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Forsmark site investigation

Reliability ranking of Borre probe III overcoring stress measurements in KFM24 at level 564 m

Matti Hakala
Stress Measurement Company Oy

Keywords: Overcoring stress measurements, Transient strain analysis, Stress reliability ranking

This report concerns a study which was conducted for Svensk Kärnbränslehantering AB (SKB). The conclusions and viewpoints presented in the report are those of the author. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

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Summary

In this work the reliability ranking method presented in the SKB report R-21-08 (Sjöberg et al 2025) is applied to the Borre probe III overcoring stress measurements conducted in the borehole KFM24 at the Forsmark site around 564 m borehole length level (Ask 2025).

Two of four measurement attempts were successful, measurement 1:3:3 has *moderate* and measurement 1:4:4 go*od* overall reliability. The reason for *moderate* reliability is the variation of Young's modulus value calculated from biaxial test results. The calculation assumptions used in the report R-21-08 resulted in 10%–27% higher stress magnitudes compared to the case where all unloading data is used. The reason is that the Young's modulus value has 1:1 effect on resulting stress magnitudes.

Sammanfattning

I detta arbete tillämpas den metod för tillförlitlighetsklassificering som presenteras i SKB-rapport R-21-08 (Sjöberg et al 2025) på Borre probe III:s överborrningsspänningsmätningar, utförda i borrhålet KFM24 i Forsmarksområdet omkring nivån vid borrhålslängd 564 m (Ask 2025).

Två av fyra mätförsök var framgångsrika. Mätning 1:3:3 har *måttlig* medan mätning 1:4:4 har *god* övergripande tillförlitlighet. Orsaken till den måttliga tillförlitligheten är variationen i värdet på elasticitetsmodulen, beräknad från resultaten från de biaxiella testerna. De beräkningsantaganden som användes i rapport R-21-08 resulterade i 10%–27% högre spänningsvärde jämfört med fallet där all avlastningsdata används. Anledningen är att värdet på elasticitetsmodulen har en 1:1-effekt på de resulterande spänningsvärde.

Content

1 Introduction

1.1 Background

The Forsmark site is the chosen location for the repository for spent nuclear fuel in Sweden. The currently planned repository will comprise a ramp down to the repository depth, where several deposition tunnels will be excavated. The canisters with spent fuel will be placed in vertical deposition holes, 1.75 m in diameter, in the tunnel floor, at an approximate depth below the ground surface of 450 m.

The rock mass is subjected to the initial (prior to any excavations) in situ stress state, which will be disturbed and redistributed by the excavation operations. The stress redistribution and resulting secondary stress state constitutes the main load during the construction of underground working. Hence, the orientation and magnitudes of the initial in situ stresses are considered important factors in the design and performance of the underground repository facility. For example, the orientation of the deposition tunnels is planned to be near parallel to the maximum horizontal stress at the site to minimize the maximum secondary stress on the excavation.

Stress measurements at the Forsmark site have mainly been conducted utilizing overcoring, with some supplementary hydraulic fracturing measurements. The overcoring method involve coring a larger diameter borehole over a coaxial small-diameter pilot hole in which a strain-measuring instrument is located, recording the strains resulting from the stress relaxation. To determine the elastic constants of the overcored samples, they are placed inside a biaxial chamber in which a radial hydraulic pressure is applied. Several loading and unloading cycles are performed and the strains as a function of pressure through the biaxial tests are recorded. The stress state is determined from the strains measuring during overcoring, and the elastic constants determined from the biaxial tests (Sjöberg et al 2003).

More than 130 overcoring stress measurements have been conducted between the years of 1975 and 2006 utilizing the Borre probe (Sjöberg and Klasson, 2003). The interpretation of the stress measurement results has proven to be challenging, because the results of the stress interpretation (Martin, 2007) show large variability in the magnitudes of the principal stresses. One of the sources of this variability is the heterogeneity of the rock mass. However, the variability is also related to factors intrinsic to the overcoring technique, e.g., variations in temperature during coring. Drilling induces heat and consequent thermal expansion, and potential reactivation of the epoxy glue used to bond the strain gauges to the borehole walls. This can result in high stresses, which can potentially damage the core. Also, high initial stresses acting perpendicular to the borehole axis can cause microcracking and/or disking of the overcored sample, thus violating the basic premises of the overcoring technique (continuous, homogeneous, linear-elastic rock behaviour).

