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Vibrating-Wire Reinforcement Strain Gauges for Performance Monitoring of Large Concrete Structures

Jauge de déformation à corde vibrante et mesures de performance de grandes structures en béton

Dehnungsmessungen am Bewehrungsstahl mit schwingenden Saiten zur Überwachung grosser Betonbauwerke

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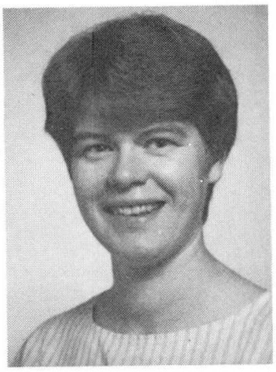
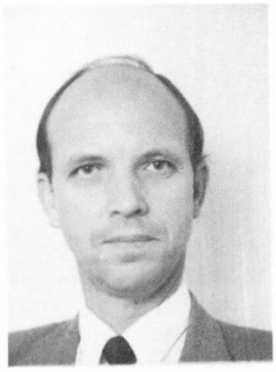




SUMMARY
The Norwegian Geotechnical Institute's vibrating wire reinforcement strain gauge is presented and the performance record of the instrument discussed. Application of the gauge in a wide variety of instrumentation projects is described in order to give an indication of the usefulness of the instrument in performance monitoring. As an example of the data that has been collected with help of the gauge, strain and creep data from Norwegian Contractors' Condeep structures are discussed briefly.

RESUME
Il s'agit de la présentation de la jauge de déformation à corde vibrante de l'Institut Géotechnique de Norvège, et des performances de cet instruement. La description de ses domaines d'application dans de très nombreux projets différents montre son utilité dans les mesures. A titre d'exemple de données recueillies à l'aide de cette jauge, un rapide exposé des données de déformation et fluage des structures Condeep de Norwegian Contractors est presenté.

ZUSAMMENFASSUNG
Die schwingende Saite des Norwegischen Geotechnischen Institutes, montiert auf Armierungsstahl, wird vorgestellt und die Messgenauigkeit des Instrumentes diskutiert. Die Anwendbarkeit des Meßgerätes auf unterschiedliche Instrumentationsprojekte wird beschrieben um die Brauchbarkeit für Kontrollmessungen zu demonstrieren. Als Beispiel für Daten welche mit Hilfe dieses Meßgerätes gesammelt wurden, werden Dehnungs- und Langzeitkriechdaten der Norwegian Contractors' Condeep Plattform kurz diskutiert.

1. INTRODUCTION

Monitoring programs for large concrete structures will generally include instruments for determining strain and/or stress in the concrete. For measurement of strain, there are three basic types of instruments that can be used; surface-mounted strain gauges, embedded strain gauges, or strain gauges attached to the reinforcing steel. The best approach for a given application depends on details of the structure and the specific information that is required.

All three types of strain gauges are used at the Norwegian Geotechnical Institute (NGI). Embedded and surface-mounted gauges are used primarily where it is necessary to determine principal stresses and stress concentrations. The technique of strain-gauging the reinforcing steel is usually preferred when the objective is to monitor the actual loading on the structure. In this case the instrumented reinforcement is located in a part of the structure where the strain measurements can be related to the applied loads. The majority of the projects that NGI has been involved with are of this kind.

In the mid-1960's a vibrating-wire strain gauge for monitoring stress in reinforcing steel was delevoped at NGI. The instrument was orginally designed and used to measure the distribution of axial loads in precast concrete friction piles. Since then the instrument has been used on a great variety of projects, and has been a valuable tool for monitoring the performance of reinforced concrete structures.

The main objectives of this paper are: to describe the NGI vibrating-wire reinforcement strain gauge, to comment on its performance, and to illustrate its use. Selected applications are presented from projects involving different types of concrete structures where it has been beneficial to monitor stress or strain in reinforcing steel as an alternative to the use of surface-mounted or embedded strain gauges.

The paper does not present results of measurements in detail, but typical data is given for most of the examples. One of the examples includes a unique 9-year record of strain measurements in an offshore concrete structure subjected to cyclic loading. Since little is known about the effects of long-term cyclic loading on the creep of concrete, a brief discussion of this data has been included.

2. THE VIBRATING-WIRE REINFORCEMENT STRAIN GAUGE

2.1 Description

Principal features of NGI's reinforcement strain gauge used to monitor axial load or stress/strain in steel reinforcement are shown in Fig. 1. The instrument is basically a small-diameter load cell welded in series with the reinforcing steel, Fig. 1(a).

The sensing element in the load cell is a vibrating-wire strain gauge. The sensor is of the constant vibration type; that is, the gauge-wire oscillates continuously and at constant amplitude as long as the gauge is connected to the external exciter electronics. The change in frequency of the gauge-wire is a measure of the axial strain or stress in the load cell as well as in the reinforcing steel attached to it.

There are two versions of the reinforcement strain gauge. One has a single vibrating-wire sensing element, Fig. 1(b), and the other has two sensing elements, Fig. 1(c).

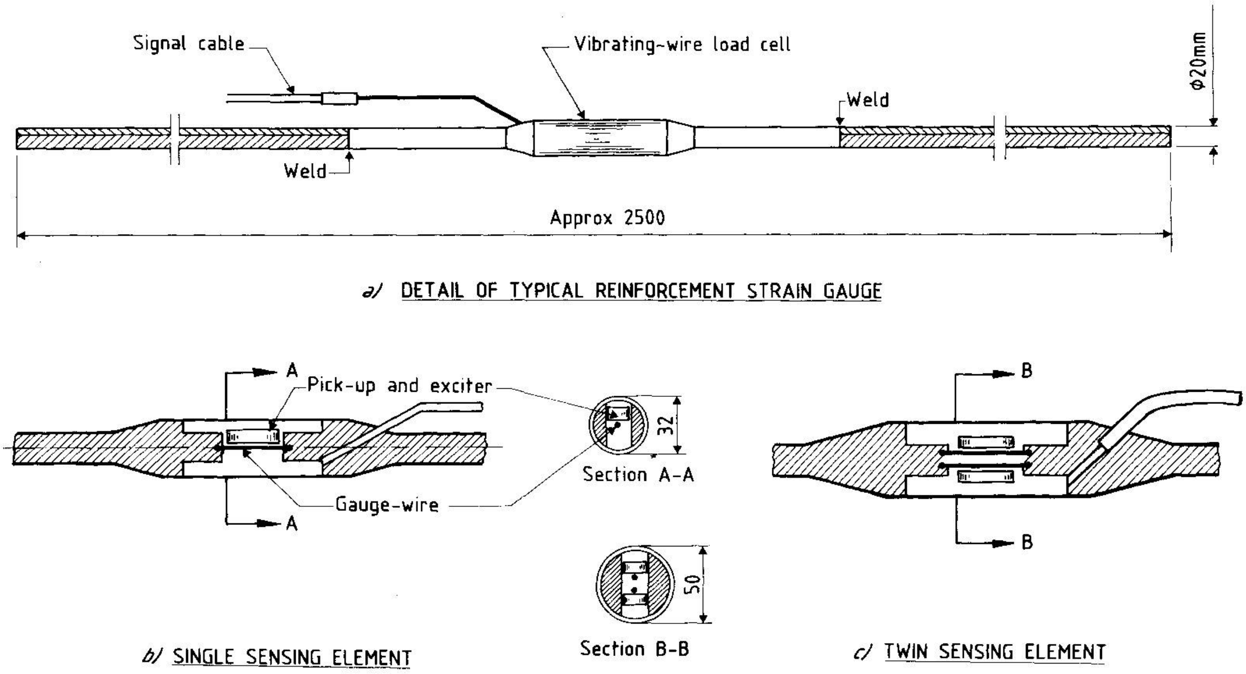


Fig. 1 NGI's vibrating-wire reinforcement strain gauge

The body of the load cell is machined from a single piece of high strength steel. It is dimensioned to have approximately the same cross-sectional area as the renforcing steel. The gauge-wire and magnet system used to excite the gauge-wire and make the frequency measurements are mounted axially in a milled slot in the gauge. For the single sensing element gauge, the axis of the gauge-wire is coincident with the longitudinal axis of the reinforcing steel. For the twin sensing element gauge, two independent gauge-wires and magnet systems are mounted either side of the longitudinal axis of the load cell. Since the load cell is fabricated of a higher strength steel than normal reinforcing steel, it operates within its elastic range even after the reinforcing has started to yield.

