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OVERCORING ROCK STRESS MEASUREMENTS IN BOREHOLE KOV01, OSKARSHAMN

Report prepared by Hans Klasson, Kent Lindblad, Ulf Lindfors and Stig Andersson
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Approved:

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Hans Klasson

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ABSTRACT

This report presents the results from three-dimensional overcoring rock stress measurements conducted in borehole KOV01, drilled in the harbour of Oskarshamn in southeastern Sweden.

Totally, 16 overcoring tests were attempted in KOV01 on the 300 m- and the 500 m levels. Of the tests conducted only five were judged successful and of use for further evaluation.

The poor result were due to mainly a high content of mud and drill cuttings trapped in the borehole during flushing prior to test installation. A vast amount of cuttings settled into the pilot hole and prevented proper bonding of the strain gauges to the rock. The possibilities of obtaining good results were hence limited. Many tests were rejected as they displayed indistinct gauge response or gauge drift during overcoring, or an irregular response to the pressure load in the biaxial test chamber.

The experience from the KOV01 overcoring test programme points out the need for a clean pilot hole for proper test installation. The tedious work to overcore bad tests and re-drill pilot holes using conventional drilling technique also became evident. Therefore, a study to drill the pilot holes using wireline technique in the future has been initiated by SwedPower and SKB. It also came clear that the designed casing and airlift pumping sealed system for flushing in KOV01 was not suitable for overcoring purposes as it left cuttings trapped in the borehole.

External supervision of the field work for qualitative purposes pointed out the need for more extensive and more detailed routines for test documentation.

Testing at the 300 m level resulted in one successful measurement. From four good tests around 500 m hole depth the resulting average magnitudes indicate the design values in the vertical- and horizontal plane as σ_H = 24 MPa, σ_h = 10.5 MPa and σ_v = 9.3 MPa.

The results point out a clear trend for the maximum principal stress but not for the intermediate and minor stresses. σ_1 is close to horizontal and trends WNW. The average orientation of σ_H derived from the results is a little bit more to the west than what could be expected from previous measurements on Äspö.

The average value for Young’s modulus derived from four biaxial tests is 66 GPa. This is lower than results from rock mechanical testing of Äspö diorite in uniaxial compressive mode (average 73 GPa). Poisson's ratio given by biaxial testing on the diorite in KOV01 is 0.28 on the average, which agrees well with laboratory test results (0.28).

1 INTRODUCTION

1.1 SCOPE

This report constitutes the fulfilment of Purchase Order 3309 placed with SwedPower AB by the Swedish Nuclear Fuel and Waste Management Company (SKB). The order states that SwedPower AB shall conduct rock stress measurements using three-dimensional overcoring equipment at two levels in borehole KOV01 in Oskarshamn. The cored borehole is located in SKB's Instrument Depot in Oskarshamn. Its geographical location is shown in Figure 1-1.

The present stress measurements are part of a test program for technology for drilling and measurement of rock properties executed in borehole KOV01.

The field campaign was divided into two periods. Field measurements started on May 9, 2000, with testing on the 300 m level. The intermission commenced on May 31 and testing on the 500 m level started on September 11. The field work was completed on October 3, 2000.

1.2 OBJECTIVES

The objectives with the stress measurements were to:

- To test the performance of the overcoring equipment in a deep water-filled borehole.
- To determine the complete stress field in the undisturbed rock mass at the 300 m- and the 500 m test level. This was to be achieved by at least 4 good tests from each level.

The report provides a detailed presentation of the stress measurements conducted. Chapter 2 summarises the instrumentation and experimental procedures employed. The field work is summarised in Chapter 3. Chapter 4 presents in detail all results obtained in borehole KOV01. Some brief comments on the results are also included in that chapter. Sources of errors are discussed in Chapter 5, whereas Chapter 6 presents the foremost conclusions from the work.

Raw data from the tests are reported in Appendices A through C.

It should be noted that the presentation is restricted to the work done and the results obtained, as such. It is neither attempted to put the data into a geological/tectonic context, nor to discuss the implications of the results for future work.

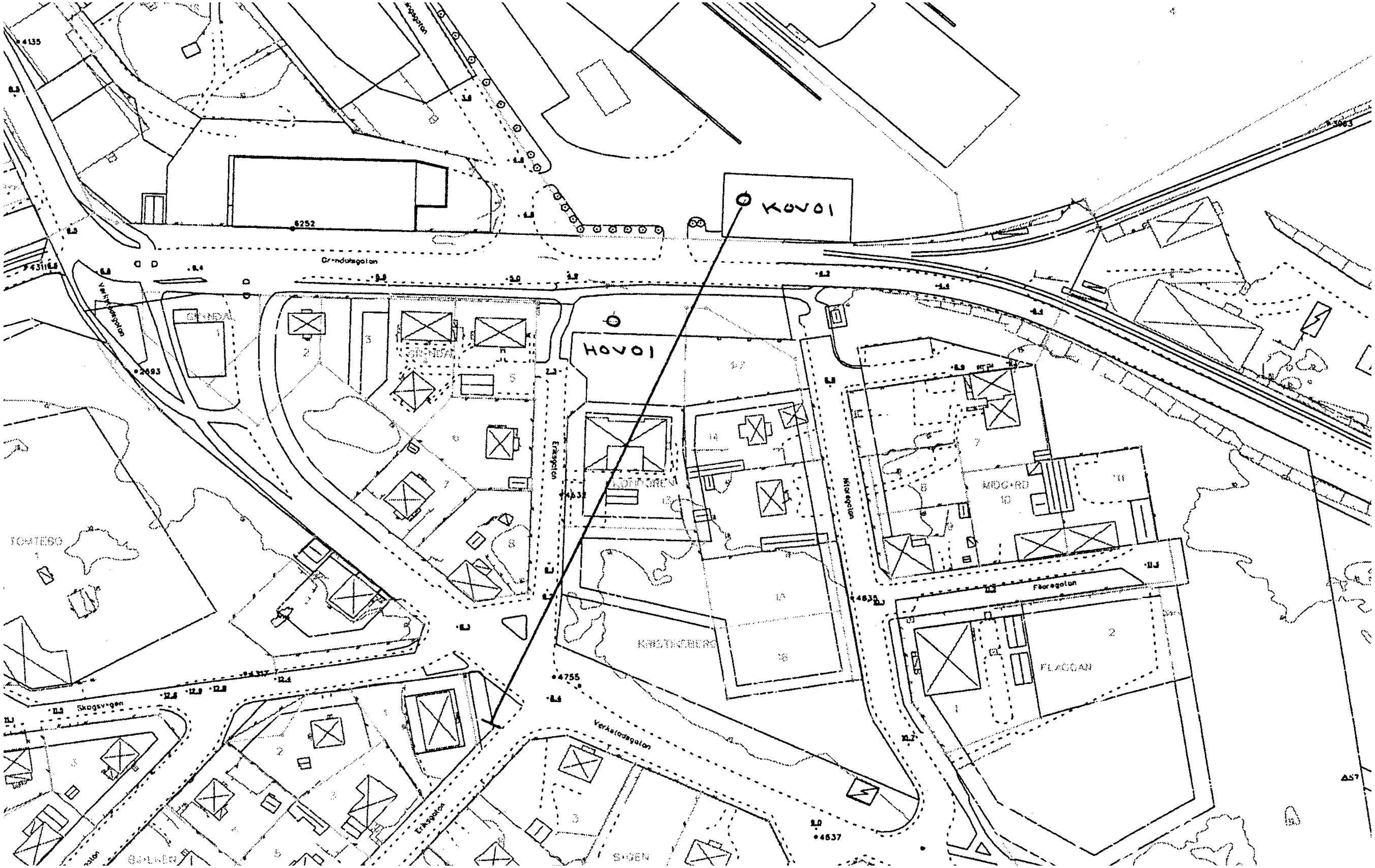


Figure 1-1. Location of the test borehole KOV01 in the harbour of Oskarshamn. Plan view.

2 EXPERIMENTAL

2.1 THE OVERCORING METHOD

2.1.1 Background

The overcoring technique to determine in situ stresses utilises the principle of stress relief. The method involves measurements of the displacements in a piece of rock when it is released from the rock mass. The in situ stresses are calculated using the measured strains and the elastic properties of the rock according to classical theory presented by Leeman and Hayes, 1966.

The past three decades have seen the development of a variety of overcoring instruments, which permit the determination of the complete three-dimensional stress tensor from a single measurement. The technique used in the present case consists of coring a borehole at large (76 mm) diameter over a coaxial small-diameter (36 mm) pilot hole in which a strain-measuring instrument is located. Thus, the cylindrical core sample is isolated from the stress field in the rock mass and the initial state of stress can be calculated from the deformations or strains occurring in the sample during overcoring.

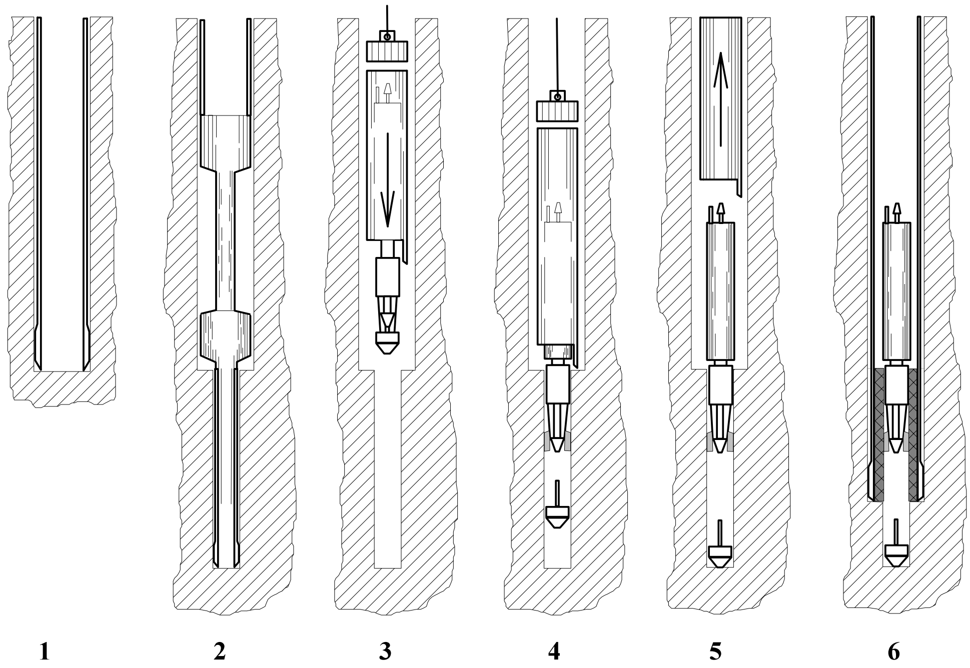
The calculation of stresses utilises the elastic theory and it is assumed that the rock behaves in a linearly, isotropically elastic manner, implying that the deformation of the core sample during stress relief is identical in magnitude to that produced by the in situ stress field but opposite in sign. It is further assumed that the rock volume is both continuous and homogeneous. Application of the elastic theory also requires knowledge of the elastic parameters of the rock material, E (Young's modulus) and ν (Poisson's ratio).

2.1.2 The Borre Probe

The Borre Probe employed by SwedPower AB is a triaxial strain-measuring instrument, which allows for the derivation of the complete state of stress tensor in three dimensions from one successful measurement.

The Borre Probe has been developed in Sweden by Vattenfall over the last 25 years to perform stress measurements in deep, water-filled boreholes drilled from surface by conventional drilling techniques. SwedPower AB has carried out more recent development and commercial operation of the equipment. The Borre Probe, described fully in Hallbjörn et al., 1990, has been used in several countries on several occasions in the 1980s and 90s. The measurement procedure is illustrated in Figure 2-1.