Large pre-existing geological deformation zones may result in a rotation of the initial stresses as a function of depth and as well as a variation of the magnitudes. Numerical simulations have been conducted to understand the possible effect of the deformation zones on the rock stresses at Forsmark (Mas Ivars and Hakami, 2005; Hakami, 2006; Hakala et al 2019; Valli et al 2023). In these works, deterministic deformation zones were modelled explicitly, and under the glacial cycle the variation of the stress magnitude was found to be similar to the magnitude of the measured stress. However, the simulated variation of the trend of the maximum horizontal stress as a function of depth was found to be different from that obtained from the interpretation of the stress measurements.

In previous stress modelling at Forsmark no stringent and quantitative quality assurance and reliability assessment of the stress measurements have been conducted. For a more accurate representation of the stress data at Forsmark and to mitigate the associated uncertainties, it is important to assess and exclude the unreliable stress measurement data. Report SKB R-21-08 Reliability ranking of overcoring stress measurements at Forsmark (Sjöberg et al 2025) describe and present the latest quality assurance and reliability assessment method applied for all Forsmark overcoring measurements done until the year 2006.

1.2 Objective

In this work the reliability ranking method presented in SKB R-21-08 (Ask 2025) is applied for Borre probe III overcoring stress measurements done between December 2nd 2024 and February 4th 2025 in borehole KFM24 at borehole depth levels 563.81 m and 564.59 m.

2 Ranking of KFM24 level 564 m measurements

2.1 Included stress measurements

Table 2-1 summarizes all reported measurement attempts in KFM24 level 564 m. Reliability ranking could be applied for attempts 1:3:3 and 1:4:4 only. Attempts 1:1:1 and 1:2:2 failed at the installation phase preventing the stress interpretation and they are consequently ranked as *rejected*.

Table 2-1 Level 564 m overcoring measurements attempted in borehole KFM24

Borehole ID	Year	Report	Measurement	Borehole length (m)	Overcoring data	Biaxial data
KFM24	2024–2025	P-25-02	1:1:1	562.49-563.08	None	None
			1:2:2	563.18-563.81	Rosette 2	Rosette 2
			1:3:3	563.97-564.59	All rosettes	All rosettes
			1:4:4	564.86-565.48	All rosettes	All rosettes

2.2 Considerations

The reliability ranking uses measurement-specific data, i.e. not the data averaged for the depth level. In report SKB P-25-02 (Ask 2025) stresses are not calculated using installation location specific elastic parameters; instead, average elastic parameters are applied. For the measurement 1:4:4 the reported measurement specific elastic parameters would result in 15%–20% lower principal stress magnitudes and 7%–16% lower horizontal/vertical principal stress magnitudes. For the measurement 1:3:3 the reported measurement specific elastic parameter values are very close to the average ones.

In report SKB P-25-02 it is mentioned that the calculation of elastic parameters does not take account of total unloading data of the biaxial tests but from 10 MPa to 4 MPa only. The reason for this is not clearly stated, although during overcoring the stress will reduce from its initial magnitude to zero. Further, report states that the used data interval is from 10 MPa to 5 MPa but based on test data the range is from 10 MPa to 4 MPa.

It should be noted also that the elastic parameters reported in SKB P-25-02 are not based on data from all strain gauges. The used gauges for the measurement 1:3:3 are Tan_R1, 45_R1, Ax_R1, Ax_R2 and Ax_R3, and for the measurement 1:4:4 are Tan_R1, Tan_R3, 45_R1, Ax_R1, Ax_R2 and Ax_R3. These gauges or combinations of two gauges result in higher Young's modulus values. Although many gauges showed shifts related to core break and rod hoisting works, the exclusion of the gauges is not explained in detail and does not coincide with observed shifts after overcoring. During the overcoring only 1:4:4: 45 R1 showed unreliable response but in biaxial testing none of the strain gauges showed unreliable or anomalous response. Compared to the solution where all gauges and total unloading is used, the SKB P-25-02 applied method resulted in 27% higher modulus for the measurement 1:3:3 (71.7 GPa vs 56.3 GPa) and 10% higher modulus for the measurement 1:4:4 (61.4 GPa vs 55.8 GPa). The Poisson's ratio values are practically not affected by the used strain gauges or biaxial stress range. It should be noted that the applied modulus has 1:1 effect on the resulting principal stress magnitudes whereas the effect of Poisson's ratio is not as straightforward, and the effect on resulting stress state is minor. The effect of Poisson's ratio standard deviation is estimated using OCS-code inverse solution.

