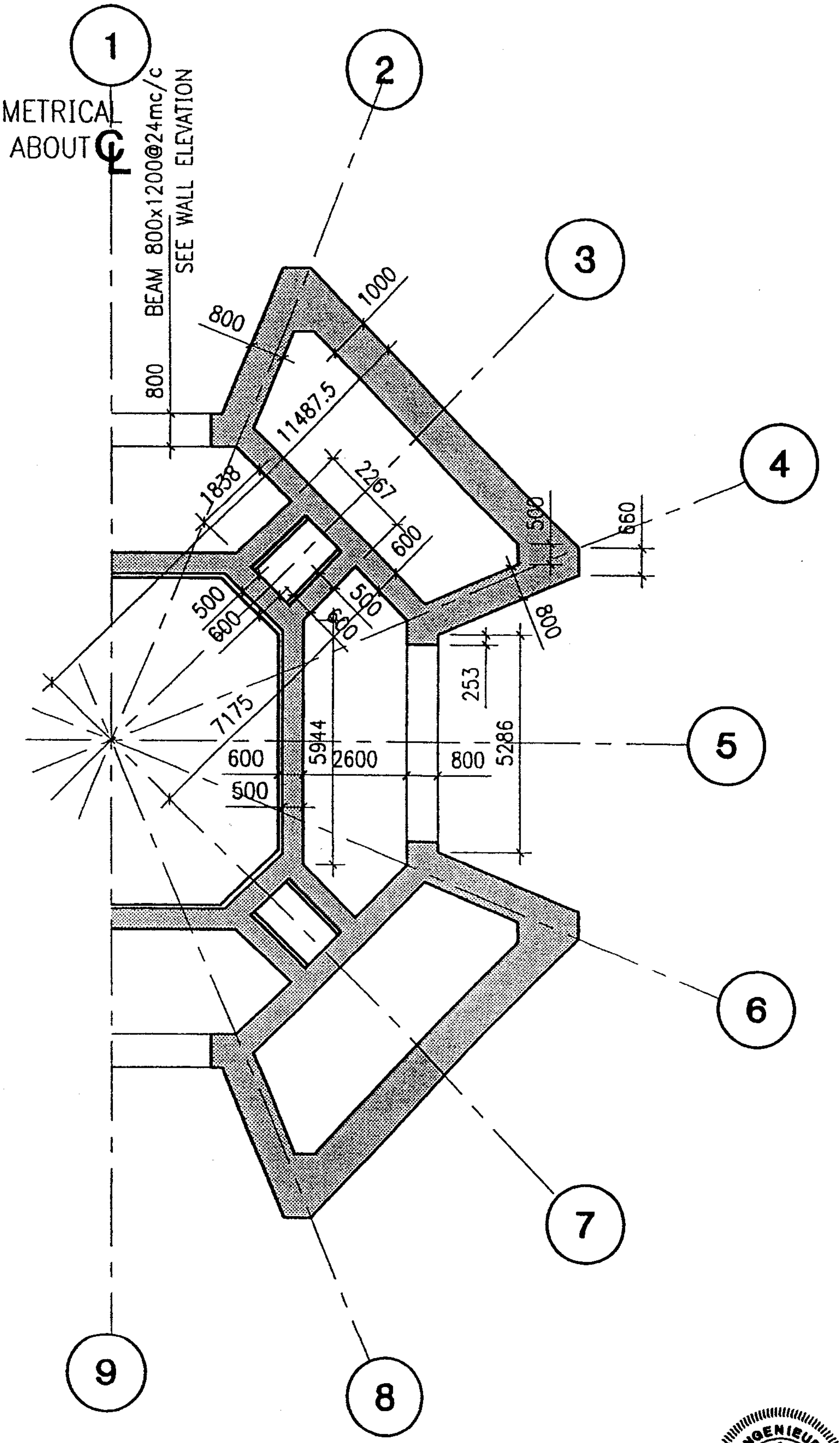
REVISION 4 98 APR. 03

FRANZ KNOLL
21016

N.C.K. Engineering Ltd.
Tel.: 416-964-3322
Fax.: 416-964-8245

Project/Title
TEHRAN TOWER COMPLEX
PLAN AT LEVEL 0.00±

year 1997	month 11	day 06	Ref. Dwg. No.
Contract No. 1095		Scale 1:125	
Dwg. No. S-SK-01-P		Revision 4	