The evaluation of the complete stress tensor from measurements with a triaxial device such as the Borre probe requires only the strains induced by overcoring, the orientation of the probe (generally to magnetic north) and the elastic properties of the rock material. Since the stiffness of the probe's gauges is negligible in comparison to the stiffness of the rock, the overcoring strains represent a complete relaxation of the core. Hence, the core dimensions do not enter into calculations, except in the evaluation of the elastic properties as determined on the core specimen.



1 Advance ϕ76 mm main borehole to measurement depth.

2 Drill ϕ36 mm pilot hole and recover core for appraisal.

3 Insert Borre probe in installation tool into hole.

4 Probe releases from installation tool. Gauges bonded to pilot-hole wall under pressure from the nose cone.

5 Pull out installation tool. The probe is bonded in place.

6 Overcore the Borre probe and recover in core barrel.

Figure 2-1. *Measurement procedure using the Borre Probe.*

The probe is cylindrical with a maximum diameter of approximately 54 mm and a length of about 550 mm. It is lowered into the borehole by rods in a combined installation tool and weight. A brief summary of the component parts of the instrument follows.

2.1.3 Strain gauges

The instrument carries nine electrical resistance strain gauges mounted in three rosettes. Each rosette comprise three strain gauges oriented parallel, at 45º angle and perpendicular to the borehole axis. Strain gauge configuration is summarised in Table 2-1.

Table 2-1. *Orientation of the strain gauges in each rosette on the Borre Probe.*

Rosette No.	Gauge No.	Orientation of gauge within rosette
1	1	Axial / Longitudinal
	2	Circumferential / Transverse
	3	45º
2	4	Axial / Longitudinal
	5	Circumferential / Transverse
	6	45º
3	7	Axial / Longitudinal
	8	Circumferential / Transverse
	9	45º

The strain-gauge rosettes are bonded to three plastic cantilever arms at the lower end of the probe, which is the only part of the instrument that enters into the pilot hole. The arms are located 120^{o} apart with a known orientation to the main body of the instrument. Thus, the nine strain gauges of the Borre Probe form an array representing seven spatially different directions. As strain measurements in six independent directions are required to determine the complete stress tensor, the Borre Probe provides redundant strain data. Hence, up to one non-parallel gauge and two parallel gauges may be rejected or malfunction during the overcoring procedure without impairing complete calculation of the stress tensor. The strain gauges are connected to a data logger up the inside of the probe.

2.1.4 Data logger

Besides the nine strain gauges, the Borre Probe also contains a thermistor and one dummy gauge to assess the temperature effects on the readings during the overcoring phase. The downhole data logger is located in the main body of the probe, Figure 2-1, and records eleven channels of data at pre-set intervals from a pre-set start time. The logger, powered by a battery also located in the probe's main body, is capable of storing 8 h of data recorded at 60 s intervals.

Prior to the installation of the probe, the data logger is connected to a portable computer and programmed with the measurement start time and recording interval. No further connection to the ground surface is required after this programming. After overcoring, the probe is recovered with the overcore sample inside the core barrel. Before removal of the sample and disconnection of the strain gauges, the probe is again connected to the portable computer and the data recorded is retrieved using communication software.

2.1.5 Installation tool

Connected to rods, the installation tool carries the probe in the hole and releases it into the pilot hole. The tool contains a mechanical latch that is triggered when the base of the tool lands on the base of the main borehole. Triggering the latch releases the probe from the tool and forces the cantilever arms and strain gauges against the pilot-hole wall.

The installation tool also contains a magnetic compass, connected to the latch and mechanically fixed in its orientation when the latch is triggered. This effectively records the orientation of the probe as it can only be set in and released from the tool in one orientation.

2.2 TEST PROCEDURE

2.2.1 Drilling the pilot hole

Stress measurements using the Borre Probe requires a centrally located, straight, clean 36 mm pilot hole at the end of the main 76 mm borehole. Diametrical accuracy is necessary as the probe has a limited operating range during installation. The pilot hole needs to be centrally located in the bottom of the 76 mm hole to enable overcoring and biaxial testing of the recovered cylindrical rock sample. At the position of the strain gauges, the pilot should be clear of drill cuttings to ensure a good bond between the gauges and the pilot-hole wall. It is preferable also to recover an intact core from the pilot hole. This core should be of sufficient quality to enable the quality of the rock in the large-diameter overcore sample to be anticipated so that the gauges are not located in a position over or adjacent to pre-existing discontinuities - normally, such locations will yield poor measurements.

Before lifting the drill string to recover and examine the pilot-hole core, flushing takes place until the return water is clear from drill cuttings. The return water is carefully examined before deciding on test installation should the pilot core be of such quality that testing is permitted. Immediately after the pilot core is recovered a test probe is sent down the borehole on a wireline in order to check if the pilot hole is clear from cuttings and other debris.

If the core break in the main borehole is not flat enough to ensure centric location of the pilot hole, a specially manufactured planing tool run on the 76 mm core barrel is used to prepare the base of the 76 mm borehole prior to drilling of the pilot hole.

If the core recovered from the pilot hole carries discontinuities adjacent to the gauge position, the pilot hole is abandoned and overcored and another pilot hole is attempted. If the pilot core indicates suitable measurement conditions, the return water is clear and the test probe indicates a clear pilot hole, the Borre Probe is prepared for installation.

In the present case, all pilot holes were drilled to a length of approximately 50 cm. Flushing continued until return water was clear before recovering the pilot core in order to improve the conditions for a successful measurement by supplying a pilot hole free of drill cuttings. It should be noted though, that the special air-lift (mammut) pumping system used in KOV01 was a sealed system which at first did not permit direct sampling of the return water and thus made it difficult to judge the presence of cuttings.

2.2.2 Installation of the Borre Probe

The connection of the strain gauges to the logger and other preparation and testing of the instrumentation is generally carried out whilst drilling the pilot hole. The data logger is programmed and the compass and the probe are attached to the installation tool. The latching mechanism in the tool is armed and the tool is attached to a weight carried on the wireline. Finally, the adhesive is mixed and applied to the strain-gauge rosettes and the gauges are then covered with a protective cone before the whole assembly is inserted into the borehole by rods.

When the installation tool reaches the end of the 76 mm borehole the release mechanism is activated as the latch touches the ledge formed between the main borehole and the pilot hole. As the probe is installed, the protective cone preventing the adhesive from being removed when entering the probe into the hole is pushed away further into the hole allowing the gauges to contact the pilot-hole wall. The tool is left in the hole until the adhesive has set completely, normally 8 hours in water-filled boreholes.

2.2.3 Overcoring

The requirements for the overcoring of the Borre Probe are that the overcore is concentric to the pilot hole, drilled at a constant and steady rate, and that a suitable length of solid core is recovered at the position of the strain gauges. Concentricity of the overcore, which is governed by the positioning of the pilot hole, is both an operational requirement to ensure the safety of the downhole equipment, and necessary for the calculations of the stress distribution and material properties from biaxial testing of the core sample. A constant drilling rate during overcoring ensures that stress relief on the core occurs in a controlled manner and that the strain-gauge response is not unduly affected by the drilling. Controlling the rate of penetration reduces the possibility of the overcore sample cracking in weaker strata. The recovery of solid core of suitable length at the gauge position is required for subsequent biaxial testing. Cracking of the core in the proximity of the gauges can also influence the strain-gauge response and possibly render the measurement incalculable.

After the epoxy setting period and as the in-hole data logger is due to commence strain readings, the installation tool is pulled out from the borehole. The compass is removed from the tool and the compass reading is noted. The drill string, now carrying the Craelius T2-76 mm drill bit is then pushed in. While holding the drill bit about 10 cm from the end of the main borehole, flush water is circulated for a 10 - 15 min period to stabilise temperatures before overcore drilling commences. Overcoring is then performed to a length beyond the end of the pilot hole in order to recover the protective cone. After breaking the core loose, the drill string is retrieved and the overcore sample and the probe are taken out from the hole. In the present measurements, overcoring was carried out to a length of 60-70 cm.

When the overcore sample has been recovered, strain gauge data recordings are immediately transferred from the logger to a laptop computer. The Borre Probe, but not the strain gauges and their respective connecting cables, is dismounted from the overcore sample. Then, if recovery of unbroken core is of sufficient length, i.e. minimum 25 cm, the overcore sample is subjected to biaxial testing in order to determine the elastic properties of the rock.

2.2.4 Biaxial testing

The biaxial testing of the overcored specimens has two purposes; Firstly, it allows the elastic constants of the rock to be determined and secondly, it provides a check of the performance of the individual strain gauges 1-9, Table 2-1. The former is required for the subsequent stress computations, and the latter provides input to the examination of overcoring strains as well as to the overall judgement of the validity of the test.

All suitable overcore samples are tested in a biaxial test chamber to determine the elastic properties of the rock. During testing the strains induced in the core sample are monitored by the strain gauges installed by the Borre Probe connected to digital strain readout.

The test sequence comprise both loading and unloading in order to study possible inelastic behaviour of the rock. The maximum load applied during biaxial testing should preferably correspond to the measured stress magnitudes. However, to reduce the risk of cracking the hollow cylinders, the maximum load applied to the core specimens is set to 10 MPa in load increments of 1 MPa. The core is then unloaded stepwise by 1 MPa increments. The results from the tests are visualised in the form of diagrams of recorded strains, plotted against applied pressure. A schematic plot is shown in Figure 2-2. Since geometry of the test is axisymmetric, the array of strain gauges of the Borre Probe represents three groups with respect to orientation, axial (parallel), circumferential (perpendicular) and at a 45^o angle (to the hole axis). Theoretically, assuming isotropic and homogeneous rock properties, the gauges within each group should respond identically.

To derive the elastic properties the theory for an infinitely long, thick-walled circular cylinder subjected to uniform external pressure is considered. The assumption of plane stress applies as shown by Obert and Duvall, 1967. In the calculation of Young's modulus (E) and Poisson's ratio (ν), the parameters that has to be known are the core dimensions and the axial and circumferential strain readings at different pressure loads.

Since the Borre Probe incorporates three pairs of circumferential and axial strain gauges, three pairs of elastic property-values are obtained from each biaxial test. The aim is to obtain rock parameters that apply to the relaxation experienced by the rock during overcoring. Therefore, the values of E and ν are taken to be secant values, calculated from strain data obtained during unloading of the core specimen.

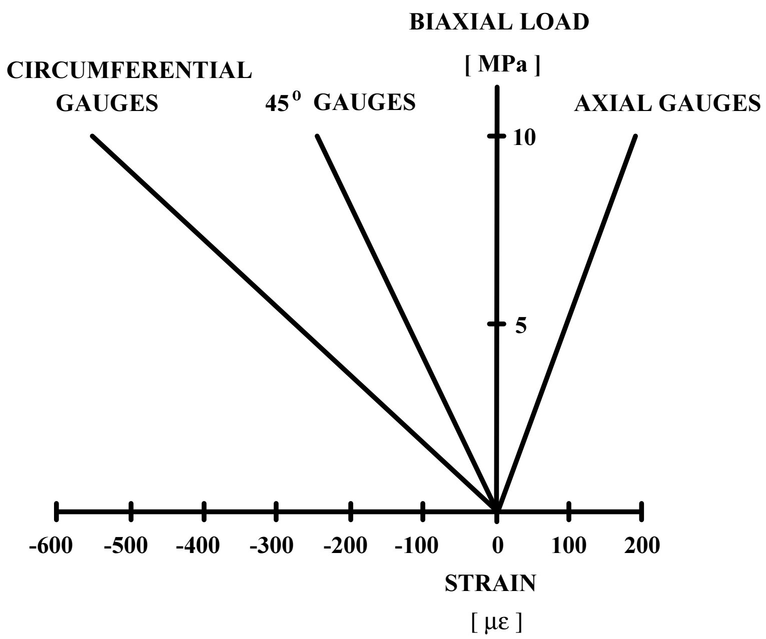


Figure 2-2. *Hypothetical results from biaxial testing of an ideal linearly elastic material using the gauge configuration of the overcoring test.*

2.3 DATA REDUCTION

The equations relating the strains occurring at the pilot hole wall as a consequence of overcoring, to the virgin stress field at the point of measurement are obtained from the classical Kirsch solution given in Jaeger and Cook, 1979. For isotropic material, the appropriate set of equations were presented by Leeman, 1968.

