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Forsmark site investigation

Transient strain analysis of overcoring measurements in boreholes DBT-1 and DBT-3

Fredrik Perman, Jonny Sjöberg
SwedPower AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Summary

This report presents a re-analysis of the overcoring stress measurements conducted in boreholes DBT-1 and DBT-3 at the Forsmark site. The measurements were originally conducted in 1981 /SSPB, 1982/. The re-analysis comprises a transient strain analysis using the method and code developed by Matti Hakala /Hakala et al, 2003/.

The analysis showed that the amount of unexplained strain is high for nearly all measurements in DBT-1 and DBT-3. The error value is particularly high for measurements below 250 metres depth. High tensile stresses were also noted with increasing measurement depths, in particular below 250 metres. This is a strong indicator of tensile damage being done to the overcore samples, which, in turn, most likely influence the test results.

The high induced tensile stress and large amount of unexplained strain correlates with reported higher stress magnitudes below 250 metres depth. More core discing was also observed in borehole DBT-1 below 320 metres depth, which can be explained as having passed the point where the induced stresses on the overcore sample exceed the damage threshold of the rock substance.

An attempt was made to discard apparent outliers in the data. The remaining stress results were analyzed and linear trends fitted to the data, resulting in the following relations for the vertical and horizontal stress components:

$$\sigma_v = 0.027z ,$$

$$\sigma_H = 0.113z ,$$

$$\sigma_h = 0.069z ,$$

where all stresses are in MPa and z is the depth below ground surface in metres. The fit is reasonably good, using a constant stress gradient with depth. Thus, the previous interpretation /SSPB, 1982/ regarding different stress regimes above and below 320 metres depth may be questioned.

Contents

1 Introduction

This report presents a re-analysis of the overcoring stress measurements conducted in boreholes DBT-1 and DBT-3 at the Forsmark site. The measurements were originally conducted in 1977–1979 /Ingevald and Strindell, 1981; SSPB, 1982/. The re-analysis comprises a transient strain analysis using the method and code developed by Matti Hakala in an on-going SKB/Posiva joint project /Hakala et al, 2003/. The re-analysis which is one of the activities within the site investigation at Forsmark, was performed according to Activity Plan AP PF 400-04-11 (SKB internal controlling document).

2 Objective and scope

The objective of this study was to (i) aid in the quality control of the old overcoring stress measurements in borehole DBT-1 and DBT-3, respectively, (ii) possibly establish bounds on the measured stresses from these boreholes, and (iii) provide additional comparisons of the results from boreholes DBT-1 and DBT-3 and the currently (2003) on-going stress measurements in borehole KFM01B (to be reported later).

The above objectives were to be achieved through a transient strain analysis of the old measurement data. The methodology presented by /Hakala et al, 2003/ was employed, which involves calculating the theoretical strains corresponding to a given stress field (by using pre-calculations from a three-dimensional numerical model). The theoretical strain response is calculated for the entire overcoring process and can thus subsequently be compared to the actual recorded strain response from the overcoring measurement.

The analysis can be used to assess whether the reported stresses for a particular measurement are reasonable given the measured strain differences. Larger deviations in terms of measured vs calculated (theoretical) strains are indications of imperfect conditions at the time of measurements, e.g. debonding, microcracking, heterogeneities, anisotropy, etc. The analysis cannot not, however, be used to detect systematic measurement errors.

All stresses are denoted using a geomechanical sign convention with compressive stresses taken as positive. Likewise, compressive strains are defined as positive. All stress orientations are given with respect to magnetic north, using a right-hand rule notation.

3 Measurements in DBT-1 and DBT-3

3.1 Measurement method

Overcoring stress measurements in boreholes DBT-1 and DBT-3 were conducted within the construction area of the Forsmark Power Plant, and during the period of 1977 to 1979. The measurements were part of a research program, aimed primarily at testing the method of measuring rock stresses in deep, water-filled boreholes, developed by Vattenfall (the Swedish State Power Board – *SSPB*). These measurements were thus the first ones using the *SSPB* stress cell (currently known as the *Borre* probe) in a deep borehole.