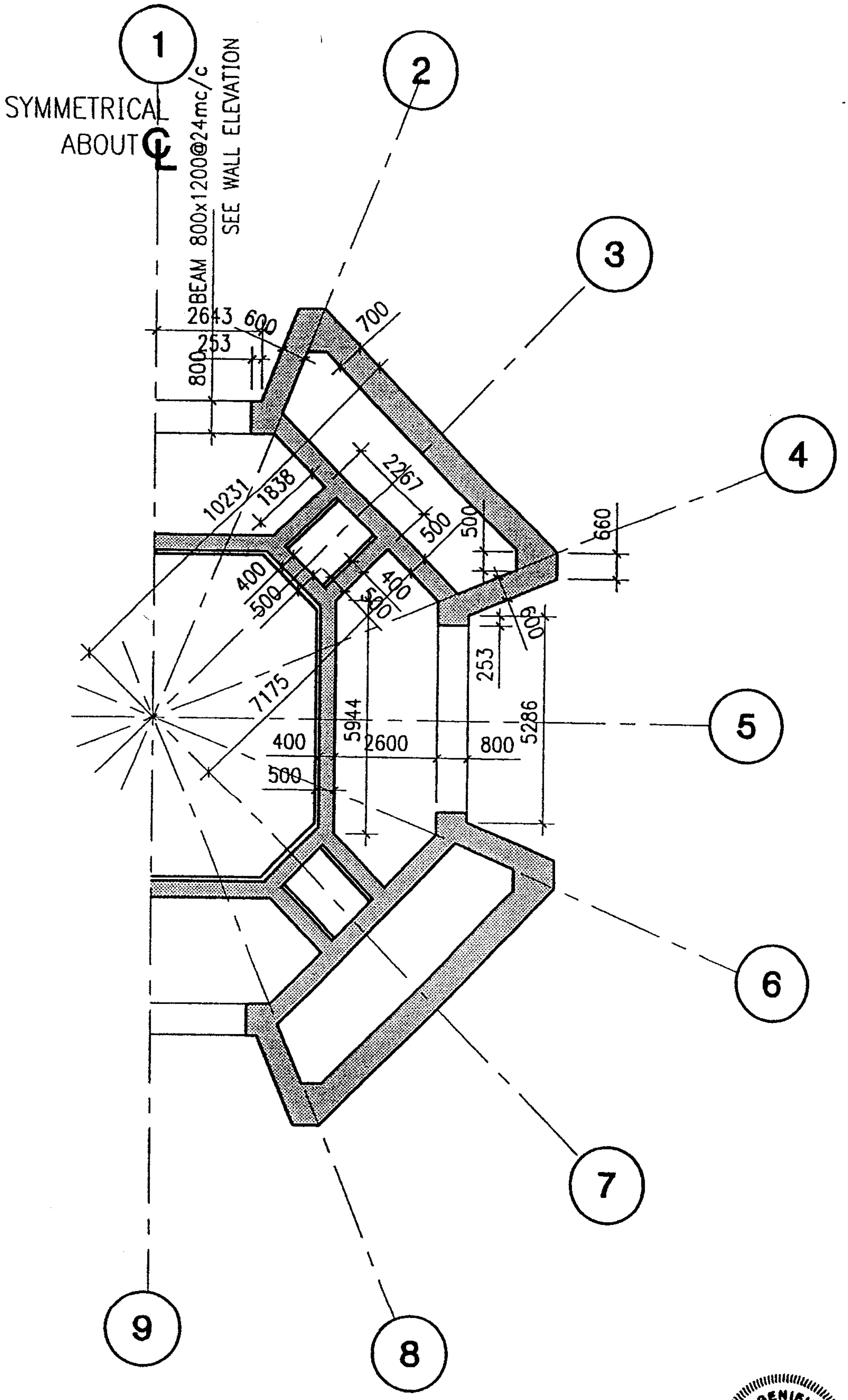


FOR INFORMATION ONLY
NOT TO BE USED FOR CONSTRUCTION. 5

REVISION 5 98 APR. 03

FRANZ KNOLL 21916

N.C.K. Engineering Ltd. **Tel.: 416-964-3322** **Fax.: 416-964-8245**	Project/Title TEHRAN TOWER COMPLEX **PLAN AT LEVEL 120.00±** 123	year 1997 month 11 day 06 Ref. Dwg. No. Contract No. 1095 Scale 1:125 Dwg. No. S-SK-02-P Revision 5