The following presentation of results does not consider water pressure.

2.3 Results

The stress measurement ranking system used here, including variables and parameter definitions, is explained in detail in the SKB report R-21-08 (Sjöberg et al 2025). Overcoring and biaxial test data are available for both measurements 1:3:3 and 1:4:4. Ranking of transient strain data is presented in Appendix 1 and summarized in Table 2-2. Elastic parameter ranking uses all unloading data from 10 MPa to 0 MPa and the parameter values are calculated first separately for each strain gauge rosette and then averaged for the measurement (Table 2-3). Note that these assumptions result in different elastic parameter values, especially for Young's modulus, than those reported in SKB P-25-02 (see chapter 2.2). Ranking of the stress solution is presented in Table 2-4.

Table 2-2 Reliability ranking of strain data

Measurement	Data set	Stability before overcoring	Strains take place within elastic region	Reliability of transient strains	Stability of transient stress magnitudes	Stability of transient stress orientations	Stress solution based on strains in the end of elastic region	Reliability of elastic stress condition	Core disking	Overall Strain Reliability
1:3:3	A	G	G	G	G	G	Y	G	N	G
1:4:4	A	G	G	G	G	G	Y	G	N	G

Table 2-3 Reliability ranking of elastic constants

Measurement	Data set	Young's modulus (GPa)			Poisson's ratio (strain/strain)		
		Mean	St.dev.	Reliability	Mean	St.dev.	Reliability
1:3:3	A	56.3	18%	M	0.21	31%	G/M*
1:4:4	A	55.8	12%	G	0.21	32%	G/M*

*) standard deviation cause moderate variability for s3 and sV magnitudes only

Table 2-4 Reliability ranking of stress solution

Measurement	s1 mag.	s1 ori	s2 mag	s2 ori	s3 mag	s3 ori	sH mag	sH ori	sh mag	sV mag
1:3:3	G	G	G	G	G	G	G	G	G	G
1:4:4	G	G	G	G	G	G	G	G	G	G

Table 2-5 Overall reliability

Measurement	OC data set	Biaxial data set	s1 mag.	s1 ori	s2 mag	s2 ori	s3 mag	s3 ori	sH mag	sH ori	sh mag	sV mag
1:3:3	A	A	M	G	M	G	M	G	G	M	M	M
1:4:4	A	A	G	G	G	G	G	G	G	G	G	G

3 Discussion

Borre probe III overcoring stress measurements 1:3:3 and 1:4:4 in borehole KFM24 at level 564 m and the biaxial tests for elastic constants were both successful. The reason for *moderate* reliability for measurement 1:3:3 stress magnitudes is due to 18% standard deviation of Young's modulus, where the limiting standard deviation value for *good* reliability is 15%. Calculation of Young's modulus in this report is based on all biaxial unloading pressure levels and all strain gauges, therefore it is different than the one presented in the SKB report P-25-02 (Ask 2025). Report SKB P-25-02 (Ask 2025) does not explain clearly why biaxial test pressure levels below 4 MPa and half of the gauges are excluded from Young's modulus calculation. General explanations are given but neither strain observations after core break nor biaxial responses support that. The Young's modulus calculation method used in SKB P-25-02 (Ask 2025) resulted in 10% to 27% higher stress magnitudes and therefore it is recommended to reconsider the final elastic parameter values (see Appendix 1).

The stress calculation presented in SKB P-25-02 (Ask 2025) does not take account of water pressure and assumes therefore that water pressure is affecting on both sides of the overcored rock cylinder during the whole overcoring process. This means that in the beginning of overcoring the well pressure affecting the pilot hole wall is compensated by the water pressure component of total stresses in rock. From the author´s understanding, this solution gives thereby effective stresses only.

4 References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.

SKBdoc documents will be submitted upon request to document@skb.se.