The measuring technique was based on the Leeman-Hayes method, for which the complete, three-dimensional, stress tensor is determined from a single measurement /Leeman and Hayes, 1966; Leeman, 1968/. The development of the *SSPB* cell is described in /Hiltscher et al, 1979/. The probe design of the old *SSPB* cell is identical to that of the present *Borre* probe in terms of strain gauge configuration /Sjöberg and Klasson, 2003/. However, the method of data recording is different – an electrical cable was used, rather than the current wireless data logger. The electrical cable was attached to the probe and to a strain logger on surface. This setup was used to monitor strain readings up until the glue had hardened completely. At this point, the installation adapter was retrieved and the electrical cable cut. Overcoring was then performed, after which the core was retrieved to surface, and the cable again attached to the strain logger. Strain readings were again recorded, now reflecting the relaxed state of the core, while the core was kept under the same temperature as in the borehole. Thus, only the strain difference (after core recovery vs before overcoring start) was recorded in these tests /Ingevald and Strindell, 1981; SSPB, 1982/.

3.2 Test method

Subsequent to overcoring, the core samples were tested to determine the elastic constants of the rock. Contrary to current procedures, the values on Young's modulus and Poisson's ratio were determined from both uniaxial and biaxial testing. The cores were first tested uniaxially, which gave values on E and v in the axial direction. The same samples were then loaded biaxially, thus giving values on E and v in the horizontal direction /Ingevald and Strindell, 1981; SSPB, 1982/. It is not expressed precisely what type of test equipment was used for either test. However, in /Ingevald and Strindell, 1981/, it is stated that a concrete-testing machine was used for the uniaxial tests. Furthermore, for some of the tests, additional strain gauges were glued to the outside circumference of the overcore sample, in addition to the strain gauges installed on the interior (pilot hole) wall. As far as can be ascertained from /SSPB, 1982/, the individual and different values of E and v in the horizontal and vertical directions of the sample were used in the stress calculation. The implications of this and the possible effects of test methods are discussed in Section 5.

3.3 Measurement data

The two boreholes (DBT-1 and DBT-3) were located approximately 120 metres apart. Borehole DBT-1 was drilled to a depth of 500 metres, whereas borehole DBT-3 was drilled to 250 metres depth.

Measurement data have been reported in a measurement report /Ingevald and Strindell, 1981/ and in a summary report including all conducted borehole investigations /SSPB, 1982/. The reported measurement data comprise borehole depth and orientation, probe bearing, elastic constants (E, v), strain differences (after vs before overcoring) for each of the nine strain gauges, and the resulting stress data (projected stresses and principal stresses) – for each of the measurement depths (Appendix A, Table A-1 and Appendix B, Table B-1). However, it is not clear whether the reported values on E and v are for the axial or horizontal direction, or an average of the two (cf Section 3.1). In the following, it has been assumed that the values on E and v in /SSPB, 1982/ are average values for all strain gauges.

It must be observed that the reported data are not the same in the two reports. Strain differences and, hence, calculated stresses are different in /SSPB, 1982/ compared to /Ingevald and Strindell, 1981/. The changes are relatively small – a few microstrains in strain difference, resulting stresses being up to a few MPa higher in /SSPB, 1982/. There is no explanation as to why these changes were made.

In this study, all measurement data used were taken from the most recent report /SSPB, 1982/, since it was believed that these data have undergone more scrutiny than the first measurement report. For borehole DBT-1, a total of 11 measurement levels were reported, with a total of 30 discrete overcoring measurements, ranging from 14 to 502 metres depth. In borehole DBT-3, measurements were taken at 9 different levels, with a total of 22 measurements at depths from 23 to 249 metres depth. In the following each measurement is given a unique number (for each borehole) corresponding to *measurement level : test number*. The strain differences used in this study are presented in Appendices A (Table A-2) and B (Table B-2).

For comparative purposes, a reference case from the current (2003) stress measurements at Forsmark has been included in the transient strain analysis. The used reference case is test 1:4:1 at 238.94 m depth in borehole KFM01B.