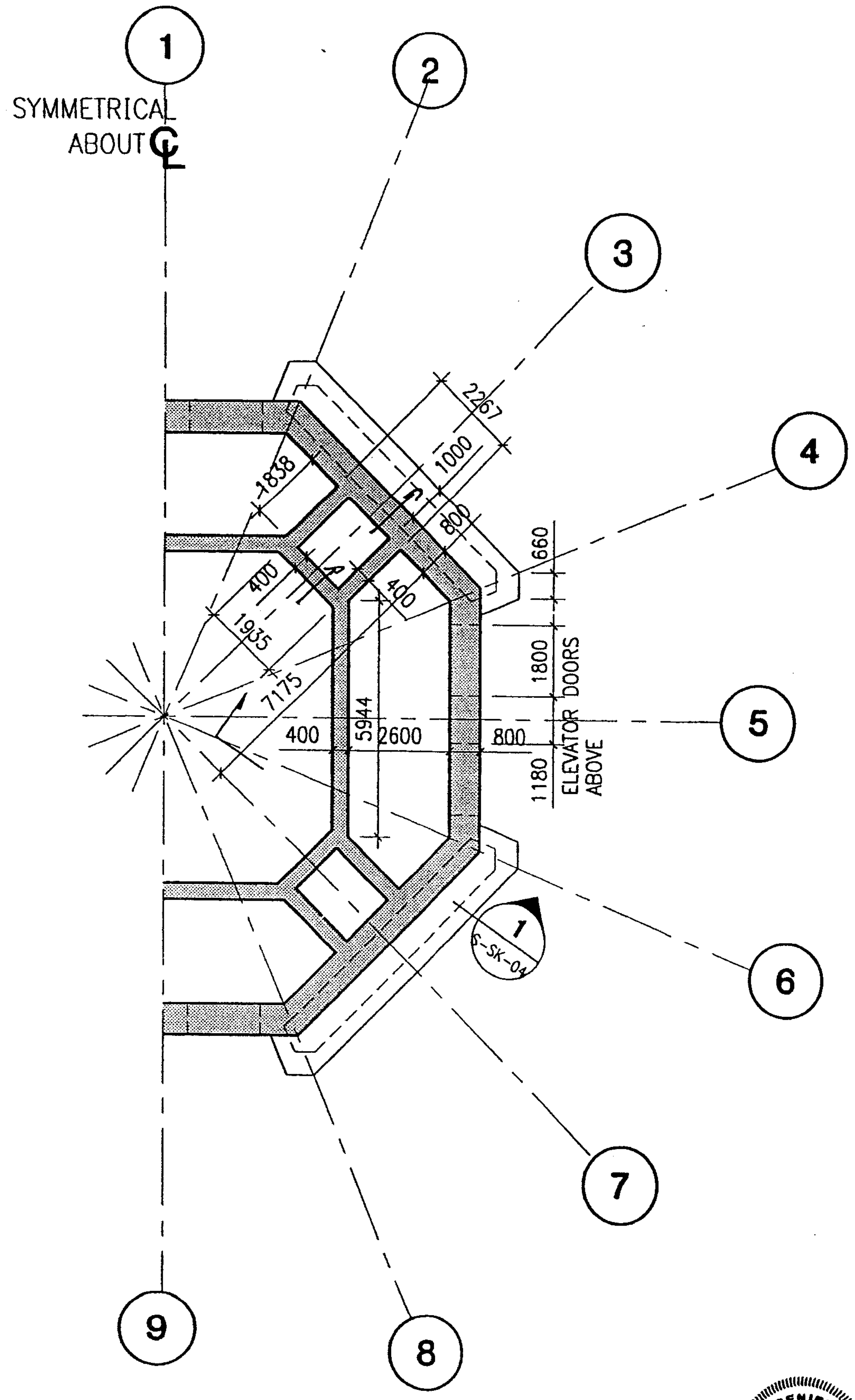


FOR INFORMATION ONLY
NOT TO BE USED FOR CONSTRUCTION. 5

REVISION 5 98 APR. 03

FRANZ KNOLL
21916

N.C.K. Engineering Ltd. Tel.: 416-964-3322 Fax.: 416-964-8245	Project/Title TEHRAN TOWER COMPLEX PLAN AT LEVEL 180.00 124	year 1997 month 11 day 06	Ref. Dwg. No.
		Contract No. 1095	Scale 1:125
		Dwg. No. S-SK-08-P	Revision 5



FOR INFORMATION ONLY
NOT TO BE USED FOR CONSTRUCTION.