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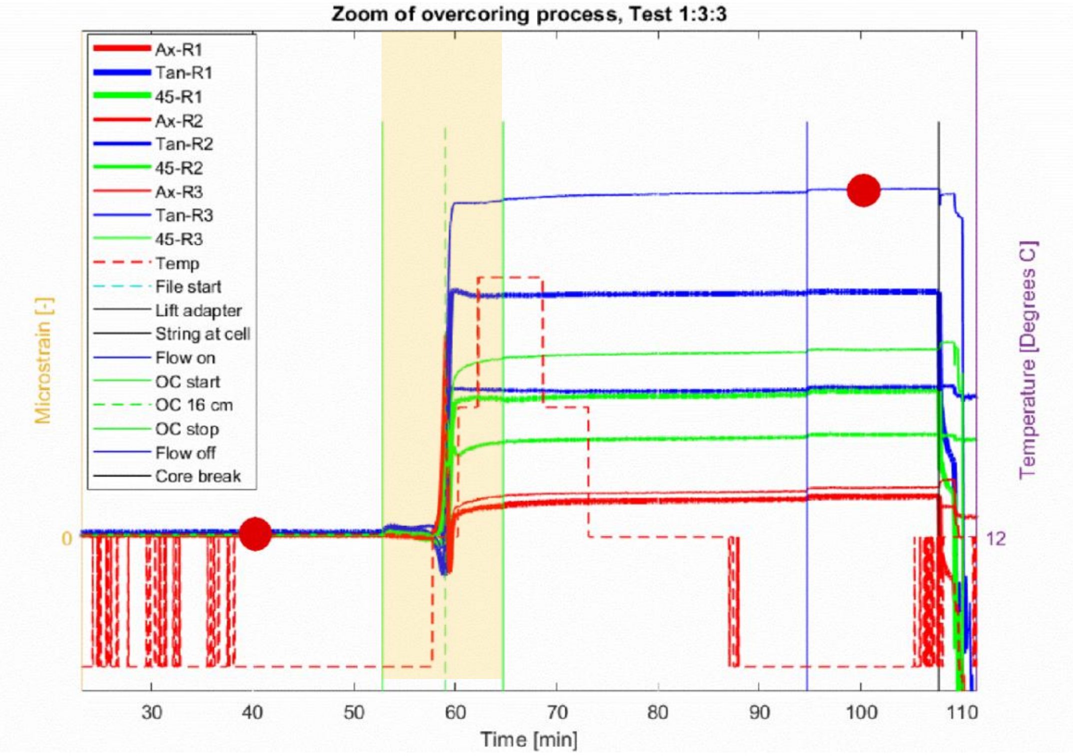
Appendix 1 – Transient strain analysis

KFM24: 1:3:3, z=561.23m

G	9/9	Strains stable before overcoring
G	9/9	Strains take place within elastic transient strain range (yellow shade)
G	9,0,0	Reliability of transient strains, number *good, moderate* and *poor* transient strains correlation (next page)
G	G,G,G	Stability of inverse stress solution after passing gauges by 60 mm for s1, s2 and s3 magnitudes
Y		Stress solution is based on strains in the end of elastic region or after stable cooling period
G		Reliability for elastic stress condition with water pressure, based on T/sigma3,max: 18 MPa/ 8 MPa
N		Core disking observed within ±130 mm from strain gauges
		Stabe readings in all measurement phases. Rosette 2 transient strains deviate most from calculated ones. Effect of drilling induced heat is minor but could be the reason for observed minor drift. Vertical stress close to gravitational (6% lower).
G		***Overall strain reliability***



Overcoring action record;

Table A4-1. Time indications of different phases during overcoring measurements in borehole KFM24.

Test	Date	Probe installed	Dense sampling	Flushing start	Overcoring start	Overcoring stop	Flushing stop	Core Break	Coring speed	Strain interval used for calculation
1:1:1	250108-09	13:30	08:00	08:18	08:22	08:29	09:02	09:11	8.3 cm/m	-
1:2:2	250115-16	09:55	08:00	08:10	08:35	08:47	09:16	09:24	7.0 cm/m	08:15:00-08:48:00
1:3:3	250122-23	11:48	07:55	08:06	08:50	08:59	09:29	09:42	7.8 cm/m	08:40:00-09:20:00
1:4:4	250202-03	14:25	08:00	08:10	08:34	08:46	09:16	09:29	5.8 cm/m	08:15:00-09:19:30