The program to calculate the stress tensor is based on the equations given by Leeman, 1968. To calculate the three-dimensional stress at a measuring point the program requires strain data from at least six independent directions (as described above), the orientation of the borehole, the orientation (magnetic bearing) of the Borre Probe and the elastic constants of the rock (Young's modulus and Poisson's ratio).

When all nine gauges function properly during a measurement, redundant strain data are obtained. The stress calculation program uses a least square regression procedure to find the solution best fitting all the strain data. From this solution, the program calculates the stress field in the horizontal plane and the magnitude and orientation of each of the three principal stresses. If more than one measurement has been carried out at the same level in a borehole, the program can be set to define all measurements in one and the same co-ordinate system and calculates mean values of the three dimensional stress field.

3 FIELD WORK

The KOV01 stress measurements were conducted during two separate phases. The first at hole depths around 300 m, and a second phase below 500 m hole depth. The first field period occurred between May 10-31, 2000. It incorporated an interruption between May16-22 due to grouting of a crushed zone at hole depth 307 m. The second field period started on September 10, 2000 and was completed on October 03, 2000.

Measurements were conducted in borehole KOV01. The hole is drilled from the floor of the Instrument Depot. The co-ordinates, given in the national grid system (RT38) and orientation data of borehole KOV01 on collar level are the following:

X-co-ordinate:	63 48516.013
Y-co-ordinate:	15 39942.059
Z-co-ordinate:	3.052
Bearing (degrees):	202.7°
Dip (degrees):	-77.3°

Dip is calculated positive from the horizontal and upward, and bearing is calculated clockwise from the Geographic North. Magnetic declination has ***not*** been accounted for. (It should be noted that this differs from the Äspö HRL local coordinate system in which the Äspö x-axis is 11.9 degrees west of Geographic North.)

Measurements during drilling showed that borehole orientation at the 300 meter hole depth was 205.7° with a dip of -69.4°, and 216.6° with a dip of -76.9° at the 500 meter hole depth. These orientation data have been used in the stress calculations for levels 1 and 2, respectively. For location of the borehole Figure 1-1 should be consulted.

The aim of the measurements was to study the method and the performance of the tests equipment together with the type of drilling and pumping systems which were planned to be used at the site investigation for nuclear waste storage. It should be mentioned that SKB had decided to test a new airlift (mammut) pumping system for flushing during drilling of KOV01. As the experience with this sealed system for flush water, designed to prohibit contamination of the borehole water, had been good so far, it had been decided to use it during the overcoring tests as well.

The test equipment functioned well but there were other problems. The major one was that the recently developed airlift pumping system for cleaning the drillhole from cutting material did not function properly. From the start of the field work evidence of drill cuttings and/or rock fragments obstructing the tests were found on top of the adapter as it was recovered before overcoring and sometimes on top of the probe after overcoring as well. As the pumping system was a sealed one, it was impossible to continuously sample the return water during flushing of the pilot hole, a procedure normally undertaken by the field crew prior to termination of the flushing process. Instead the amount of cuttings in the water had to be judged while the water was still running in transparent hoses and containers. Later during the field period, the surface part of the pumping system was modified so that sampling of return water could take place. However, even if the judgement after sample examination of the return water said it was clean, numerous test attempts still failed due to mud-sized cuttings stuck on the walls of the pilot hole preventing proper cementing of the strain gauges to the rock. The presence of mud in the pilot hole also yielded an overall uncertainty regarding the evaluation of measured strains for those test that were judged being successful.

The airlift (mammut) pumping system had been developed before drilling of KOV01 started, and tests had shown that the system functioned well. Soon after the stress measurements had started, it was found that the mud-sized cuttings in the pilot hole were the main problem to overcome. The field crew first tried to extend flushing periods but for no good. It was concluded that cuttings could be trapped between the inner and outer casings at the top 100 m of the borehole during flushing; the casing set up being part of the pumping system. Then, when the drill string was lifted mud-sized cuttings in suspension came back into the drillhole and started to settle. In order to clean the walls of the pilot from mud a brush was mounted at the bottom of the test probe, which was run through the hole on a wire-line after the pilot core, had been recovered. Moreover, another brush was welded on to the bottom of the glue cup in an attempt to clean the walls immediately before the gauges were bonded in place. These precautions improved the rate of successful tests, but it was also concluded that cuttings could cause problems still. But it was not until the very end of the field period that the casing was modified. That action, coupled with close examination of the return water and the set of brushes on in-the-hole equipment, provided a pilot hole that was as clean as it could under the circumstances.

Another problem was related to the pilot hole drilling equipment. At the 300 m level this equipment was damaged twice while attempting to drill a pilot hole. It seemed that the pilot core barrel had taken a direction off centre of the main hole and as drilling continued the core barrel got bent and finally it broke. After examination of the wrecked equipment the field crew concluded that the amount of cuttings at hole bottom was very high. The water channels in the steering guide used to centre the pilot drill bit at hole bottom were too few to permit the cuttings to pass upwards when flushing started. Thus, as the steering guide was kept a bit above the bottom of the 76 mm hole when pilot hole drilling commenced, the drill bit was not centred and drilling continued in an angled direction. A number of extra channels through the steering guide were drilled and welds reinforced the adapter between the drill string and the pilot hole equipment. From then and on the pilot hole drilling equipment performed as expected.

4 RESULTS

4.1 GENERAL TEST DATA

The measurements in borehole KOV01 included a total of 16 tests of which 5 yielded successful results. The strain gauge response curves registered during the overcoring process are presented in Appendix A.

On level 1, around hole depth 300 m, 6 overcoring tests were attempted of which only one test rendered useful results. Test 2, which was included in the early evaluation, was finally rejected, as the gauge responses before and during the overcoring phase were concluded too unstable.

Testing on level 2, just below 500 m hole depth, comprised 10 tests of which 4 have yielded results judged useful for further evaluation. Test 1, 4 and 6 were included in the preliminary evaluation, but when analysed further test 1 and test 4 yielded suspiciously low values for σ_3 as well as for σ_h and σ_v, whereas test 6 displayed a lot of drift in gauges prior to and after they are overcored. Table 4-1 summarises the general information from all test attempts. The main reason for the failed tests was that mud and cuttings trapped in the borehole during flushing, obstructed proper bonding of the gauges to the pilot hole wall.

Table 4-1. *General test data from measurements in borehole KOV01, Oskarshamn.*

Level No.	Measuring Point No.	Hole Depth (m)	Comment	Incl. in Evaluation	Rock type
1	1	289.08	Failed	No	*Äspö diorite*
1	2	290.31	Unstable, drift	No	*Äspö diorite*
1	3	314.88	Failed	No	*Äspö diorite*
1	4	322.74	Failed	No	*Äspö diorite*
1	5	325.83	Test OK	Yes	*Äspö diorite*
1	6	326.85	Failed	No	*Äspö diorite*
2	1	511.78	Uncertain result	No	*Äspö diorite*
2	2	512.77	Failed	No	*Äspö diorite*
2	3	513.79	Failed	No	*Äspö diorite*
2	4	514.79	Uncertain result	No	*Äspö diorite*
2	5	515.80	Test OK	Yes	*Äspö diorite*
2	6	516.89	Drifting gauges	No	*Äspö diorite*
2	7	519.84	Test OK	Yes	*Äspö diorite*
2	8	520.71	Compass failure	Yes	*Äspö diorite*
2	9	521.61	Failed	No	*Äspö diorite*
2	10	527.46	Biax incompl.	Yes	*Äspö diorite*

Note: Hole depth calculated from the floor level in the SKB Instrument Depot.

4.2 BIAXIAL TESTING

All suitable overcore rock samples were tested in the biaxial cell to determine the elastic properties. The gauge response-curves from these tests are given in Appendix B. Table 4-2 shows the values of E and ν as interpreted from the biaxial tests. Test results are only shown for the tests which were included in the subsequent stress calculation. The elastic parameters were determined using the secant method from the unloading part of the biaxial testing curves.

Biaxial testing of the overcore samples was only possible for 7 out of 16 tests. In some cases improper gauge response during either the overcoring process or during the biaxial test caused the rejection of the biaxial test result. The main reason for the poor outcome was that drill cuttings had obstructed proper cementing of the gauges to the hole wall as it had been trapped in the borehole during flushing.

Table 4-2. *Results from biaxial tests on overcore Äspö diorite rock samples from borehole KOV01, Oskarshamn. Only tests from successful stress measurement points are presented.*

Level No.	Measuring point No./ Test No.	Hole Depth (m)	Young's modulus, E [GPa]	Poisson's ratio, ν
1	5	325.83	66	0.21
2	5	515.80	56	0.21
2	7	519.84	77	0.37 *(0.3)*
2	8	520.71	66	0.35 *(0.3)*
	Average:		**66**	**0.28 *(0.26)***

Note 1: Hole depth calculated from the floor level in the SKB Instrument Depot.
Note 2. For stress calculations from tests in granitic rock, Poisson's ratio ν has been maximised to 0.3.

For Test 1 and Test 5 on level 2, one and two rosettes of strain gauges respectively was lost before or during the biaxial test. When comparing the load response (strain-pressure curve distribution) of strain gauges of the same orientation, it is seen that the curves differ in almost every test. This can be explained by anisotropy effects or, more likely, by poor cementing of the gauges to the rock caused by a high content of mud and drill cuttings left in the borehole before installation of the probe.

For Test 10 at level 2, biaxial testing was incomplete (cf. Table 4-1). For the evaluation of rock stresses at this point, a mean value of E = 66 GPa was used (also similar to the nearby Test 8), and a Poisson's ratio of 0.25 (typcial for this type of rock).

From the KOV01 tests, a mean value on the Young's modulus is 66 GPa is derived (interval 56-77 GPa). For Poisson's ratio, ν, the average equals 0.28 (interval 0.21-0.37).

Fairly recent laboratory testing of the mechanical properties of the Äspö diorite (Nordlund et al., 1999) gave a mean value for Young's modulus (E_{50}) equal to 73 GPa (interval 70-75 GPa) and a mean Poisson's ratio (ν_{50}) of 0.28 (interval 0.27-0.29).

4.3 PRINCIPAL STRESSES

For the principal stresses measured in KOV01 the results are given in Table 4-3 through 4-5. A graphical presentation of the principal stress orientations is given in Figure 4-1. Note that for Test 10 at level 2, estimated values of 66 GPa and 0.25 were used for Young's modulus and Poisson's ratio, respectively, in the stress evaluation (incomplete biaxial test). Note that for Test 8 at level 2, no orientation could be determined due to compass failure; hence it is not possible to calculate any orientations for the principal stresses (only magnitudes). Consequently, data from Test 8 could not be included in the average value given in Table 4-3. Also note that plunge is defined positive downward from the horisontal plane. The stress calculation data for each test point on the two levels are given in Appendix C. Compass failure

Table 4-3. *Principal stress magnitudes as determined by overcoring, borehole KOV01.*

Level No.	Measuring point No.	Hole Depth (m)	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)
1	5	325.83	28.0	7.8	4.9
	300 m lev. ave.		*N/A*	*N/A*	*N/A*
2	5	515.80	30.8	8.8	6.9
2	7	519.84	25.7	10.9	4.0
2	8	520.71	(25.7)	(9.4)	(7.3)
2	10	527.46	26.3	13.2	6.1
	500 m lev. ave.	*excl. mp 8*	***24.1***	***11.0***	***8.6***

Table 4-4. *Principal stress orientations as determined by overcoring, borehole KOV01. Orientations are given as trend/plunge of the stress vectors σ_1, σ_2 and σ_3.*

Level No.	Measuring point No.	Hole depth (m)	σ_1 Trend/pl.	σ_2 Trend/pl.	σ_3 Trend/pl.
1	5	325.83	298/21	039/26	174/55
	300 m lev. ave.		*N/A*	*N/A*	*N/A*
2	5	515.80	288/01	019/37	197/54
2	7	519.84	300/08	037/36	200/51
2	8	520.71	-	-	-
2	10	527.46	242/01	142/83	332/07
	500 m lev. ave.		***278/01***	***009/30***	***186/60***

Note 1: Trend is calculated clockwise from the bearing of geographic north. Plunge is defined as being zero in the horisontal plane and positive downward. Declination not adjusted for.
Note 2: During test 8, level 2, the compass failed to lock, thus no stress direction can be given.