3.4 Observations during measurements

/Ingevald and Strindell, 1981/ state that measurements were taken without any major problems in the whole of borehole DBT-3, and down to approximately 320 metres depth in borehole DBT-1. Of these measurements, 92% of the prepared measurement attempts resulted in completed measurements.

A heavily fractured zone was intersected at 320 metres depth in DBT-1. Below this level, extensive core discing was observed. The overcored sample exhibited 12–18 mm thick discs, which effectively inhibited successful measurements in several instances. /Ingevald and Strindell, 1981/ report that out of 15 attempted installations (in which the strain gauges had been glued to the pilot hole wall), only 8 were successfully overcored with strain data retrieved. These measurements correspond to measurement levels 9, 10, and 11 (Appendix A). It is not stated how many (if any) attempts were made without installing the probe into the pilot hole. It should also be noted that the same values for E and v were used for the last eight measurements, which is an indication that it was difficult to achieve overcore samples that were sufficiently long for biaxial and/or uniaxial testing from these measurement levels.

The severe problems of core discing have been confirmed through contacts with some of the personnel involved in these measurements. The large distance between some of the tests (40 metres for level 10) is an additional indicator of core damage-related problems during measurements. Furthermore, the frequency of induced fractures noted in the core log for DBT-1 is high, which may be taken as indication of stress-induced damages. However, the frequency of inducted fractures is only slightly lower for the upper portions of DBT-1.

It is also stated that the obtained stress magnitudes for the measurements below 320 metres depth in DBT-1 cannot be considered representative, since the samples with extensive core discing (in which measurements could not be made) must have been subjected to even higher stresses /Ingevald and Strindell, 1981/. The relevance of the obtained stresses is discussed more in Chapter 5 of this report.

4 Transient strain analysis

4.1 Methodology

Transient strain analysis was carried out using the code and methodology developed by /Hakala et al, 2003/. For each test (measurement point), the reported stress state and accompanying field parametres were input to the transient strain analysis program. Transient and final strains were calculated and the final strains compared with the measured final strains. An example of calculated transient strains compared to measured (final) strains is shown in Figure 4-1.

In addition, the amount of unexplained strain was calculated using the program. Initially, the strain differences from the measurement were used to calculate stresses. A least-square regression procedure was used to find the solution best fitting all the strain data (measurements in seven independent orientations fitted to the six components of the stress tensor). The resulting stresses were then used to back-calculate the corresponding strains for each of the strain gauges of the probe. The amount of unexplained strain was defined as the sum of absolute differences between measured and calculated strains divided by sum of calculated strains, i.e. /Hakala et al, 2003/.

$$AUS > \frac{\sum_{i=1}^{9} \left| (\varepsilon_i - \varepsilon\_calc_i) \right|}{\sum_{i=1}^{9} \varepsilon\_calc_i} \quad ,$$

where

AUS = amount of unexplained strain,

ε_i = measured strain for each of the strain gauges (i=1, 2,..9), and

ε_calc_i = back-calculated strain from the calculated stress state for each of the strain gauges (i=1, 2,..9).

A higher value on AUS indicates a larger difference between measured and theoretical strain values. This value can thus be used to estimate the heterogeneity, anisotropy, reliability, or successfulness of measurements. An example of calculated unexplained strain is shown in Figure 4-2. The final value is that at 160 mm coring advance.

The stress path developing during the overcoring process was also calculated, including the maximum tensile stress acting on the overcore sample. A high value on the tensile stress is an indicator of high possibility of tensile damage of the rock during overcoring. Strength values are not known for this site. For illustrative purposes, a uniaxial compressive strength of 230 MPa and a uniaxial tensile strength of 20 MPa were assumed to define a failure criterion. An example is presented in Figure 4-3. Note that only linear-elastic analysis is conducted; hence, very high tensile stresses can develop, which, in reality, would be limited as the strength of the rock is exceeded. The post-peak process and associated stresses and strains can, obviously, not be studied with this computer program.