The gauge-wire is sealed in a small metal tube and furthermore the entire load cell is sealed with O-rings and an outer thin-walled sleeve so that the entire instrument is completely watertight. Electrical connections are made via a specially designed compression gland.

The outer sleeve separates the body of the load cell from the concrete. Thus it eliminates concrete bond and transfer of shear stresses along the side of the load cell. The sleeve is held in place only by O-ring friction. Transfer of stresses from the concrete to the tapered ends of the load cell is minimized by means of a layer of soft rubber at the interface which separates the gauge from the concrete.

2.2 Advantages

NGI's system design philosophy is to use vibrating-wire type instruments wherever possible for geotechnical and structural field instrumentation applications of a complex nature. Typical conditions for such projects are long cable runs, integration into a complicated construction sequence, construction activities that are potentially hazardous to delicate instruments and system components, the need in some cases to install instruments several years before actual use, and submergence in salt water under relatively high pressure.

The primary reasons for using vibrating-wire type instruments are:

- proven reliability
- proven long-term stability
- mechanical robustness
- frequency output signal (minimal noise problems)
- minimum of electronics within the transducer
- uncomplicated cabling procedures, and
- relative ease of production of small series of instruments

NGI has concentrated on the development and use of reinforcement gauges as opposed to embedded gauges for measuring strain in concrete because measured strains in reinforcement appear to give more consistent results for the types of projects that NGI is involved in. The instrument can be calibrated directly in terms of stress or strain and the modulus of elasticity is constant.

The reinforcement strain gauge is robust and easier to install than embedded gauges. It can be shop-welded to short lengths of reinforcing steel and installed as a "sister bar" with minimum disturbance to other construction operations.

The reinforcement strain gauge with two sensors, Fig. 1(c), makes it possible to discriminate between axial stresses and bending stresses carried by the reinforcement. This can be an important advantage for some applications. If, however, bending stresses are negligible, the second vibrating-wire provides a back-up or redundant sensor.

2.3 Performance record

2.3.1 Accuracy

The accuracy of the vibrating-wire reinforcement strain gauge will depend on the range of measurements that is required, but generally speaking it is better than 1 percent of full scale for non-conformity, hysteresis and repeatibility errors combined.

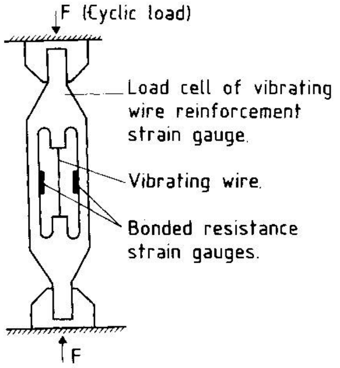
2.3.2 Temperature sensitivity

The temperature sensitivity of the reinforcement strain gauge depends on the type of steel used to fabricate the instrument since it depends on the difference in the coefficients of thermal expansion between the gauge-wire and the body of the instrument. Typical temperature sensitivity ranges from

0.2 to 0.6 $\mu\varepsilon/^{o}C$. The value 0.2 $\mu\varepsilon/^{o}C$ is typical for the most commonly used instruments.

2.3.3 Dynamic response

The dynamic response of the vibrating-wire strain gauge is suitable enough for most civil engineering applications. The principal limitation lies in the electronic circuitry used to determine the frequency of the output signal and not in the strain gauge itself.



a/ TEST ARRANGEMENT

Frequency of loading Hz	Difference as % of indicated value *
4.0	+0.33
6.7	-0.61
8.3	-1.73
10.0	-1.04

*Difference between measured change in load for vibrating-wire strain gauge compared to resistive gauge, given as a % of the value indicated by the resistive gauge.

b/ TEST RESULTS

Fig. 2 Dynamic response test of reinforcement strain gauge

Satisfactory operation of the vibrating-wire reinforcement strain gauge has been confirmed by controlled tests up to 10 Hz. This was done in 1974 in order to qualify instruments for use on offshore structures. In these tests the dynamic response of the vibrating-wire reinforcement strain gauge and bonded electrical resistance strain gauges were compared using the test specimen shown in Fig. 2(a). The gauges were subjected to cyclic loading in steps up to 10 Hz (limited by the testing machine). No significant differences were found between the vibrating-wire reinforcement strain gauge and the resistance strain gauge, Fig. 2(b).

2.3.4 Long-term stability

The excellent zero point stability of vibrating-wire instruments is well known, and this explains their wide spread use in long-term monitoring programs. Stability tests started at NGI in 1967 using 12 vibrating-wire strain gauges show a long-term zero point drift corresponding to 0.3 percent of full scale after 20 years.

The long-term stability of a reinforcement strain gauge, over an 8-year period has been established by ongoing measurements on an actual project. A "dummy" reinforcement strain gauge was installed as part of the instrumentation for a concrete tunnel lining. The dummy gauge is installed in such a way that it is not loaded but is otherwise subjected to the same environmental conditions as the other instrumentation. Data from this in-situ test is presented in Fig. 3 and shows that the long term drift of the instrument is less than 2 microstrain over 8 years.