The average stress magnitudes given in the tables above have been obtained by transformation of all applicable results to one common co-ordinate system, and then solving the average stress tensor for its eigenvalues.

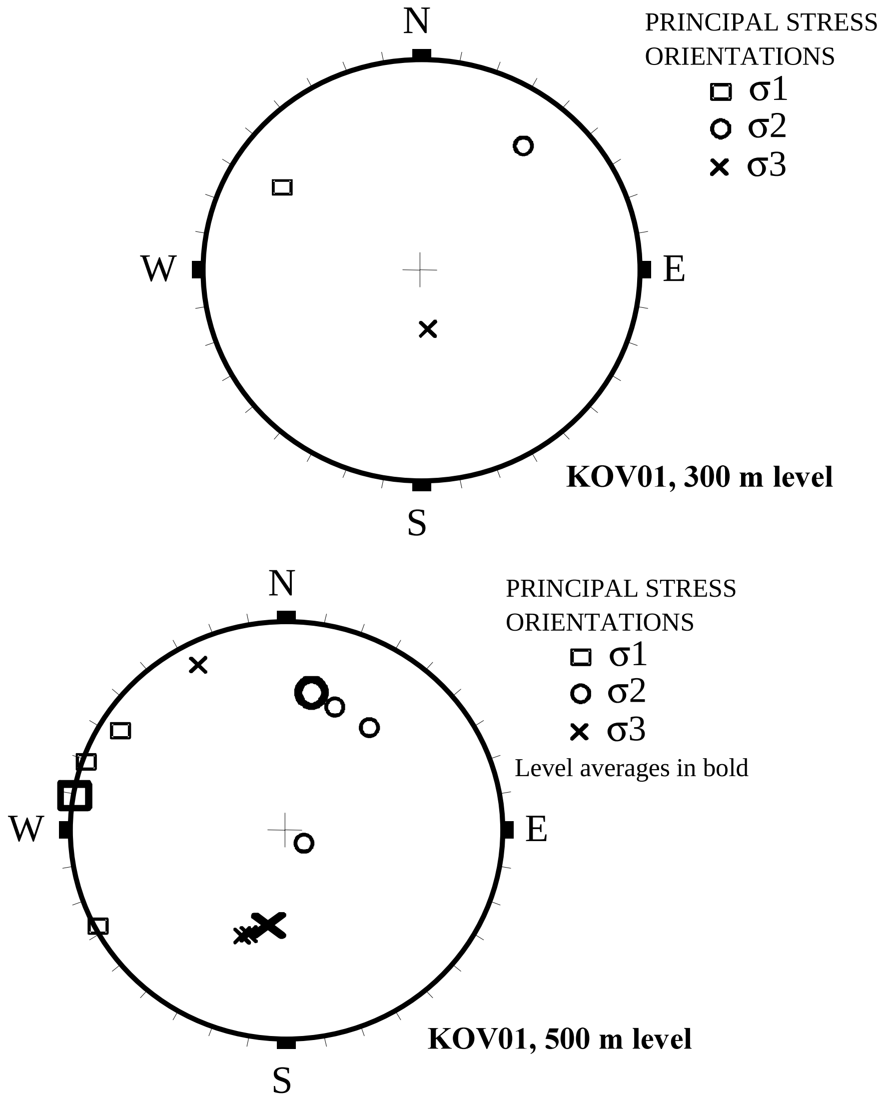


Figure 4-1*. Principal stress directions, borehole KOV01. Lower hemisphere, schematic plot. North refers to geographic north. Data taken from Table 4-4. Declination not adjusted for.*

4.4 HORIZONTAL AND VERTICAL STRESSES

For the horizontal and vertical stresses measured in KOV01 the results are given in Table 4-5). Test 8 at level 2 was not included in the average since no orientation of the horizontal stresses could be determined due to compass failure during measurement. For stress calculation input data Appendix C shall be consulted.

Table 4-5. *The horizontal- and vertical stress state as determined by overcoring, borehole KOV01.*

Level No.	**Measuring point No.**	**Hole Depth (m)**	**σ_H (MPa)**	**σ_h (MPa)**	**σ_v (MPa)**	**Trend σ_H** (º clockwise fr. geogr.. North)
1	5	325.83	25.1	7.2	8.5	117
	300 m lev. ave.		*N/A*	*N/A*	*N/A*	*N/A*
2	5	515.80	30.8	8.1	7.6	108
2	7	519.84	25.3	8.3	6.9	119
2	8	520.71	(24.8)	(8.0)	(9.6)	-
2	10	527.46	26.3	6.2	13.1	062
	500 m lev. ave.	*excl. mp 8*	***24.0***	***10.5***	***9.3***	***098***

Note 1: Trend is calculated clockwise from the bearing of geographic north. Declination not adjusted for.
Note 2: During test 8, level 2, the compass failed to lock and thus, no stress direction was identified.

Figure 4.3 illustrates the direction of the maximum horizontal stress, σ_H, in the rock at hole depth as measured in borehole KOV01.

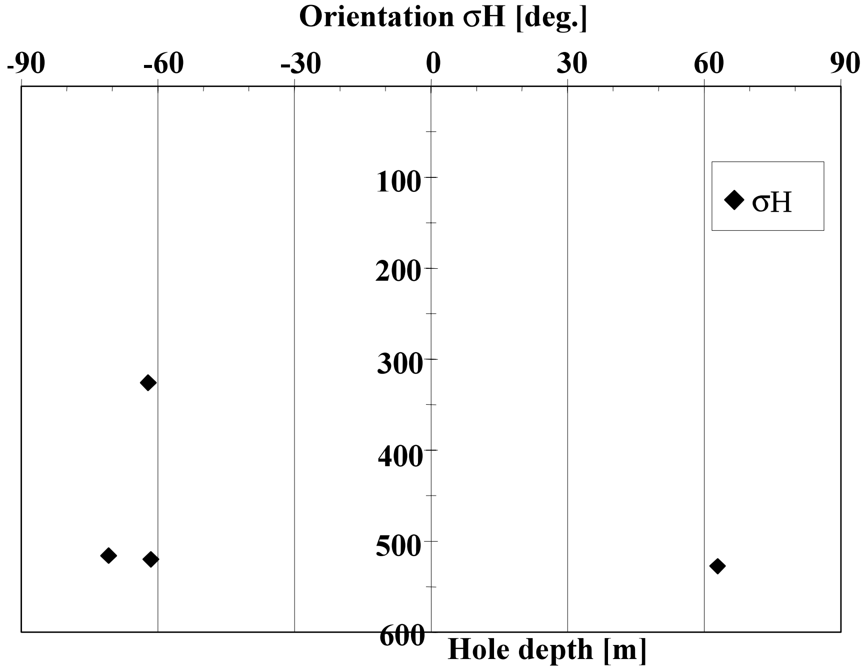


Figure 4-2. *Orientation of the maximum horizontal stress, σ_H, as referred to geographic north, borehole KOV01. Declination not adjusted for.*

4.5 COMMENTS ON THE RESULTS

- For most measurement attempts the mud and drill cuttings trapped in the borehole prevented proper bonding of the strain gauges to the rock. Hence, the possibilities of obtaining good results were limited. As it came to be, many tests displayed fluctuating and poor gauge response, unstable or lost gauges, and were unusable in the further evaluation process.

- The magnitude around 28 MPa for the major principal stress, σ_1, measured in Test 5 on the 300 m level is higher than expected for the depth, Table 4-3. The data lacks redundancy and it is thus questioned if it is representative as a general value for σ_1 at that depth.

- For Level 2, around hole depth 500 m, the σ_1-magnitude varies between 26 MPa and 31 MPa. In comparison to these values, the intermediate and minor principal stresses display low magnitudes, Table 4-3, the relation σ_1/σ_2-ranging between 2 and 4 with an average around 2.5.

- The maximum principal stresses is close to horizontal; σ_1 trends 98º east of geographic north, Table 4-4 and Figure 4-1.

- Overall, the measurements yield similar magnitudes for σ_2 and σ_3. Discrete orientations for both stresses are somewhat fluctuating, Table 4-4 and Figure 4-1. The latter is common when principal stresses are close in magnitude.

- It is noted that the average magnitude of σ_v at the 500 m level (9 MPa) is only about 60% of the stress corresponding to the overburden pressure at that depth. One test gave a result equal to 13 MPa, which could be expected for σ_v on 500 m depth. It is noted that the single successful test on the 300 m level indicates that σ_v corresponds to the litostatic pressure at that depth, Table 4-5.

- The direction of σ_H is not uniform within the depth interval, Figure 4-2. Transformed with respect to geographic north the results yield a WNW-ESE direction for the maximum horizontal stress.

5 SOURCES OF ERRORS AND DATA CONFIDENCE

When discussing the accuracy of a measurement result it must be distinguished between the degree of agreement between a measurement result and the real stress state in the point/location on one hand, and on the other hand, the representativity of the discrete measurement for the stress distribution in the rock mass. Here we only discuss the former issue.

The scatter in a result could arise from (i) measuring errors (systematic and non-systematic) attached to each test, (ii) true variations in the stress state along the borehole, or (iii) a combination of (i) and (ii).

By experience and testing it is known that instrument errors (that is; the difference between the actual strain subjected to a discrete gauge and the corresponding readout value) can be neglected for given circumstances. Temperature induced measuring errors have been found, given typical field conditions, to be less than ± 1 MPa (Leijon, 1988).

From measurements in rock that may be classified as almost ideal in the respect of homogeneity and linear elastic behaviour etc. (i.e. uncertainties concerning Young's modulus can be neglected), it is known that the scatter in magnitude for a group of measurements at the same location is in the interval ± 1 MPa to ± 3 MPa for magnitudes in the order of 15 - 25 MPa. This spread can be regarded as a conservative estimate of the non-systematic measurements. Thus, the interval ± 1 - 3 MPa is a conservative estimate of the total measurement error, keeping in mind the assumption that the rock allows for optimum measurement conditions.

The problem is then to estimate the errors introduced by the fact that the rock does not fulfil the assumptions of homogeneity and linear elastic behaviour. By studying the results from the biaxial testing, Appendix B, it can be seen (in the strain gauge scale) that the material behaves in a varying manner, but on average is acceptable. The material defects consist of heterogeneity, inelasticity and in some cases non-linearity. All these factors do, of course, introduce errors. On the other hand, we know that the redundancy existing in each measurement and the calculation of mean values for locations subjected to the same loading, effectively evens out the errors that can be related to heterogeneity.

It is normally judged that the errors in the results for a rock material, which behaves nearly ideally, do not exceed 15%. In this particular case, the large amount of rock cuttings in the borehole may have adversely affected the measurements, possibly resulting in larger error. However, it is not possible to give a precise and quantitative estimate of the total error in this case.