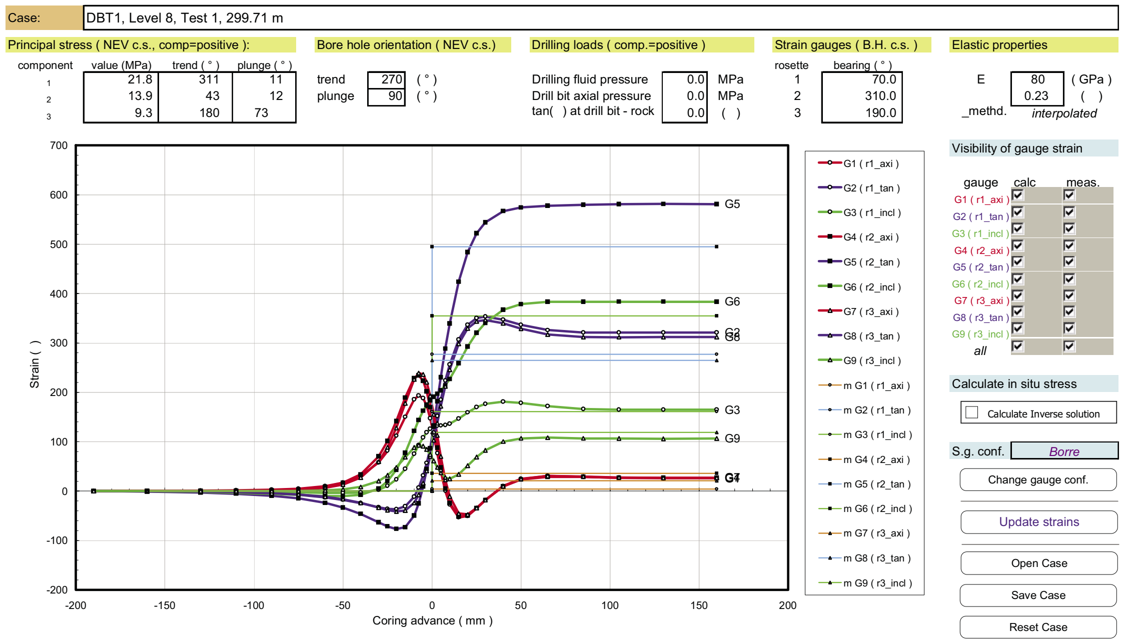

***Figure 4-1.** DBT-1 Test 8:1: Calculated vs measured strain response during overcoring for all strain gauges.*

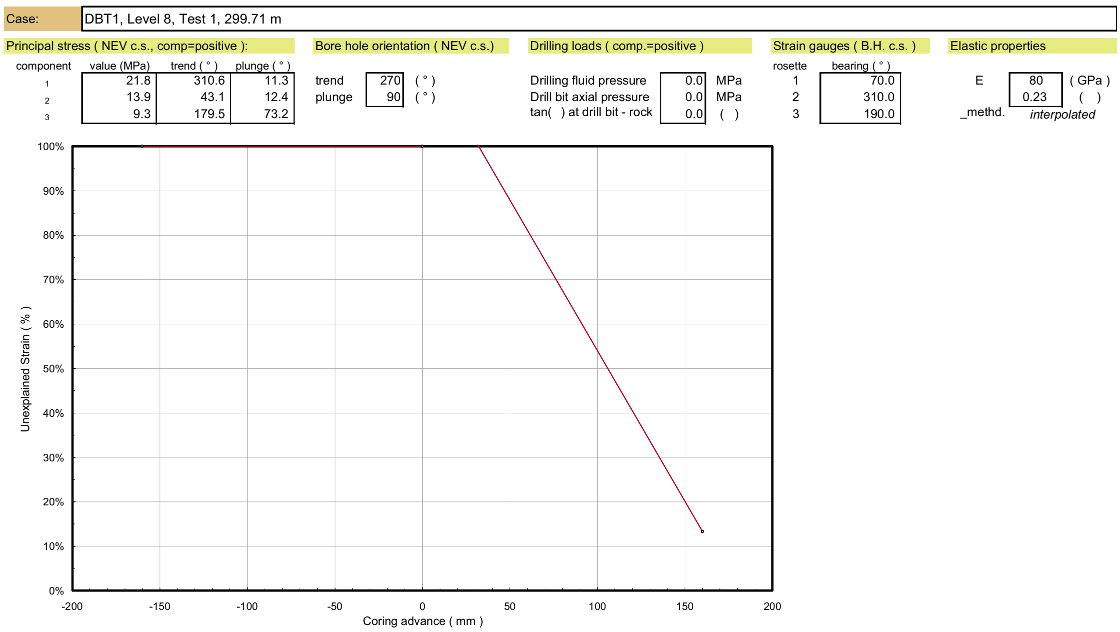

***Figure 4-2.** DBT-1 Test 8:1: Amount of unexplained strain in the stress solution.*

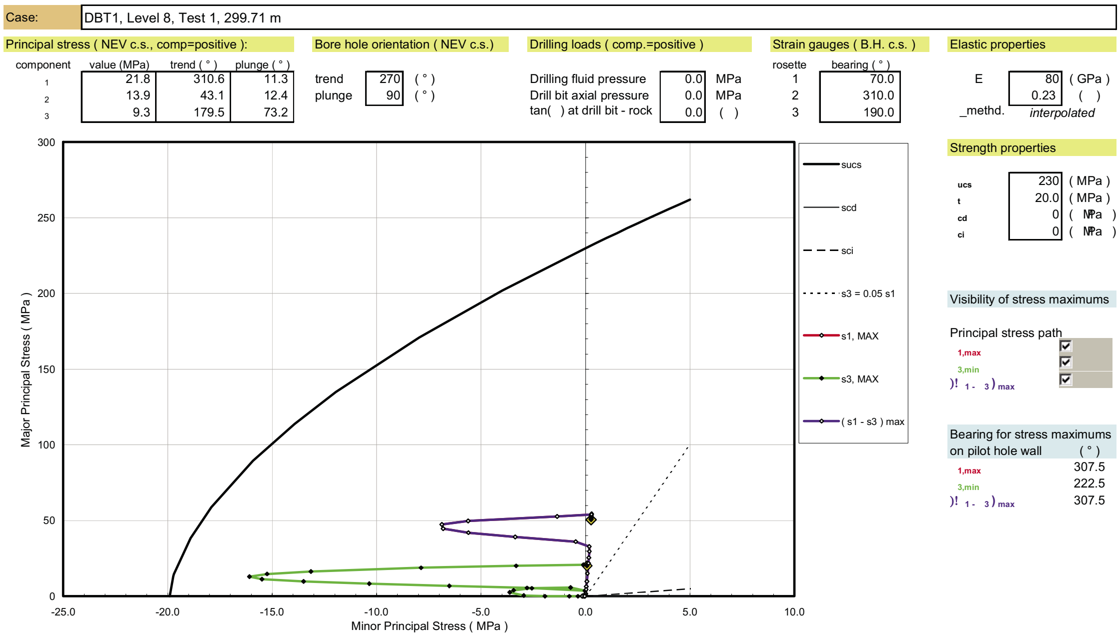

__Figure 4-3.__ DBT-1 Test 8:1: Calculated induced stresses in the overcore sample during overcoring (strength values were assumed in absence of test results).

4.2 Conducted analysis

The strain analysis was conducted on measurements in boreholes DBT-1 and DBT-3, divided into three stages, as follows:

1. All tests where σ_1 had a dip of 20° or more (9 tests).
2. All tests below 220 metres measurement depth (23 tests including step 1).
3. All tests below 100 metres measurement depth (38 tests including step 1 & 2).

This step-wise procedure was adopted to test whether e.g. certain measurement depths resulted in less reliable stress estimates. Note that only the strain differences (after vs before overcoring) were measured; hence, no comparisons could be made of the transient strain behavior during overcoring (cf Figure 4-1). This limits, to some extent, the conclusions that can be drawn with respect to the development of high axial strains during the overcoring process. The latter is often seen in conjunction with stress-induced damages and/or micro-cracking.