OCS solution for KFM24 1:3:3 using E=71.7 GPa, v=0.22 and reported stress state

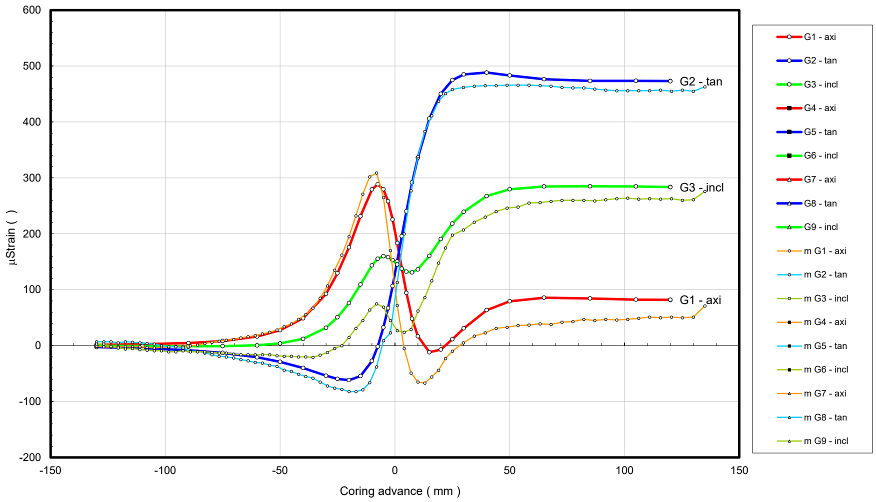
Transient strain comparison and reliability ranking