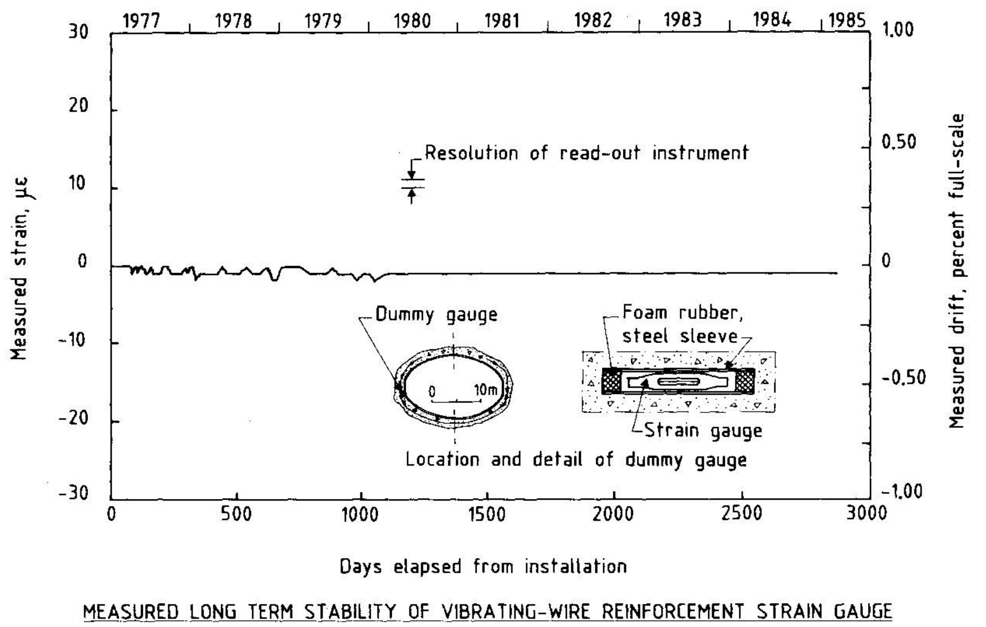


Fig. 3 Measured zero point drift of vibrating-wire reinforcement strain gauge

2.3.5 Long-term reliability

Except for some offshore applications most of the structures instrumented by NGI have been observed for only a few years. For this reason there is little information regarding the long-term reliability of the reinforcement strain gauges. Performance data spanning over a 6 to 7 year period is available from one offshore structure. Sixty strain gauges were installed on this structure during construction in 1979-80. When last checked at the end of 1986, all 60 instruments were operating normally and giving data that appears reasonable in every respect.

3. APPLICATIONS

Although strain monitoring programs for concrete structures may differ significantly from structure to structure, the main objectives are usually design verification and documentation of adequate safety of the structure. Three common circumstances where strain measurements can provide information of practical or economical value are outlined below.

- The loading on the structure is well defined and understood, but the effects of the loads on the structure are uncertain. Thus, the function of the instrumentation is to determine the response of the structure to the applied loads. This generally requires that critical parts of the structure be instrumented to measure the stresses that occur. In this case the results of the measurements enable the structural engineer to compare predicted stresses with observed values and thereby verify the integrity of the structure.

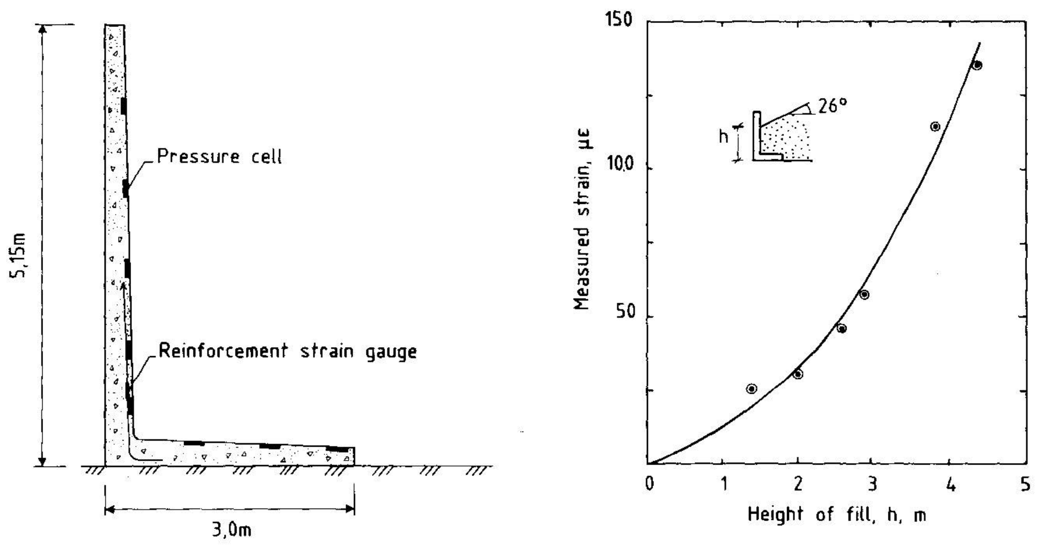
- The uncertainty is in the loading on the structure and not the integrity of the structure itself. The monitoring program in this situation may be entirely different from one intended to provide structural response data. In this case the instrumented structure functions in reality as a load measuring system. The results of the measurements are used to verify design estimates of the loading and to provide information regarding soil/structure interaction.

- Some construction procedures may cause special loading conditions on the structure as it is being built. When this is so, it is essential to monitor and control the construction process to ensure that the work is progressing safely and that no damage occurs to the structure. In this case instrumentation is used actively as a construction control tool, and the monitoring program has to be designed to detect unacceptable performance in time to initiate contingency action if the situation is judged to be critical.

NGI has used the reinforcement strain gauge on a wide variety of projects both onshore and offshore. The following examples have been selected to illustrate various uses of the gauge in monitoring programs of the type outlined above. In each case the use of the gauge is briefly described and where possible some typical data presented.

3.1 Retaining wall

The reinforcement strain gauge has been used to optimize the design of retaining structures. The retaining wall shown in Fig. 4(a) was the first of a number of concrete structures to be constructed for bulk storage of chemical fertilizer.



a/ CROSS SECTION OF RETAINING WALL

b/ MEASURED STRAIN IN REINFORCEMENT

Fig. 4 Strain measurements in a retaining wall

A full scale test was carried out on the first structure to provide a basis for the design of the other storage bins that were to be built. The instrumentation consisted mainly of pressure transducers since the aim of the investigation was to find the pressures acting on the wall during the filling of the storage area. The reinforcement strain gauge was used to monitor the stress developed in the reinforcing steel near the base of the wall. The moment at the base of the wall determined from the strain gauge readings, Fig. 4(b), provided an overall check on the loading. On the basis of the measurements empirical rules were developed for the design of the storage bins.

3.2 Friction piles

A series of loading tests [1] have been carried out using cylindrical and conical precast concrete friction piles driven into a very loose deposit of homogeneous sand, Fig. 5(a). One of the main objectives of the test program was to determine the magnitude and distribution of skin friction along the piles. This was done by using reinforcement strain gauges to measure the axial load at regular intervals along the piles. In order to correlate the strain gauge readings to axial load, the piles were calibrated in a loading frame before and after the tests. Typical results from the pile load tests are shown in Fig. 5(b).