As mentioned above, some of the results differ from previously obtained values from Äspö — most notably the magnitudes of intermediate and minor principal stress. However, the fact that most of the successful measurements give similar results indicates that either (i) a potential error is of systematic nature, or (ii) that the measurements reflect the actual stress state. It has not been possible to confirm any systematic error, aside from the large amount of rock cuttings. The presence of rock cuttings affect the ability of obtaining good measurements; however, it is not known whether they also affect stress results for measurements that are judged successful by conventional standards.

During the field period, the quality of the work was supervised by SKB with the objective to increase the hit rate of testing and diminish the risk of mishaps due to the technical malfunctions or the human factor. The supervision pointed out the need for modified field work routines. These routines shall be continuously improved should the need for such actions arise. The supervision also concluded the importance of a clean pilot hole for arriving at successful tests. It was also noted that if the test checklist had contained a more careful inspection of the pilot core barrel and of the water channel passages in the steering guide, excentrical drilling resulting in a wrecked core barrel could have been prevented.

6 CONCLUSIONS

6.1 GENERAL

The outcome of the rather extensive test programme in borehole KOV01 was poor. In total, 16 overcoring tests were attempted. Seven of these failed completely due to drill cuttings obstructing proper installation of the test. Four tests displayed a drift in the gauges or suspiciously low magnitudes for at least one of the principal stresses that could be attributed to improper cementing. Thus, they were rejected from further evaluation. One test carried a compass failure and the results could just be used for comparison with magnitudes from the four other tests judged successful.

A series of anomalous events rendered a reduced number of successful results. The new sealed airlift pumping system used did not permit continuous inspection and sampling of the return–water during flushing. Moreover, the bottom of the pilot hole contained an unusually high content of cuttings during test installation as the air-lift pumping system kept cuttings trapped within the borehole during flushing and thus, proper bonding between gauges and rock was prevented

Improper cementing of gauges is also reflected in the biaxial tests. On occasion debonding of gauges or of full rosettes took place as they were dismounted from the gauge holder after overcoring. Often many gauges showed poor response to the pressure increase, yielding poor redundancy in both E- and ν-values between rosettes.

The poor outcome of the KOV01 testing points out the importance of a clean pilot hole before installation of the test. In this case, the system and process used to flush the hole did not meet the requirements set by the overcoring measurements.

Another event stalling the measurements was the damaging of the pilot hole core barrel on two occasions. This was caused by extensive amount of cuttings combined with water holes in the pilot hole drilling equipment, which were too narrow.

6.2 STRESS ORIENTATIONS

Since 1988 stress measurements have been conducted at depth in the Äspö area. The main part of those tests concludes a NW-SE trend for the maximum horizontal stress, σ_H.

The five tests used in the final analysis in KOV01 recognise an average orientation of σ_H in the undisturbed rock mass that is a little bit more to the west than what could be expected from Äspö data.

Overall, the results point out a clear trend for the maximum principal stress but not for the intermediate and minor stresses. σ_1 is close to horizontal and trends WNW.

For σ_2 and σ_3 the measurements yield similar magnitudes, but discrete orientations fluctuate for both stresses. The latter is a frequently observed feature when principal stresses are close in magnitude and also especially common for the intermediate and minor stresses in the Äspö area.

6.3 STRESS MAGNITUDES

In the tests judged successful the maximum principal stress, σ_1, arrive at magnitudes round 25 MPa or above for both the 300 m level and the 500 m level. Magnitudes for the intermediate and minimum stresses are considerably lower. Compared to previous tests at corresponding depths on Äspö, the resulting magnitudes for σ_2 and σ_3 in KOV01 are underestimated. This could be attributed to poor bonding between the strain gauges and the rock.

The results reported here generally show lower values for the vertical stress than what was expected, Table 4-5. However, discrete tests display results corresponding to magnitudes calculated from the overburden.

Taken from the measurement results in borehole KOV01 the design values in the vertical- and horizontal plane at 500 m hole depth are given by the average magnitudes as: σ_H = 24 MPa, σ_h = 10.5 MPa and σ_v = 9.3 MPa, cf. Table 4-5.

6.4 BIAXIAL TESTS

The outcome of the biaxial test was poor, the main reasons being that drill cuttings prevented proper bonding between the gauges and the rock in the pilot hole wall. The average values for Young's modulus (66 GPa) is lower than results derived from rock mechanical testing of Äspö diorite in uniaxial compressive mode (average 73 GPa). Average value of Poisson's ratio from the biaxial tests, on the other hand, is similar to the mean value obtained from laboratory tests (0.28).

7 REFERENCES

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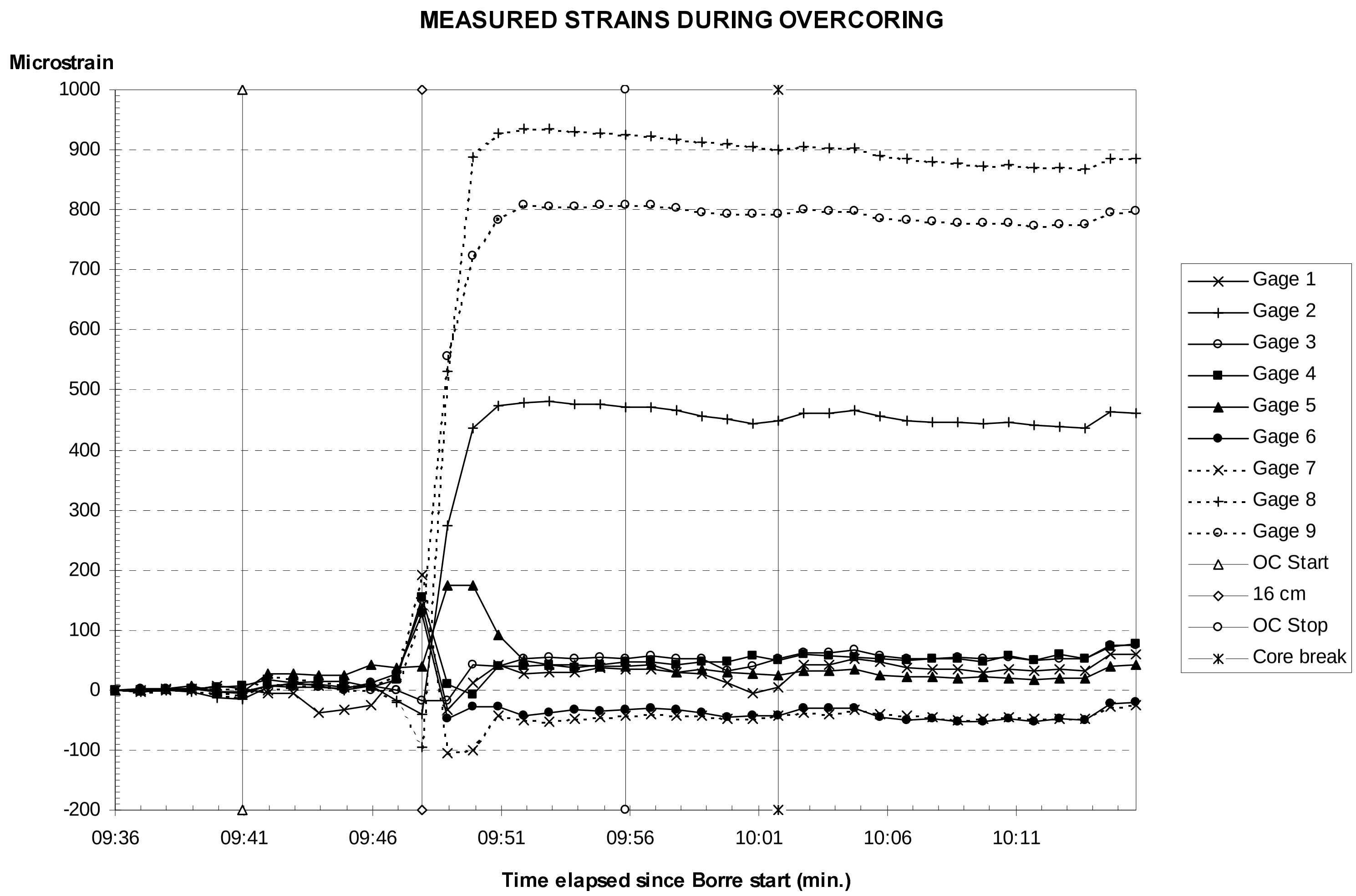
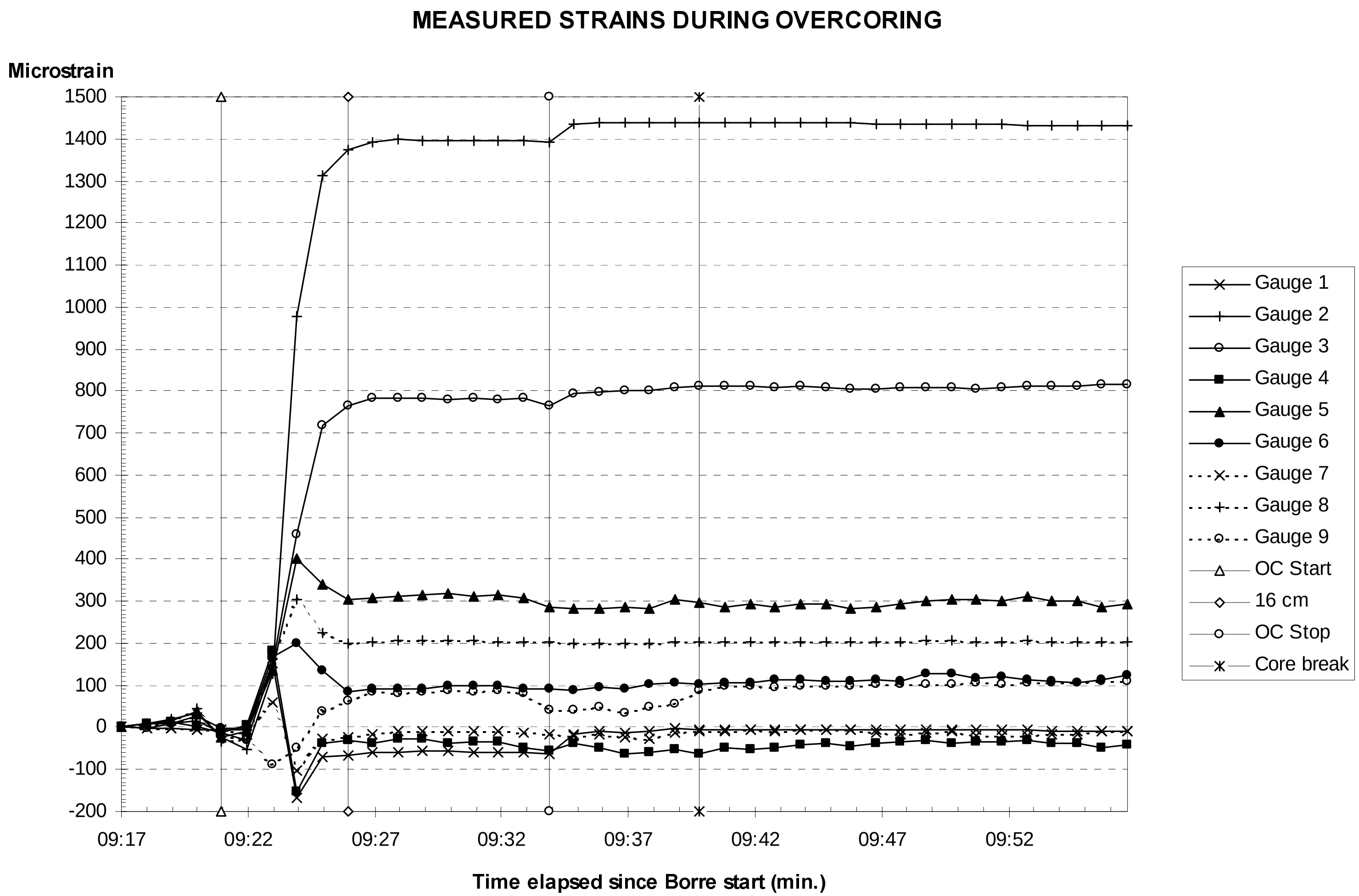
Appendix A: Registered strains during overcoring Oskarshamn area, borehole KOV01 (6 pp)