- maximum relative difference of intermediate max or min and final values

– measured strains at 135 mm are for original Sicada reported solution

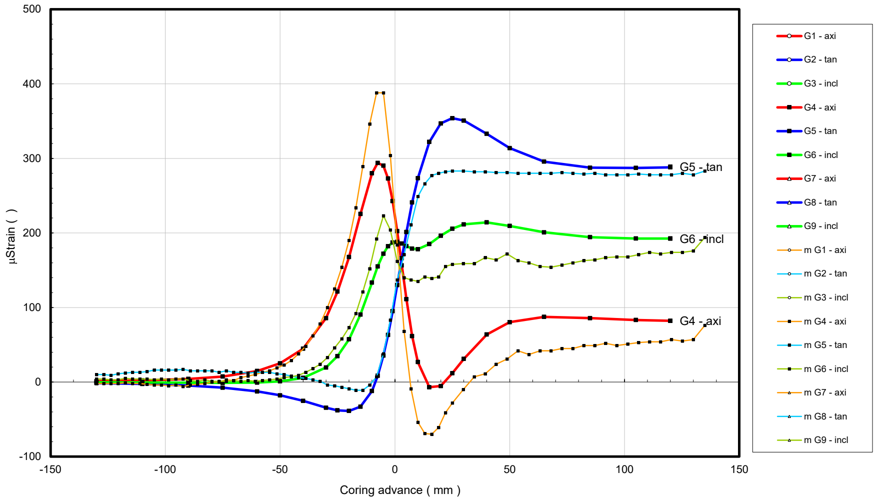
Rosette 1

G1,axi		
1.1/6.2	0.87	G
G2,tan		
1.3/0.95	0.98	G
G3,incl		
20/0.97	0.97	G



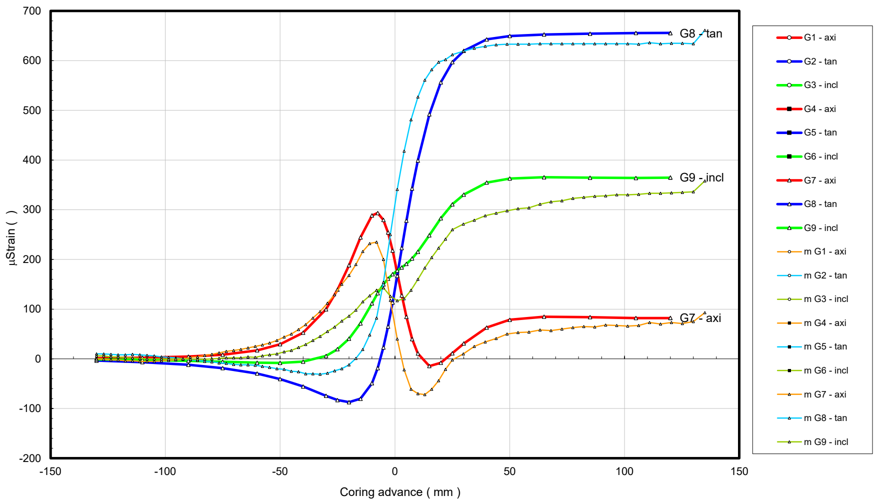
Rosette 2

G1,axi		
11/1.3	0.93	G
G2,tan		
0.3/0.8	0.98	G
G3,incl		
0.95/1.0	1.0	G



Rosette 3

G1,axi		
5.5/0.8	1.1	G
G2,tan		
0.36/1.0	1.0	G
G3,incl		
0.12/0.98	0.98	G



OCS

Original Sicada reported and other solutions

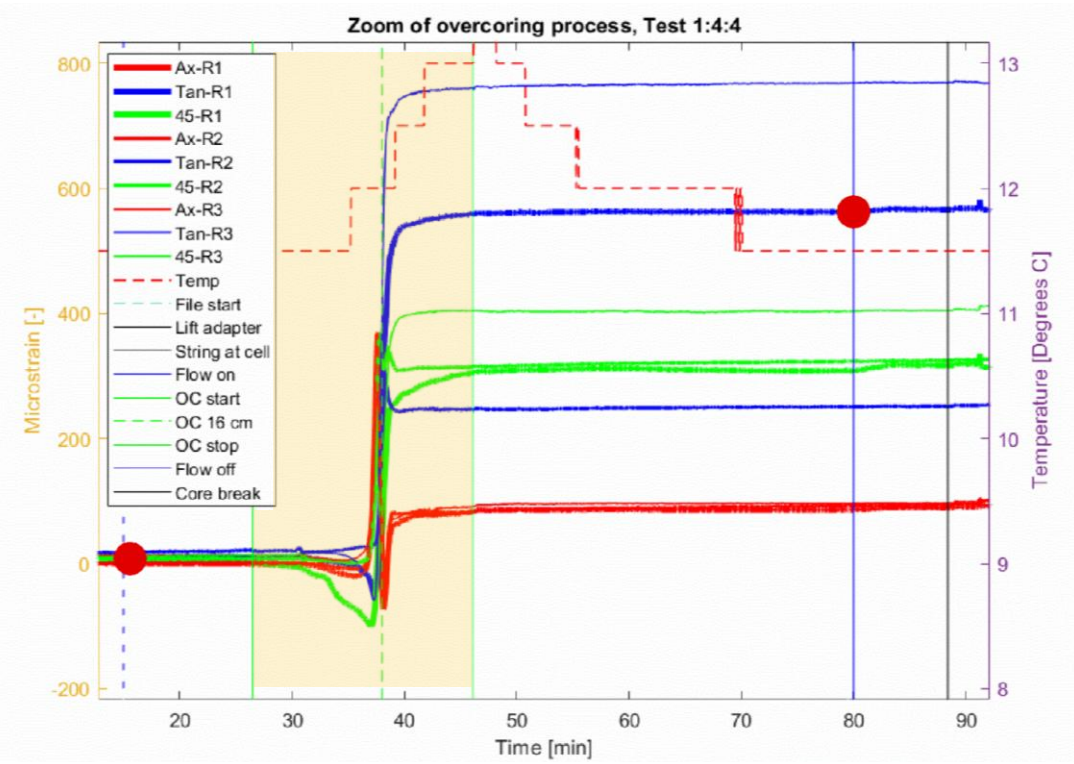
- Sicada reported original solution
- Various OCS solutions without water pressure

	σ_1			σ_2			σ_3			σ_H		σ_h	σ_v
	mag	**Trend**	**Plunge**	**mag**	**Trend**	**Plunge**	**mag**	**Trend**	**Plunge**	**mag**	**Trend**	**mag**	**mag**
Sicada	22.6	121	5	14.5	213	25	13.9	21	64	22.6	121	14.4	14.0
OCS	22.6	120	4	14.3	212	24	13.5	21	65	22.5	120	14.3	13.7
OCS @85mm	21.5	121	5	13.7	212	3	11.0	-30	84	21.5	121	13.7	11.1
OCS Pr-St.dev	22.1	120	5	13.9	211	11	12.0	8	78	22.0	120	13.8	12.1
OCS Pr+St.dev	23.5	120	4	16.3	236	81	14.8	30	8	23.5	120	14.8	16.4
OCS. Biaxial E,v	17.6	120	4	11.2	212	18	10.3	17	71	17.6	120	11.1	10.4