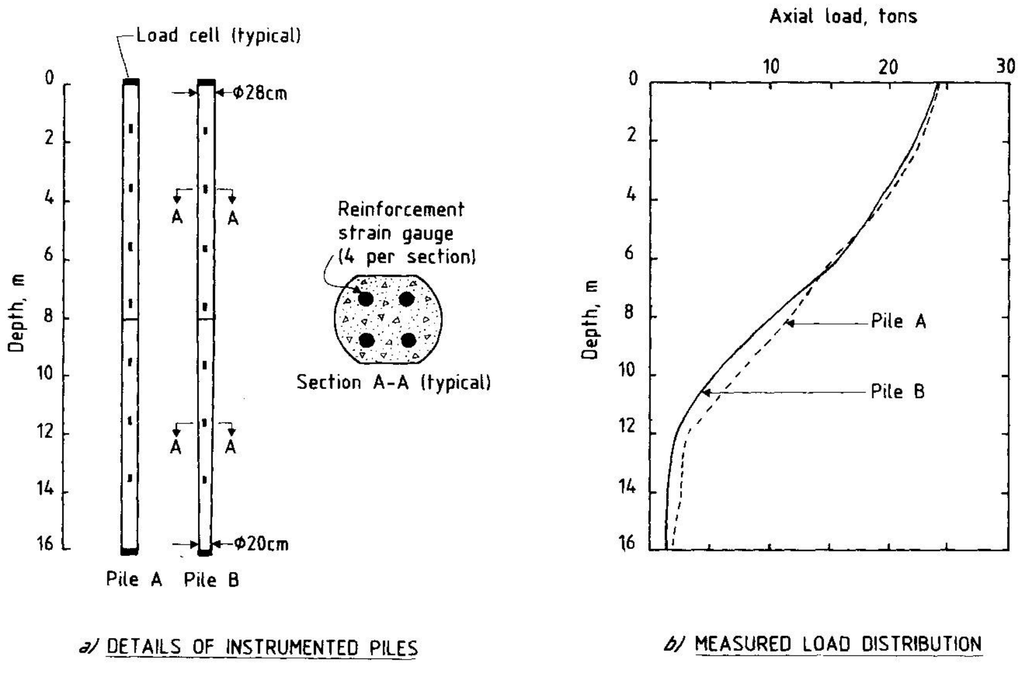


Fig. 5 Measurement of axial load in friction piles

3.3 Tunnel lining

One of the underground stations on the Oslo east-west railway line consists of a rock tunnel with a reinforced concrete lining. The first section of the tunnel was instrumented in order to monitor the stresses developed in the lining, Fig. 6(a). On this project both vibrating-wire reinforcement strain gauges and vibrating-wire embedded strain gauges were cast in the concrete lining of the tunnel.

Results from an embedded strain gauge and a reinforcement strain gauge installed at the same location are shown in Fig. 6(b). The measured strains are in good agreement for the two types of instruments. The "dummy" gauge used to obtain the long-term performance data reported in Fig. 3 was part of this instrumentation program.

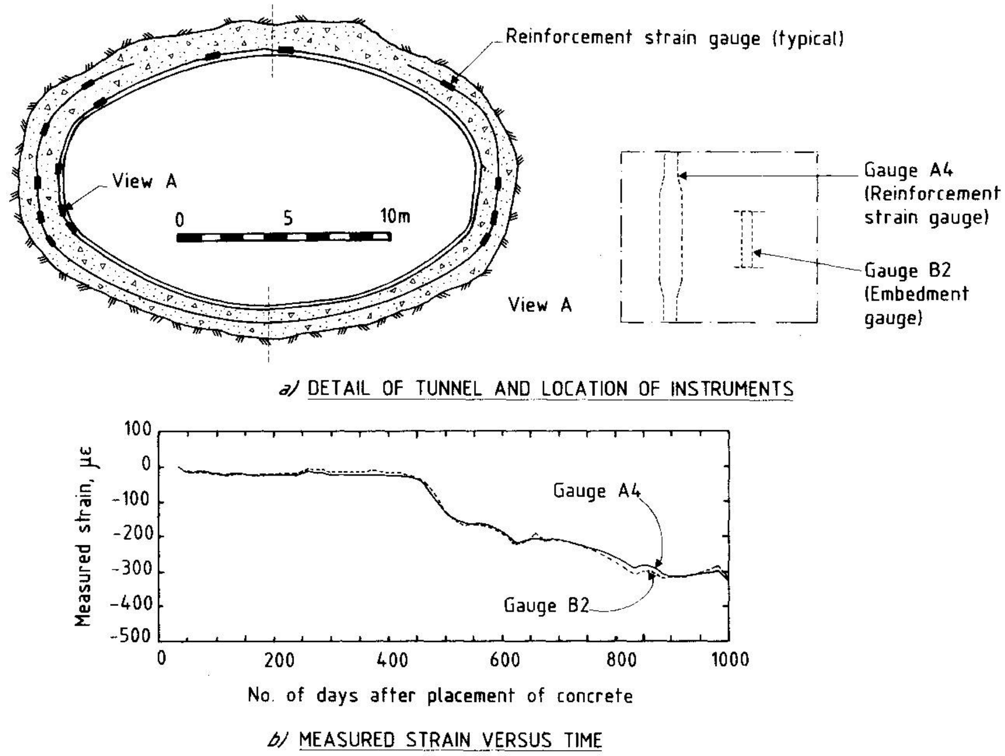
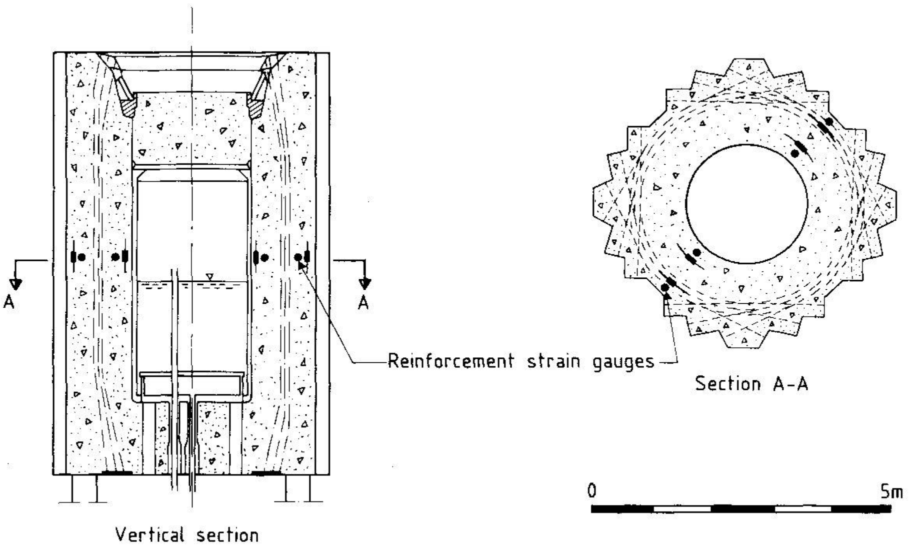


Fig. 6 Strain measurements in a reinforced concrete tunnel lining

3.4 Prestressed concrete reactor vessel

A model prestressed concrete reactor vessel was built as part of a Scandinavian nuclear energy research project. The test vessel, Fig. 7, of a scale of 1:3, was thoroughly instrumented to determine the effects of high internal pressure and temperature on the integrity of the structure. This is an example where the loading on the structure is known but the response of the structure to these loads has to be verified by measurements. The objectives of the project were to test the design of the removable lid and the adequacy of the thermal insulation system. In the final phase of the test program the vessel was pressurized hydraulically to failure. Measurements of thermal stress and stress concentrations near the penetrations through the base of the vessel and around the removable lid were of prime concern. These were measured with embedded strain gauges, 250 in all, since they are better suited for measurements of the state of stress at a point within the concrete. The monitoring program also included vibrating-wire reinforcement strain gauges installed at mid-height of the vessel as indicated in the figure for monitoring axial and circumferential strains.