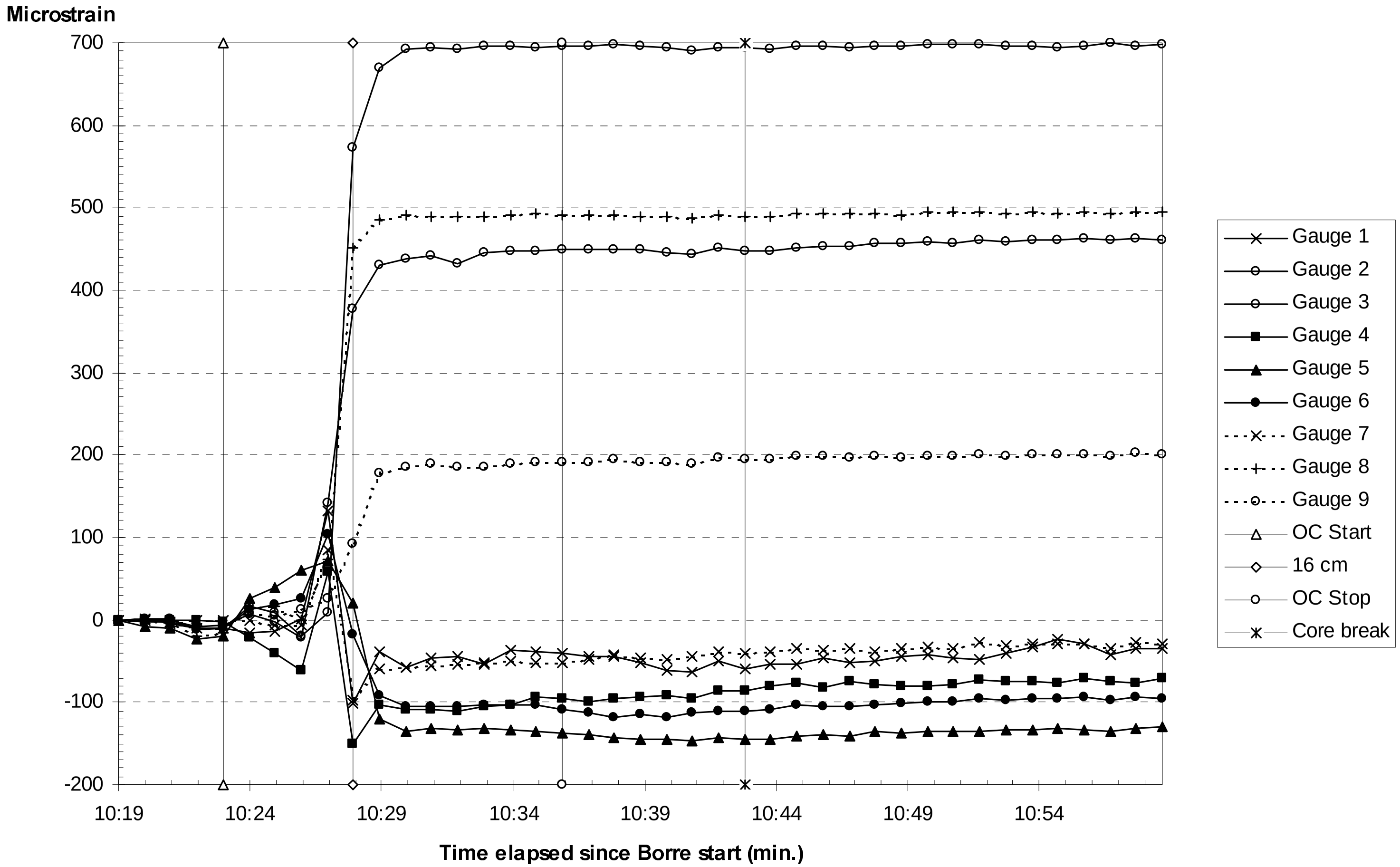


KOV01: Measuring point 5, level 1, hole depth 325.83 m

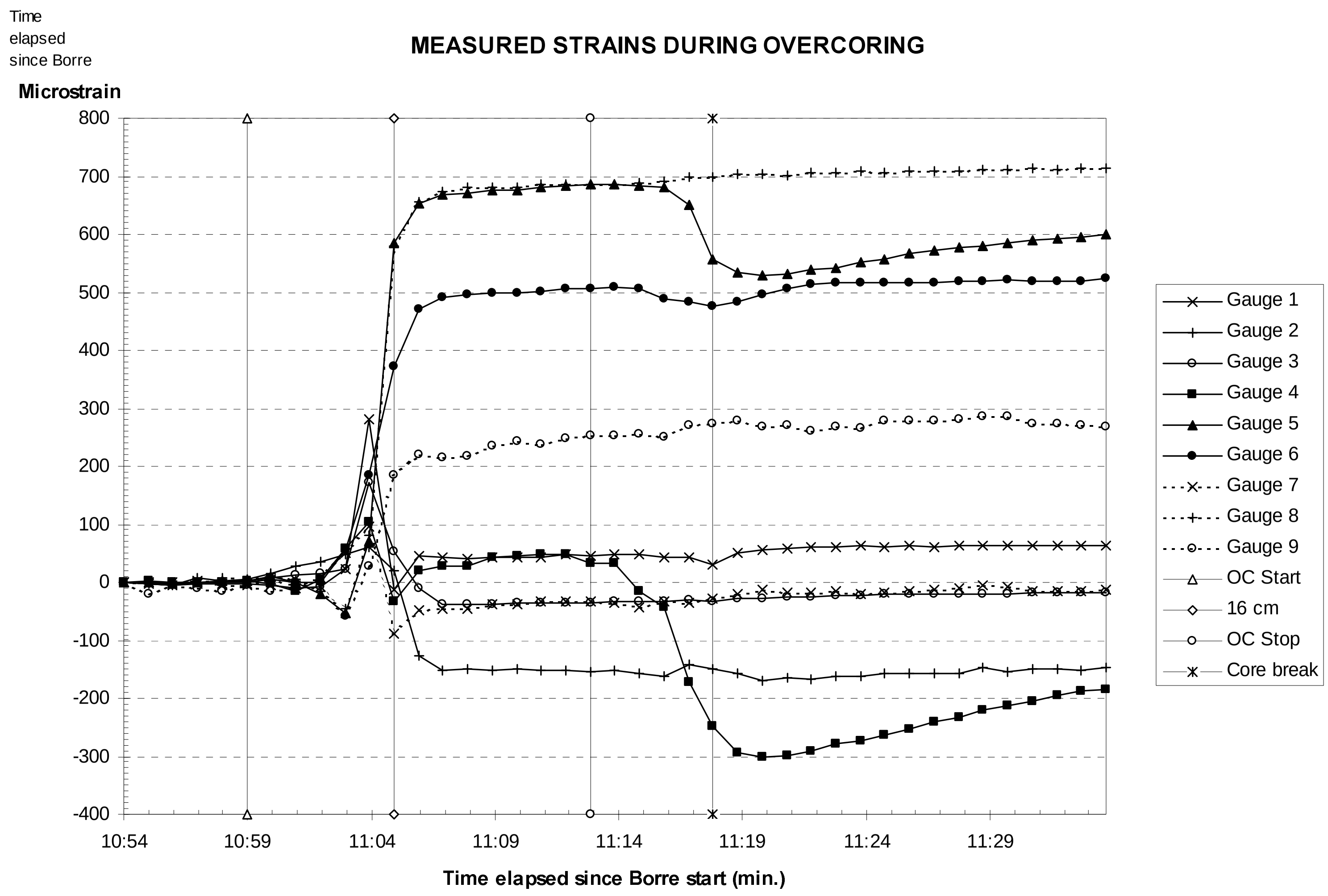


KOV01: Measuring point 5, level 2, hole depth 515.80 m

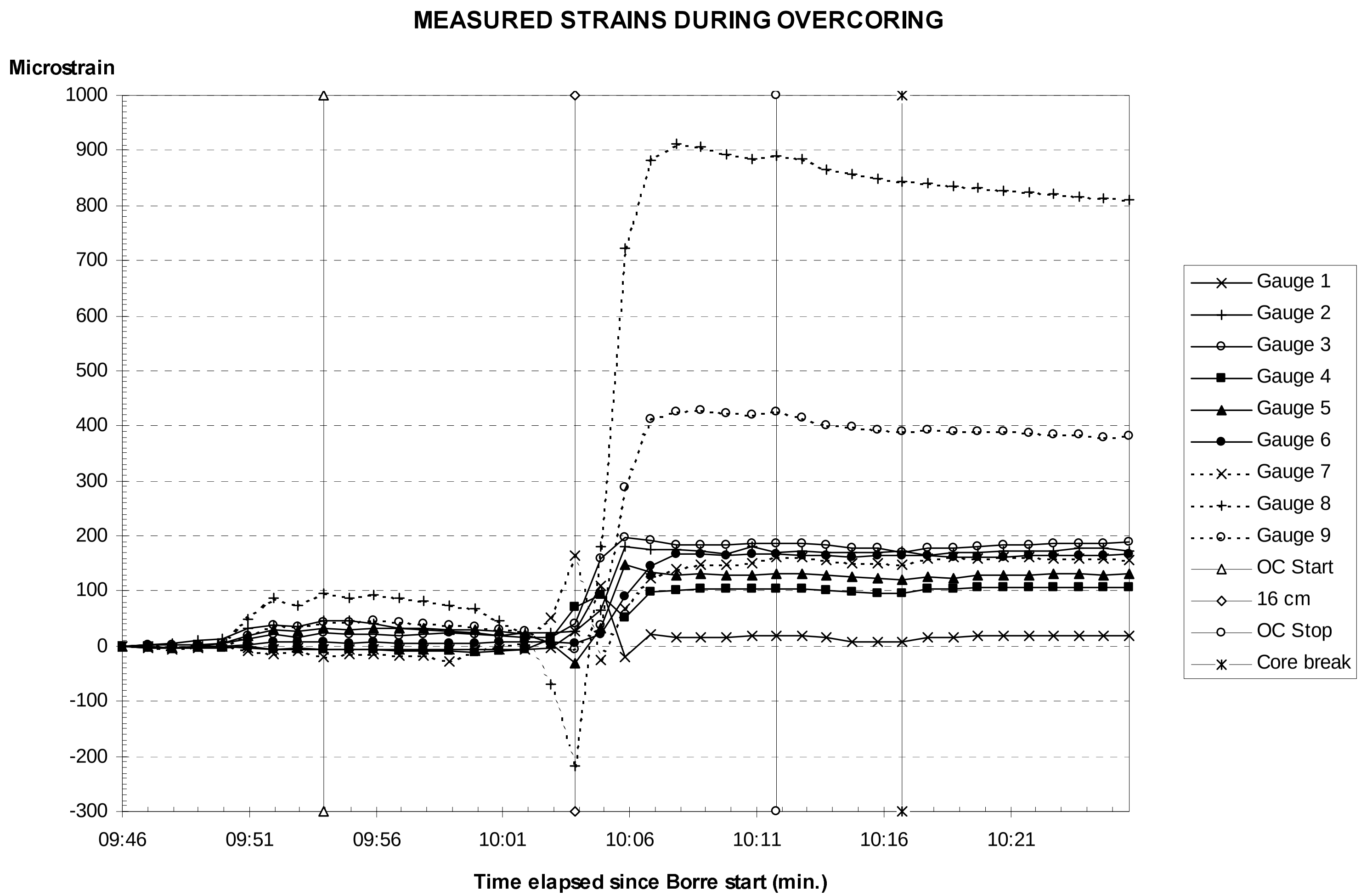
MEASURED STRAINS DURING OVERCORING



KOV01: Measuring point 7, level 2, hole depth 519.84 m



KOV01: Measuring point 8, level 2, hole depth 520.71 m