AoUS = amount of unexplained strains
Pr+-St.dev = solution with Poisson's ratio +- it's standard deviation
Biaxual E.v = solution using full biaxial unloading data from 10 MPa to 0 MPa

KFM24: 1:4:4, z=562.12m

G	9/9	Strains stable before overcoring
G	9/9	Strains take place within elastic transient strain range (yellow shade)
G	8,0,1	Reliability of transient strains, number *good,moderate* and *poor* transient strains correlation (next page)
G	G,G,G	Stability of inverse stress solution after passing gauges by 60 mm for s1, s2 and s3 magnitudes
Y		Stress solution is based on strains in the end of elastic region or after stable cooling period
G		Reliability for elastic stress condition with water pressure, based on T/sigma3,max: 18 MPa/11 MPa
N		Core disking observed within ±130 mm from strain gauges
		Stable readings in all measurement phases, except for gauge 3 (inclined in rosette 1). Rosette 3 transient strains are the best compared to calculated ones. Effect of drilling induced heat is minor. Vertical stress close to gravitational (9% higher).
G		***Overall strain reliability***



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1:3:3	250122-23	11:48	07:55	08:06	08:50	08:59	09:29	09:42	7.8 cm/m	08:40:00-09:20:00
1:4:4	250202-03	14:25	08:00	08:10	08:34	08:46	09:16	09:29	5.8 cm/m	08:15:00-09:19:30

OCS solution for KFM24 1:4:4 using E=71.7 GPa, v=0.22 and reported stress state

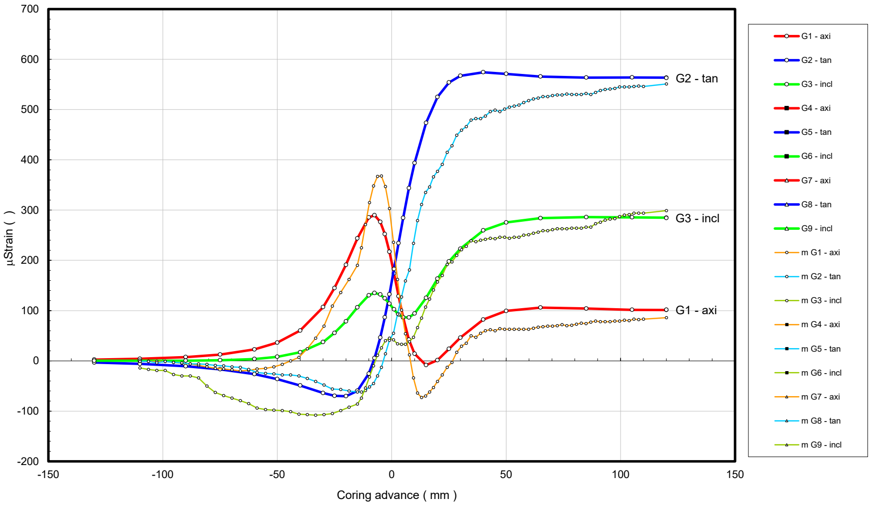
Transient strain comparison and reliability ranking