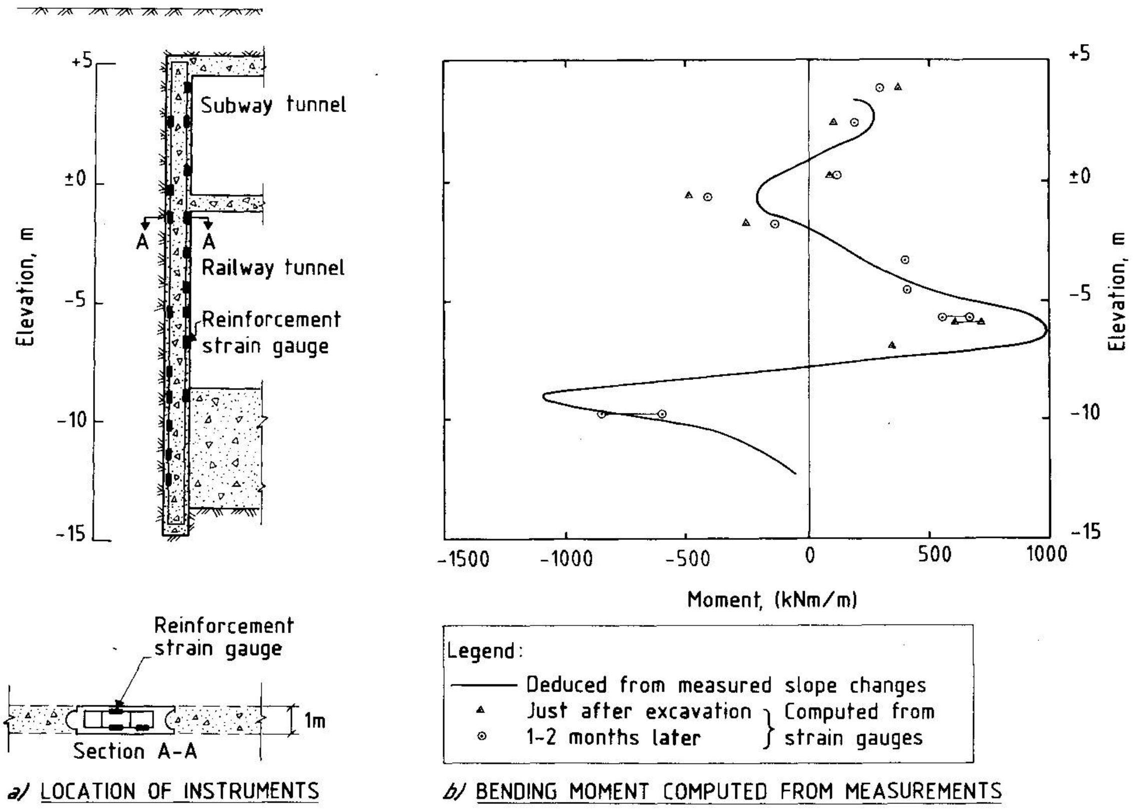


DETAIL OF TEST STRUCTURE AND LOCATION OF INSTRUMENTS

Fig. 7 Strain measurements in a prestressed concrete pressure vessel

3.5 Slurry-trench walls

The deepest part of the underground or subway system in Oslo was constructed in soft clay by the cut and cover method using slurry trench techniques [2]. This



a) LOCATION OF INSTRUMENTS

b) BENDING MOMENT COMPUTED FROM MEASUREMENTS

Fig. 8 Monitoring of strain in reinforcement of a slurry trench wall involves the use of a slurry to stabilize the trench during excavation and then replacing the slurry with concrete to form an in-situ wall element. A unique excavation and bracing procedure had to be followed during excavation of the clay between the longitudinal walls of the subway tunnel. An extensive construction control program was carried out on this difficult project. This included instrumenting one of the first sections of the slurry-trench wall with reinforcement strain gauges, Fig. 8(a), as part of an extensive monitoring program to determine the loading on the tunnel during construction. An example of the bending moments in the wall derived from the reinforcement strain gauge data is given in Fig. 8(b).

3.6 Bridges

Fig. 9 presents two examples of the use of the reinforcement strain gauge in bridge structures. In both cases measurements of the load and moment carried by the bridge piers were needed to monitor and control construction operations. To measure the loading, the piers were instrumented with reinforcement strain gauges, one in each corner. The relative locations of the strain gauges used on these structures are shown in the figure. Fig. 9(a) shows the unsymmetrical Norddalsfjord bridge [3] which has short, ballasted cantilevered spans towards land. It was instrumented in order to assess the safety of the structure during the free cantilevering construction procedure that was used. Fig. 9(b) shows Nordsund bridge which was instrumented because of torsional effects on the main span and support during construction of the curved approach span.

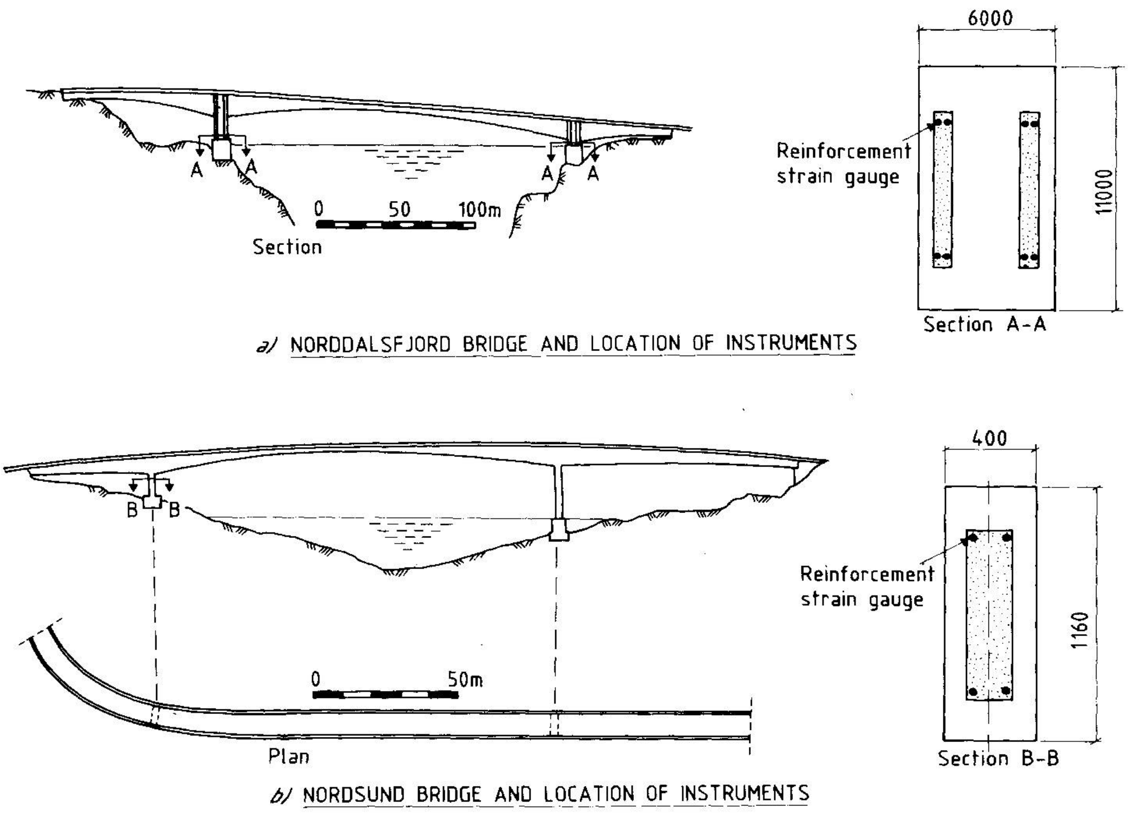


Fig. 9 Instrumentation for monitoring bridge construction

3.7 Gullfaks C test structure

A large scale soil penetration test was carried out in the North Sea in 1985. In more than 200 m of water a concrete test panel, 2.4 m wide, 0.4 m thick and 23 m long was penetrated 22 m into the seabed to provide important design information for Statoil's Gullfaks C platform [4]. The base of this Condeep structure is fitted with 1400 running metres of concrete foundation skirts that must penetrate 22m into the soil. The large scale test was carried out to confirm that penetration of the 22m long skirts of the structure would be possible. Fig. 10(a) shows overall details of the 360 ton test stucture, and Fig 10(b) shows the maritime operations during the penetration test. Included in the instrumentation program were four vibrating-wire reinforcement strain gauges installed in the corners of the test panel, 3 m above the tip. These instruments were used to determine if any significant bending moments were developed in the cantilevered part of the test panel as it penetrated into the soil. As it turned out, at a particular stage in one of the tests rather large bending moments were developed in the tip of the concrete panel. The strain gauge readings showed this quite convincingly. Fig. 10(c), for example, shows some data from the test at a stage where the moment is decreasing but there are still large tensile strains in the reinforcing steel on one side of the test panel.