KOV01: Measuring point 10, level 2, hole depth 527.46 m

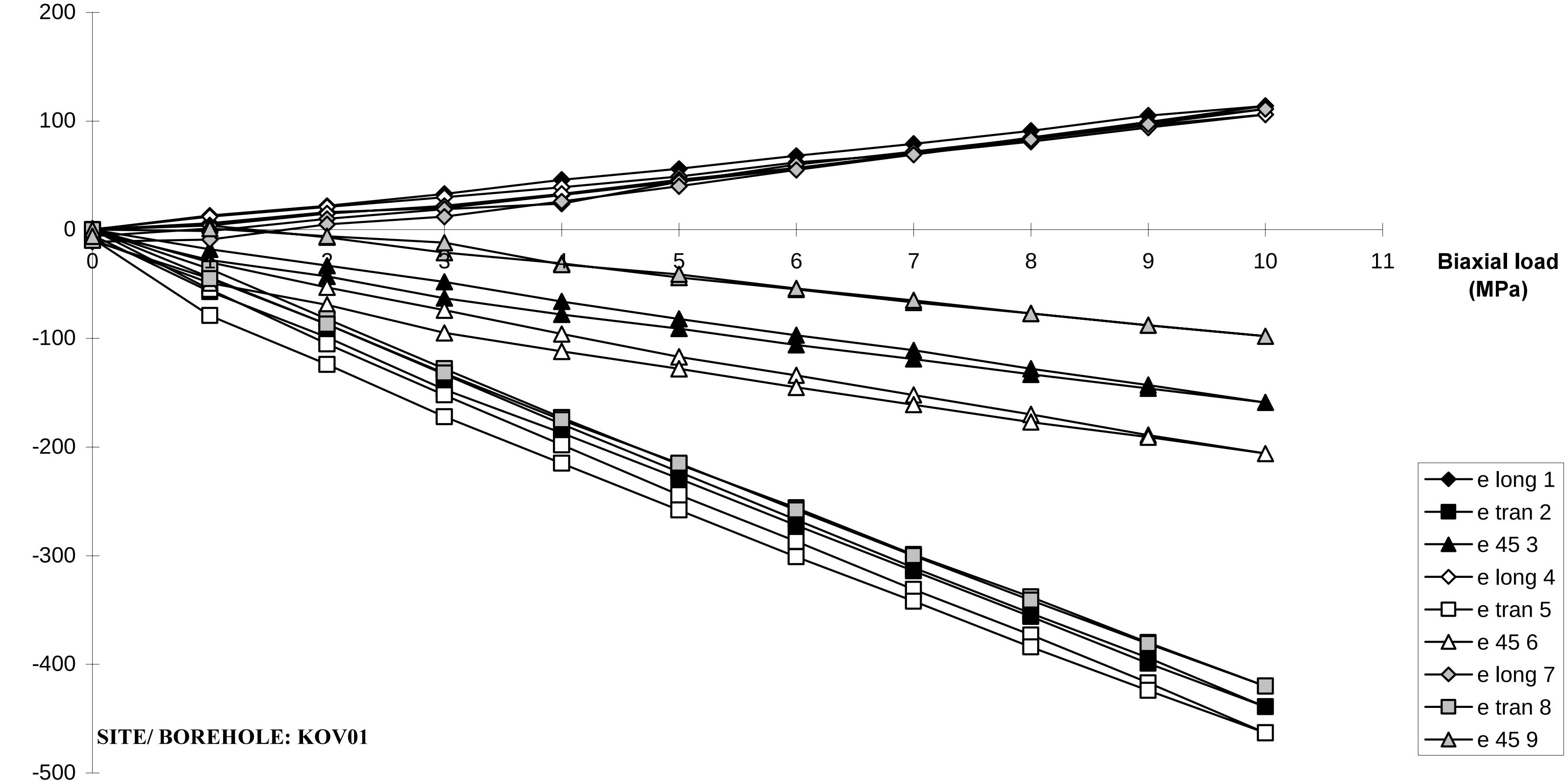
Appendix B: Biaxial tests

Oskarshamn area, borehole KOV01

(5 pp)

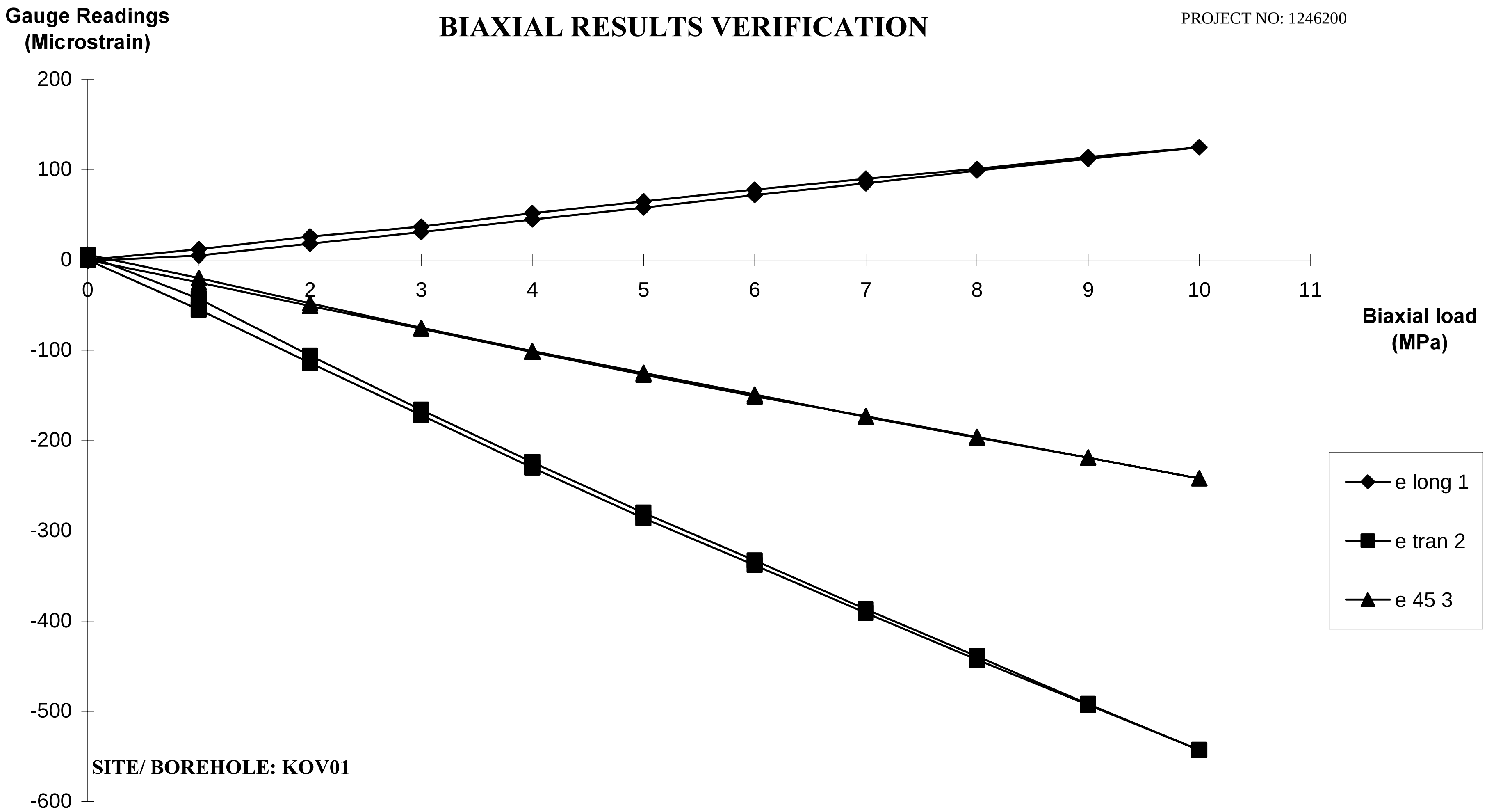
BIAXIAL RESULTS VERIFICATION

PROJECT NO: 1246200



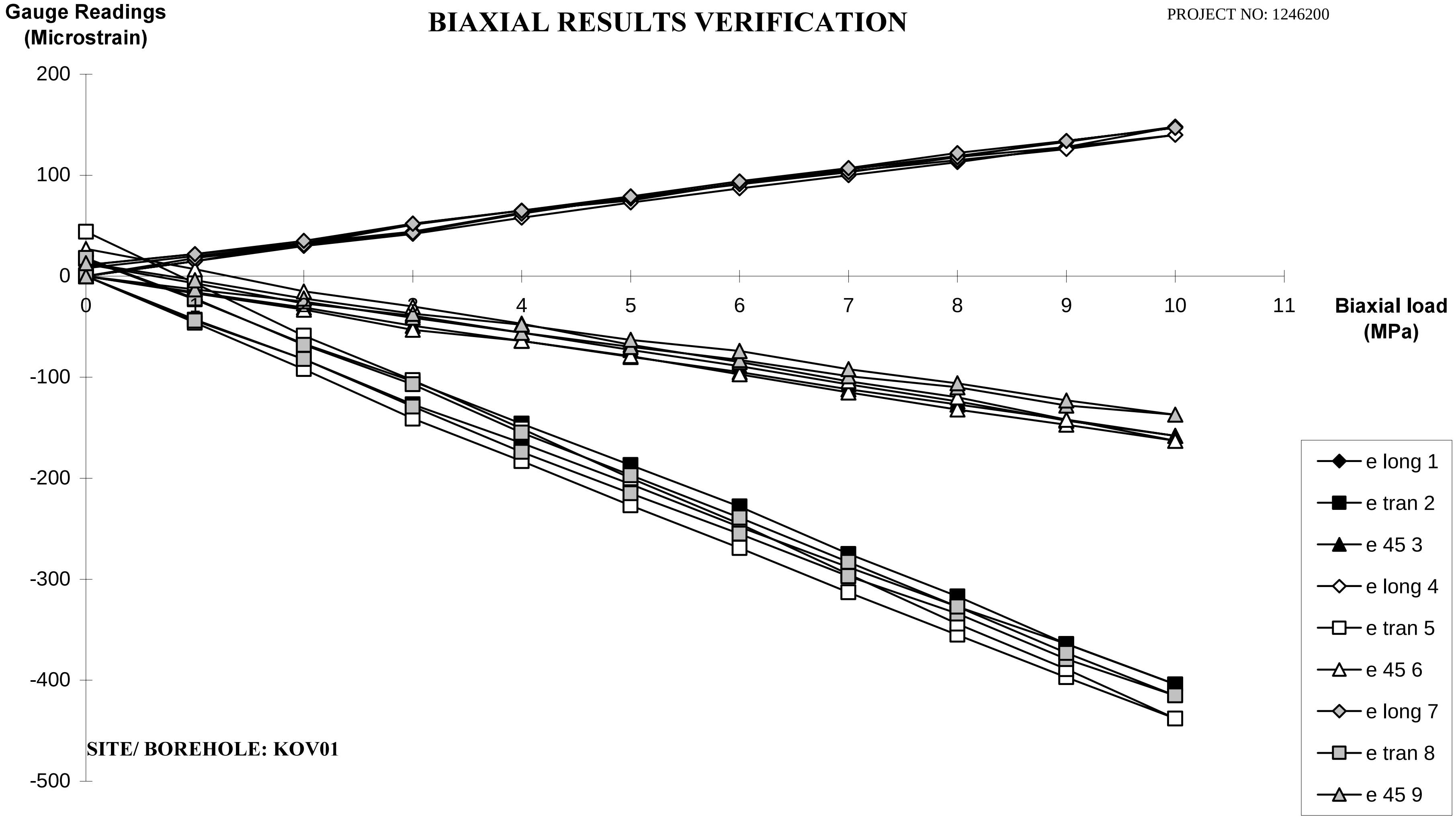
TEST 5, LEVEL 1, MEASUREMENT DEPTH: 325.83 m