- maximum relative difference of intermediate max or min and final values

– measured strains at 120 mm are for original Sicada reported solution

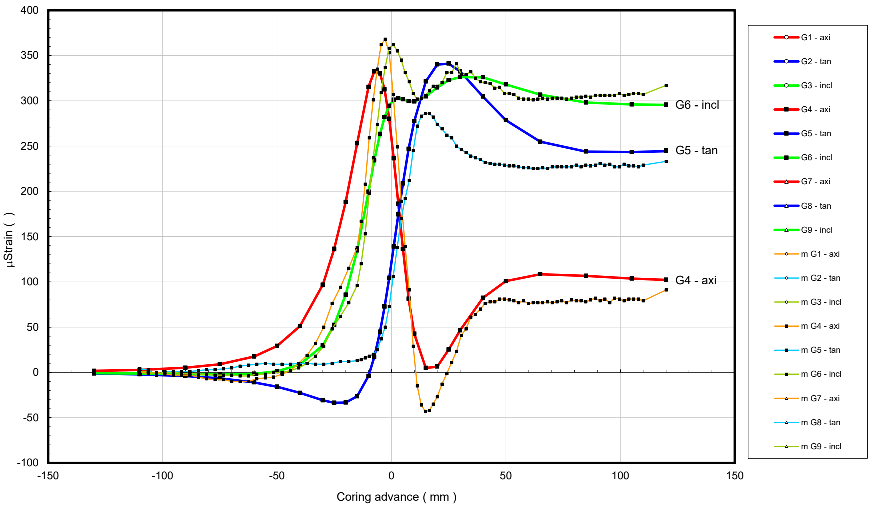
Rosette 1

G1,axi		
9.8/1.3	0.82	G
G2,tan		
0.89/0.96	0.97	G
G3,incl		
-/1.1	1.0	P



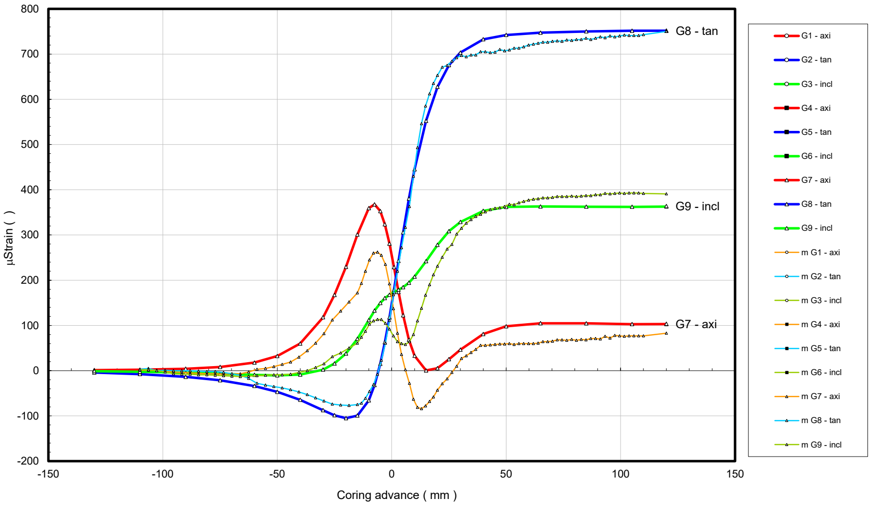
Rosette 2

G4,axi		
15/1.1	0.76	G
G5,tan		
-/0.84	0.94	G
G6,incl		
-/1.1	1.0	G



osette 3

G7,axi		
-/0.72	0.75	G
G8,tan		
0.74/1.0	0.99	G
G9,incl		
1.3/1.1	1.1	G



OCS

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- Various OCS solutions without water pressure

	σ_1			σ_2			σ_3			σ_H		σ_h	σ_v
	mag	**Trend**	**Plunge**	**mag**	**Trend**	**Plunge**	**mag**	**Trend**	**Plunge**	**mag**	**Trend**	**mag**	**mag**
Sicada	26.3	121	2	19.0	214	52	12.0	29	38	26.3	121	14.6	16.3
OCS	26.5	120	2	19.0	213	51	11.8	29	39	26.5	120	14.6	16.2
OCS No G3	22.4	120	2	15.7	213	48	9.6	29	42	22.4	120	12.3	13.0
OCS @85mm	25.7	121	5	18.0	216	47	10.8	26	42	25.7	119	14.1	14.8
OCS Pr-St.dev	25.7	120	2	17.5	213	43	10.0	28	47	25.7	120	14.1	13.5
OCS Pr+St.dev	27.6	120	1	21.0	212	60	13.5	30	30	27.6	120	15.4	19.2
OCS Biaxial E,v	20.5	120	2	14.5	213	50	9.0	29	40	20.4	120	11.3	12.2
OCS Biaxial E,v No G3	20.5	120	2	14.5	213	50	9.0	29	40	20.4	120	11.3	12.2

AoUS = amount of unexplained strains

Pr+-St.dev = solution with Poisson's ratio +- it's standard deviation

Biaxual E.v = solution using full biaxial unloading data from 10 MPa to 0 MPa