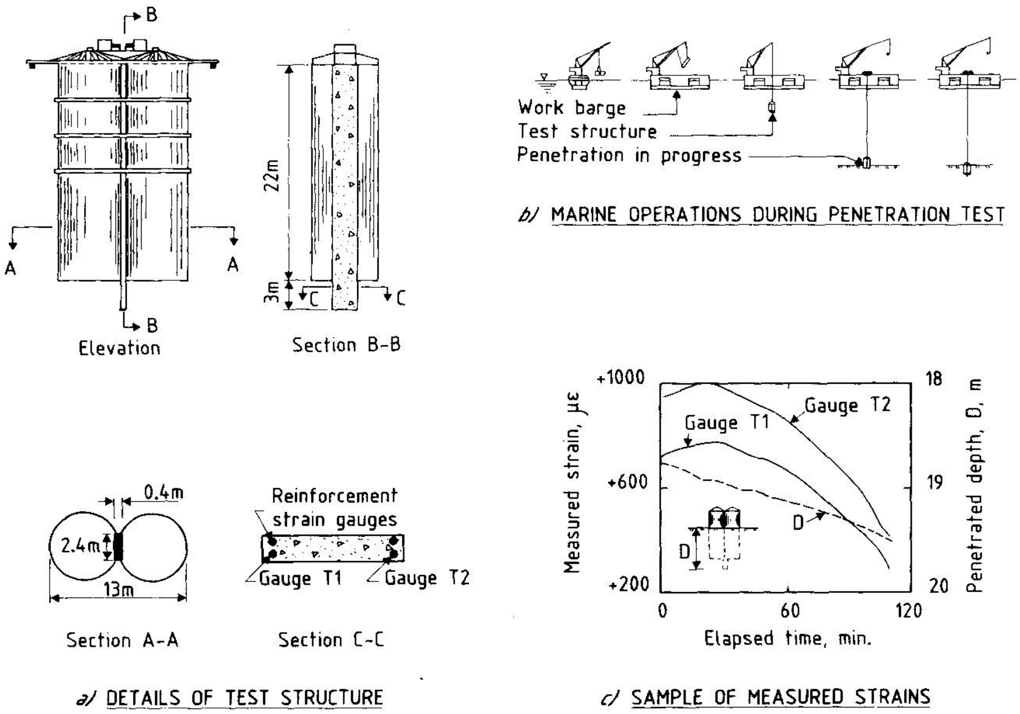


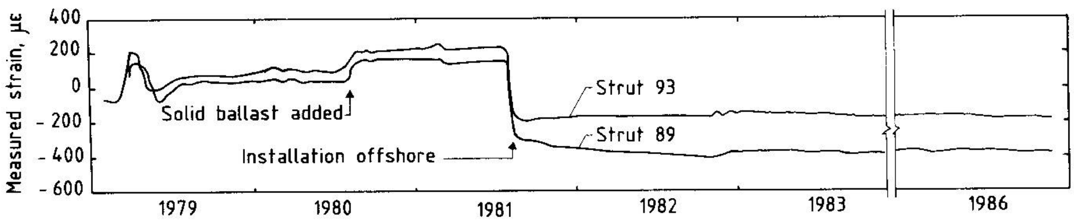
Fig. 10 Strain measurements in the Gullfaks C test structure

3.8 Condeep structures

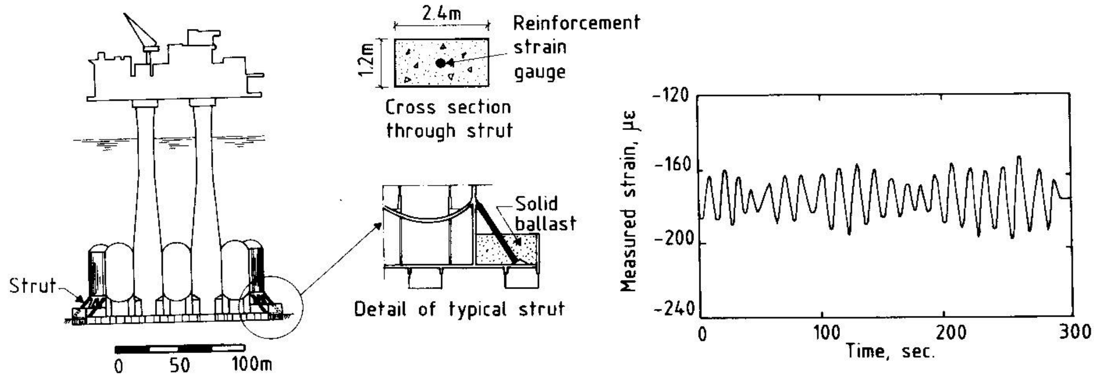
One of the principal uses of NGI's vibrating-wire reinforcement strain gauge has been offshore on the Condeep gravity base structures built by Norwegian Contractors [5]. The instruments have been used both to ensure safe installation of the structures and for long-term performance monitoring needed for design verification purposes and to confirm the integrity of the structures. Three different examples are given below to illustrate why and how the reinforcement strain gauges have been used on these structures.

3.8.1 Monitoring forces in parts of the structure

One structure was designed with a concrete slab around the periphery of the base to increase the foundation area. This slab is supported by massive inclined prestressed concrete struts as shown in Fig. 11(a). Selected concrete struts were instrumented with reinforcement strain gauges to satisfy requirements imposed by the certifying authority. The primary objective of the measurements was to obtain quantative and qualitative information concerning mud line forces caused by wave loading. These instruments have been incorporated into the long-term monitoring program for the structure and static and dynamic strains in the struts have been monitored systematically.



b/ MEASURED STRAIN VERSUS TIME



a/ DETAIL OF STRUCTURE AND INSTRUMENTED STRUTS

c/ SAMPLE OF DYNAMIC STRAIN MEASUREMENTS

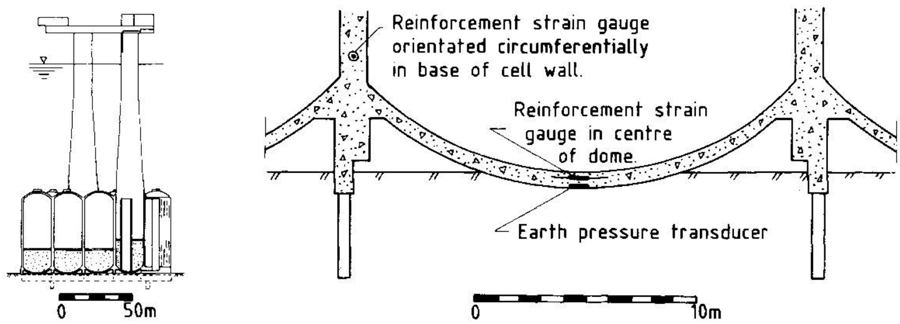
Fig. 11 Monitoring forces in the struts of a Condeep structure

Typical data from the reinforcement strain gauges in the struts are given in Fig. 11(b). Two important activities which had significant bearing on the measured strains are indicated on the figure although others, such as prestressing of the cables and the effects of increased hydrostatic pressure on the caisson during deep submergence and deck mating operations are readily identified. A sample of dynamic strain measurements from a typical strut is given in Fig. 11(c). Such data forms the basis for an evaluation of the mudline forces mentioned above.