BIAXIAL RESULTS VERIFICATION



TEST 5, LEVEL 2, MEASUREMENT DEPTH: 515.80 m

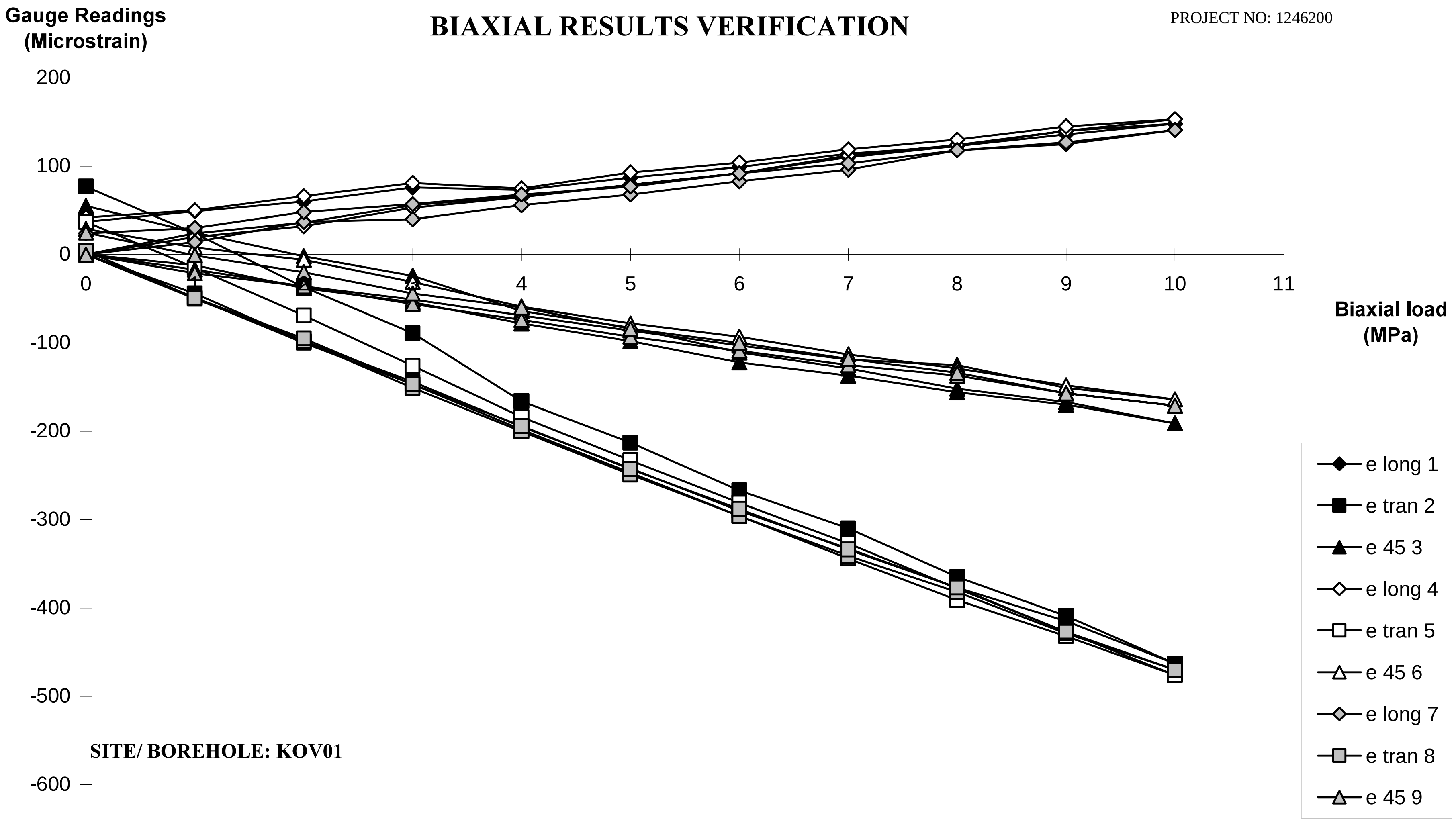
BIAXIAL RESULTS VERIFICATION



TEST 7, LEVEL 2, MEASUREMENT DEPTH: 519.84 m

BIAXIAL RESULTS VERIFICATION

PROJECT NO: 1246200



TEST 8, LEVEL 2, MEASUREMENT DEPTH: 520.71 m

Appendix C: Stress calculation input data and results

Oskarshamn area, borehole KOV01

(4 pp)

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OVERCORING STRESS MEASUREMENTS

Project Description : KOV01 Oskarshamn, Level 1
Date : 2002-02-20
Borehole Dip : 69.4
Borehole Bearing : 205.7
Measurement depth : 325.83 meter

Input Data

Bearing (ball) - X [º]	Young's modulus [GPa]	Poisson's ratio	Gauge factor	Resistance fact.
145	66	0.21	2	1

Strains

ε_{L1} (gauge no. 1) [µstrain]	ε_{T1} (gauge no. 2) [µstrain]	ε_{45_1} (gauge no. 3) [µstrain]	ε_{L3} (gauge no. 4) [µstrain]	ε_{T2} (gauge no. 5) [µstrain]	ε_{45_2} (gauge no. 6) [µstrain]	ε_{L3} (gauge no. 7) [µstrain]	ε_{T3} (gauge no. 8) [µstrain]	ε_{45_3} (gauge no. 9) [µstrain]
5	480	52	5	36	-35	5	930	714

Principal Stresses

σ_1 [MPa]	σ_1 - Dip [º]	σ_1 - Bearing [º]	σ_2 [MPa]	σ_2 - Dip [º]	σ_2 - Bearing [º]	σ_3 [MPa]	σ_3 - Dip [º]	σ3 - Bearing [º]
28	21.2	298.4	7.8	25.9	39.2	4.9	55.5	174.1

Horizontal and Vertical Stresses

Major stress σ_A [MPa]	σ_A - Bearing [º]	Minor stress σ_B [MPa]	σ_B - Bearing [º]	Vertical stress σ_z [MPa]
25.1	117	7.2	27	8.5

Error (sum of squares)
0.1

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OVERCORING STRESS MEASUREMENTS

Project Description : KOV01 Oskarshamn, Level 2
Date : 2002-02-20
Borehole Dip : 76.9
Borehole Bearing : 216.6

Input Data

Depth [m]	Bearing (ball) - X [º]	Young's modulus [GPa]	Poisson's ratio	Gauge factor	Resistance fact.
515.8	250	56	0.22	2	1
519.84	285	77	0.3	2	1
520.71	355	66	0.3	2	1
527.46	265	66	0.25	2	1

Strains

Depth [m]	ε_{L1} (gauge no. 1) [µstrain]	ε_{T1} (gauge no. 2) [µstrain]	ε_{45_1} (gauge no. 3) [µstrain]	ε_{L3} (gauge no. 4) [µstrain]	ε_{T2} (gauge no. 5) [µstrain]	ε_{45_2} (gauge no. 6) [µstrain]	ε_{L3} (gauge no. 7) [µstrain]	ε_{T3} (gauge no. 8) [µstrain]	ε_{45_3} (gauge no. 9) [µstrain]
515.8	-54	1416	795	-14	340	92	-5	241	102
519.84	-29	704	451	-104	83	-96	-53	505	198
520.71	8	-27	-39	8	671	496	8	680	217
527.46	90	171	181	90	130	169	90	981	426

Calculated Principal Stresses

Depth [m]	σ_1 [MPa]	σ_1 - Dip [º]	σ_1 - Bearing [º]	σ_2 [MPa]	σ_2 - Dip [º]	σ_2 - Bearing [º]	σ_3 [MPa]	σ_3 - Dip [º]	σ3 - Bearing [º]
515.8	30.8	1.1	288.3	8.8	36.7	19.1	6.9	53.3	196.8
519.84	25.7	7.8	300.3	10.9	37.5	36.4	4	51.4	200.5
520.71	25.7	compass failure	compass failure	9.4	compass failure	compass failure	7.3	compass failure	-
527.46	26.3	1.3	242	13.2	82.6	141.9	6.1	7.3	332.1
Average	*24.1*	-	-	*11*	-	-	*8.6*	-	-

Calculated Horizontal and Vertical Stresses

Depth [m]	Major stress σ_A [MPa]	σ_A - Bearing [º]	Minor stress σ_B [MPa]	σ_B - Bearing [º]	Vertical stress σ_z [MPa]	Error (sum of squares)
515.8	30.8	108.2	8.1	18.2	7.6	1522.7
519.84	25.3	118.8	8.3	28.8	6.9	2934
520.71	24.8	compass failure	8	compass failure	9.6	0
527.46	26.3	62	6.2	152	13.1	0
Average	*24*	-	*10.5*	-	*9.3*	

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OVERCORING STRESS MEASUREMENTS

Project Description : KOV01 Oskarshamn
Date : 2002-02-20
Borehole Dip : 76.9
Borehole Bearing : 216.6

Test 8 excluded (to get average orientations)

Input Data

Depth [m]	Bearing (ball) - X [º]	Young's modulus [GPa]	Poisson's ratio	Gauge factor	Resistance fact.
515.8	250	56	0.22	2	1
519.84	285	77	0.3	2	1
527.46	265	66	0.25	2	1

Strains

Depth [m]	ε_{L1} (gauge no. 1) [µstrain]	ε_{T1} (gauge no. 2) [µstrain]	ε_{45_1} (gauge no. 3) [µstrain]	ε_{L3} (gauge no. 4) [µstrain]	ε_{T2} (gauge no. 5) [µstrain]	ε_{45_2} (gauge no. 6) [µstrain]	ε_{L3} (gauge no. 7) [µstrain]	ε_{T3} (gauge no. 8) [µstrain]	ε_{45_3} (gauge no. 9) [µstrain]
515.8	-54	1416	795	-14	340	92	-5	241	102
519.84	-29	704	451	-104	83	-96	-53	505	198
527.46	90	171	181	90	130	169	90	981	426

Calculated Principal Stresses

Depth [m]	σ_1 [MPa]	σ_1 - Dip [º]	σ_1 - Bearing [º]	σ_2 [MPa]	σ_2 - Dip [º]	σ_2 - Bearing [º]	σ_3 [MPa]	σ_3 - Dip [º]	σ3 - Bearing [º]
515.8	30.8	1.1	288.3	8.8	36.7	19.1	6.9	53.3	196.8
519.84	25.7	7.8	300.3	10.9	37.5	36.4	4	51.4	200.5
527.46	26.3	1.3	242	13.2	82.6	141.9	6.1	7.3	332.1
Average	*N/A*	*1.4*	*278.3*	*N/A*	*30*	*9.1*	*N/A*	*60*	*185.8*

Calculated Horizontal and Vertical Stresses

Depth [m]	Major stress σ_A [MPa]	σ_A - Bearing [º]	Minor stress σ_B [MPa]	σ_B - Bearing [º]	Vertical stress σ_z [MPa]	Error (sum of squares)
515.8	30.8	108.2	8.1	18.2	7.6	1522.7
519.84	25.3	118.8	8.3	28.8	6.9	2934
527.46	26.3	62	6.2	152	13.1	0
Average	*N/A*	*98.1*	*N/A*	*8.1*	*N/A*	