4

REVISION 4 98 APR. 03

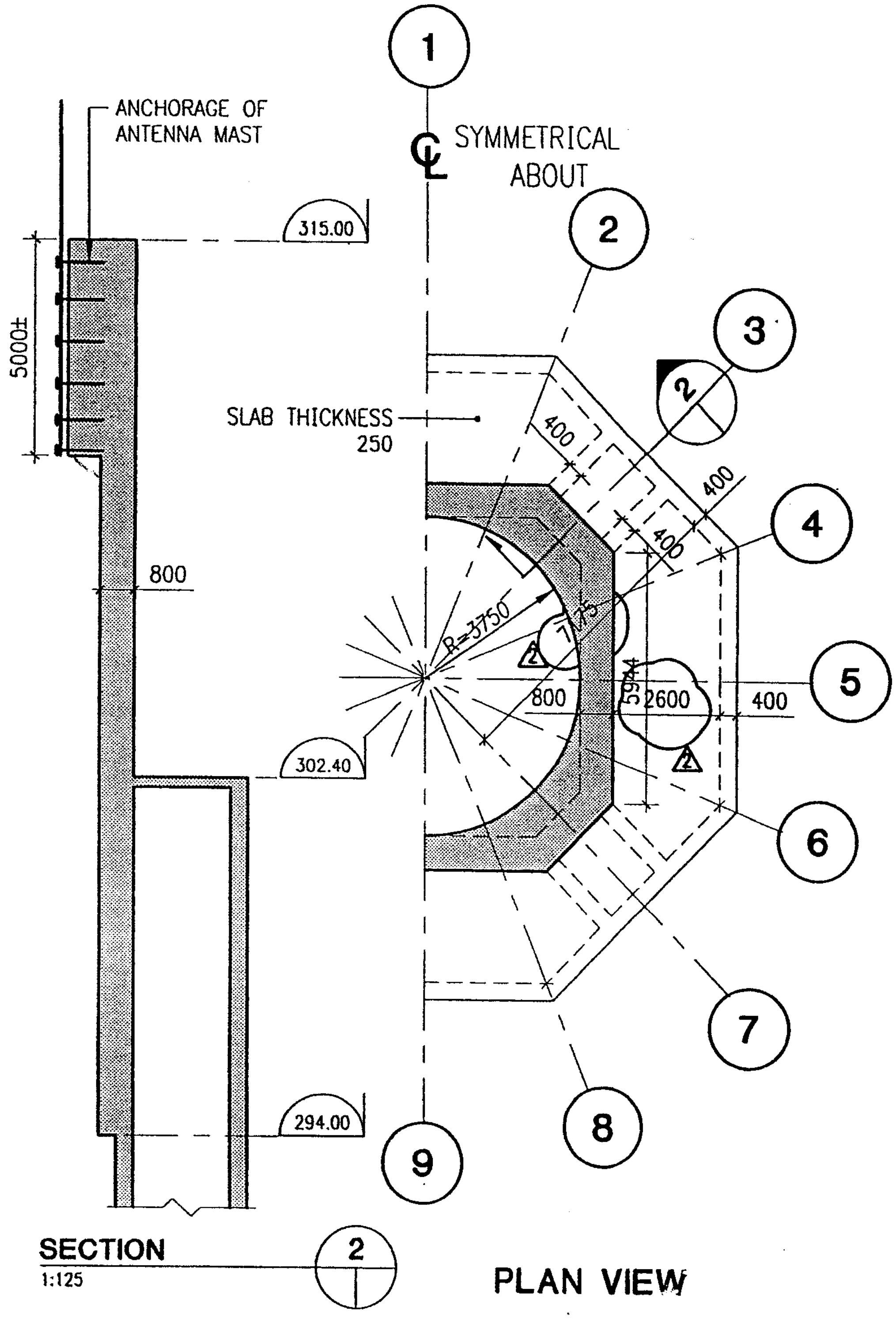
FRANZ KNOLL
21816

N.C.K. Engineering Ltd.
Tel.: 416-964-3322
Fax.: 416-964-8245

Project/Title
TEHRAN TOWER COMPLEX
PLAN AT LEVEL 240.00
125

year	month	day	Ref. Dwg. No.
1997	11	06	

Contract No. 1095
Scale 1:125
Dwg. No. S-SK-03-P
Revision 4



SECTION
1:125

PLAN VIEW

PRELIMINARY

REVISION 2 98 APR. 03

FRANZ KNOLL
21816

N.C.K. Engineering Ltd.
Tel.: 416-964-3322
Fax.: 416-964-8245

Project/Title
TEHRAN TOWER COMPLEX
TOP OF CONCRETE SHAFT
PROPOSED DESIGN

year	month	day	Ref. Dwg. No.
1997	12	04	

Contract No. 1095
Scale 1:125
Dwg. No. S-SK-11-P Revision 2