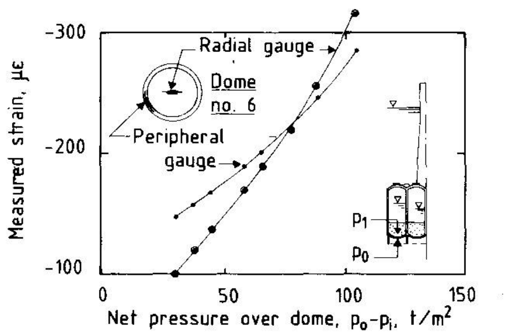
3.8.2 Monitoring critical operations during installation

The base of most Condeep structures consists of a cluster of spherical domes that are generally penetrated slightly into the foundation soil. It is desirable to press the platform as deep into the seabed as possible because this means a reduction in the amount of underbase grout that is injected between the seabed and the undersisde of the platform. While seating the domes during installation of the structure it is therefore important to monitor that the domes are not overstressed.

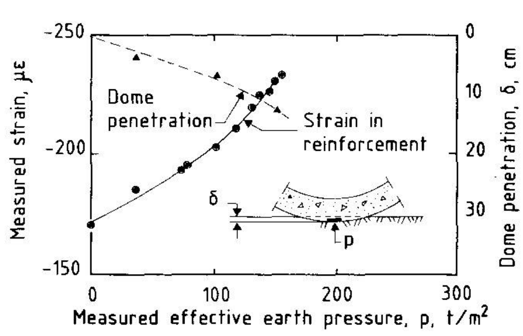
Monitoring the safety of the domes is not a simple task because the contact area and penetration resistance change as the dome penetrates into the soil. Three different techniques have been used to monitor dome seating. As shown in Fig. 12(a), reinforcement strain gauges are used to monitor the strain in the centre of the domes and/or at the base of the cell wall where the resulting hoop stresses can be correlated to the loading on the dome. In addition, the contact pressure between the dome and soil is measured directly by means of an earth pressure transducer mounted flush at the centre of the dome. By using the instrumentation to monitor the loading, the safe and economical installation of the structures have been ensured.



a) DETAIL OF STRUCTURE AND TYPICAL INSTRUMENTATION, LOWER DOMES



b) STRAINS DUE TO CHANGES IN HYDROSTATIC LOADING DURING TEST SUBMERGENCE



c) TYPICAL MEASUREMENTS WHILE SEATING DOMES DURING INSTALLATION OF STRUCTURE

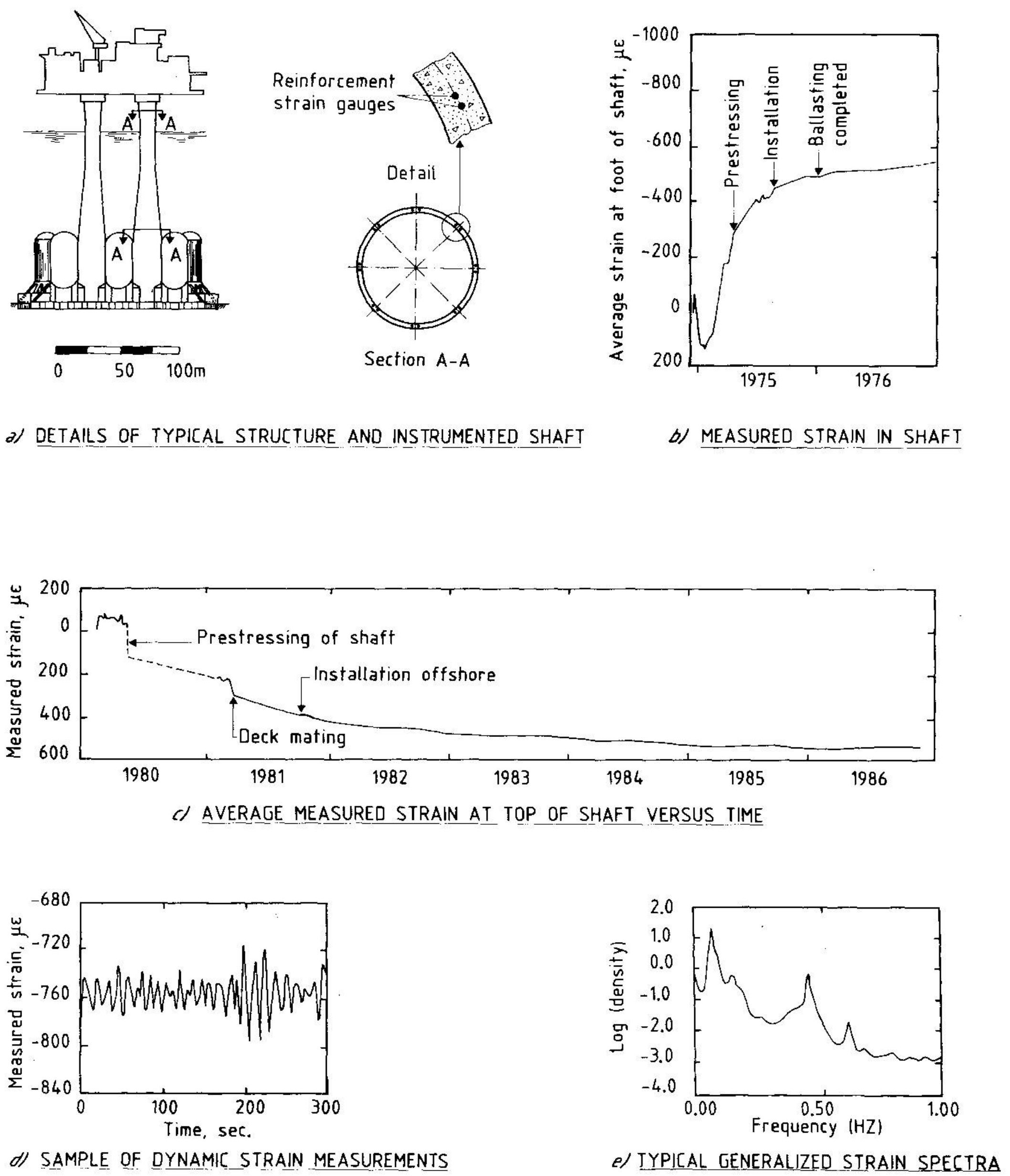
Fig. 12 Strain measurements in the lower domes of Condeep structures

Fig. 12(b) presents typical data from the test submergence of a Condeep structure, which is carried out as preparation for the deck-mating operation. During the test submergence it is possible to verify the operation of the instruments in the dome by comparing the strain gauge readings to the known hydrostatic loading on the lower domes. Fig. 12(c) presents data from seating of one of the domes during installation of a structure.

3.8.3 Monitoring of environmental loading and creep in the concrete

Long-term performance programs for several Condeep structures have included vibrating-wire reinforcement strain gauges for measurement of the static and dynamic axial strains in the shafts.

The first measurements of this kind were initiated as an alternative to direct measurement of the hydrodynamic pressures on the structure [6]. By instrumenting the shaft with strain gauges, Fig. 13(a), it has been possible to determine the resulting environmental loading on the shafts and to use this information to check computational models used during the design. In addition, measured long-term variations in strain have made it possible to study the effects cyclic loading on creep in the concrete.



a/ DETAILS OF TYPICAL STRUCTURE AND INSTRUMENTED SHAFT

b/ MEASURED STRAIN IN SHAFT

c/ AVERAGE MEASURED STRAIN AT TOP OF SHAFT VERSUS TIME

d/ SAMPLE OF DYNAMIC STRAIN MEASUREMENTS

e/ TYPICAL GENERALIZED STRAIN SPECTRA

Fig. 13 Strain measurements in the shafts of Condeep structures

Typical data from the vibrating-wire reinforcement strain gauges in the shaft are given for two different structures in Fig. 13(b) and (c), with important activities indicated. Considerable data have been collected over the years and outstanding material for creep analysis is now available. This is discussed further in the next section.

Dynamic measurements, Fig. 13(d), obtained with the reinforcement strain gauges have been used in a design verification study to compare actual response of the structure to the calculated response. Spectral density plots from the reinforcement strain gauges in the shaft, of which a typical plot is given in Fig. 13(e), and information about displacements and curvatures were obtained from the data.

4. REVIEW OF STRAIN AND CREEP DATA

Some Condeep structures have been extensively instrumented for performance monitoring and data from several years have been collected. Much of the structural data have not been analysed to their full potential. This is unfortunate especially when the extent of the data that exists is considered: data from construction periods, time histories, dynamic response during storms, long-term cyclic loading, etc. In order to give an indication of the potential of the data collected, the following is a comparison between measured values and calculated values of strain in the shaft of one structure.

4.1 General

Reinforcement strain gauges were placed vertically in the centre of the shaft wall 5 metres above the base of the shaft, see Fig. 13(a). The distance from the fixed end was chosen in order to reduce the influence of end effects.

The measured values are presented in Fig. 14(a) showing the development of strain subsequent to completion of slipforming. The calculated values shown in the figure are based on the formulae and curves presented in CEB-FIP Model Code of 1978.

4.2 Concrete

The 28-day cube strength for the concrete used in the shafts was 60.7 MPa. Portland cement with increased fineness was used to achieve a faster slipform-rate and higher compressive strength. The cement content was 400 kg/m^3. The aggregates were fragments of gneisses and granites quarried from large moraine deposits. The water/cement ratio was about 0.40. A superplasticizing admixture, 5l/m^3 was used. The slump was about 200 mm. A modulus of elasticity of 29 GPa for the concrete was measured by standard tests at 28 days.

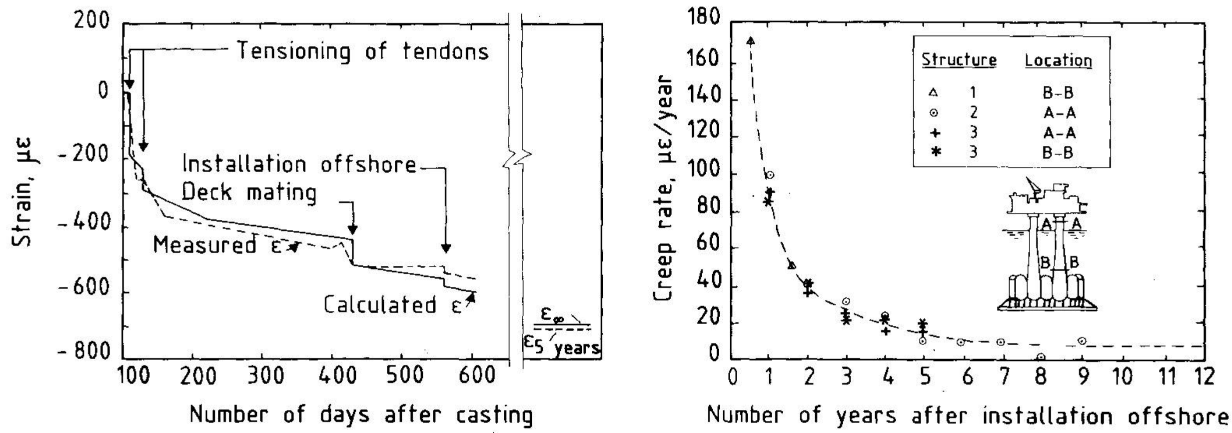
4.3 Loading history

The slipforming of the shafts started in January 1980. The first loading on the instrumented cross section was the weight of fresh concrete. After a few hours the heat of hydration caused a temperature rise. Temperature measurements made in another shaft show a maximum temperature in the centre of +45 deg. C. As the air temperature was about zero, the cooling of the section caused a significant tensile strain in the centre of the wall which can be seen from the measured curve, Fig. 13(c). This tensile strain diminished after some time due to relaxation. In May, once the slipforming had been completed, the ring beam on top of the shafts was cast and then 122 prestressing tendons, which are terminated in the lower part of the shaft, were stressed. The remaining 40 tendons which extended to the top of the shaft were stressed, from both ends, in the first week in June. Fig. 13(c) shows the prestressing of the top of the shaft, i.e., only the tensioning of the last 40 tendons, while Fig. 14(a) shows the strains at the base of the shaft and therefore the tensioning of both sets of tendons.

During the interval from June 1980 till deck mating at the end of March 1981 no significant loads were applied to the structure. The installation of the structure took place in August 1981 at which time the water pressure on the structure increased.

4.4 Comparison of curves

Fig. 14(a) shows a generally good correspondance between the observed and the calculated strains. The tensioning of the first prestressing tendons was chosen as a clearly defined starting point for the calculated curve since effects such as increase in shaft weight, curing temperature, etc., complicate the calculations for the initial part of the curve. It appears that the instant elastic deformation in the first part of the curve (tensioning of tendons) is somewhat underestimated although an increasing E-modulus was used. The development of creep and shrinkage strain with time show a very good agreement with the measured values. After approximately five years the measured strain appears to approach a limiting value of about 700 microstrain which is the same value calculated for the strain at infinite time, ε_∞.



a) COMPARISON OF MEASURED AND CALCULATED STRAIN

b) MEASURED LONG TERM CREEP FOR THREE STRUCTURES

Fig. 14 Strain and creep data from the shafts of Condeep structures

A comparison of the observed creep rate for three Condeep platforms is shown in Fig. 14(b). The data represents long-term creep data for structures that have been subjected to cyclic loading for several years, one structure for more than nine years. The three rates are almost identical. This is perhaps to be expected since the structures are similar in concept, designed in the same manner, and subjected to the same type of loading.

5. CLOSING REMARKS

The vibrating-wire reinforcement strain gauge has proven to be a very useful and versatile instrument for monitoring strains in large concrete structures. With the good performance record of the gauge and with continually new problems facing the structural engineer, e.g. fjord crossings, oil platforms at deep water sites, new bridge designs, etc., the gauge should continue to play an important role in performance monitoring programs.

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