In addition to the transient strain analysis, a few stress calculations were conducted to check the reported stress magnitudes, given the reported strain differences. These calculations were conducted using the current stress calculation program used by SwedPower (based on the classical theory by Leeman, 1968), see also SKB MD 181.001 (SKB internal controlling document).

5 Results

5.1 Calculated stresses and influence of elastic constants

Test calculations of stresses for a few selected measurements, using the reported strain differences and values on elastic constants in /SSPB, 1982/, gave somewhat different stresses than those reported in /SSPB, 1982/. In most (but not all) cases, slightly lower stress magnitudes were obtained as well as slightly different orientations (within a few degrees). This confirms that stresses were calculated slightly differently for the measurements in DBT-1 and DBT-3 compared to current procedures. The most likely reason for this is that different values on E and v have been employed for different orientations (different gauges). The relatively small differences indicate that anisotropy is very mild at this site.

More serious is the fact that by using different values on E and v for different gauges in the stress calculation, the transient strain response cannot be replicated completely in the transient strain analysis methodology by /Hakala et al, 2003/. The "error" introduced may, however, not be very significant for moderate differences in E and v for different orientations, although this cannot be confirmed through this study.

The fact that a concrete-testing machine was used for the uniaxial tests to determine Young's modulus, may also have some effect on the results. Considering the state-of-the art in laboratory testing of rock samples in the late 1970s in Sweden, it is likely that the test machine was relatively soft, compared to current servo-controlled stiff loading frames. This choice of test setup may have influenced the resulting values on the elastic constants; however, with no additional details provided in either report, it is not possible to elaborate on this further.

5.2 Strain analysis results

The analysis results are presented in Appendix A, Table A-2 and Table A-3, and Appendix B, Table B-2 and Table B-3, for DBT-1 and DBT-3, respectively. The results are also stored in the SKB database SICADA under Field Note number XX. The corresponding values from measurement 1:4:1 (at 238.94 m depth) in borehole KFM01B are presented as a reference case from the currently on-going measurements at Forsmark. This measurement gave high stresses (σ_H > 40 MPa) with extensive discing of the lower portion of the overcore sample.

These tables compare calculated (from the computer program) and measured final strains. Both absolute and relative differences are presented. The amount of unexplained strain (defined above), and the maximum calculated tensile stress that develop during overcoring are both shown (Table A-2 and Table B-2). These parametres are also plotted vs measurement depth in Figure 5-1 and Figure 5-2. The theoretical value on the vertical stress, assuming overburden weight, compared to the measured value on the vertical stress component, is shown in Table A-3 and Table B-3, and plotted in Figure 5-3. The results from each of the analysis steps are briefly commented below.

Step 1 (all tests where σ_1 had a dip of 20° or more)

The amount of unexplained strain is between 18 and 34%, with an average value of 23%. The maximum tensile stress for these tests is 11–30 MPa, with an average of 17 MPa. The tangential gauges display the largest absolute difference compared to the measured values (average of 70 μstrain). The longitudinal gauges exhibit the largest relative difference (on average 334%).

Step 2 (all tests below 220 metres depth)

The amount of unexplained strain is 13–34% with an average of 23%. Maximum tensile stress varies between 11 and 47 MPa (22 MPa average). The tangential gauges show the largest absolute differences (average of 150 μstrain), whereas the largest relative differences were found for the longitudinal gauges (on average 60%). Compared to Step 1, the absolute differences are larger, but the relative differences are smaller.

Step 3 (all tests below 100 metres depth)

The average amount of unexplained strain is 23% (varies between 13 and 36%). The maximum tensile stress is 9–47 MPa with an average of 23 MPa. The largest absolute differences were found for the tangential gauges (average of 115 μstrain). The longitudinal gauges showed the largest relative differences (average of 27%). Both the absolute and the relative differences are smaller compared to the results from Step 2 above.

5.3 Interpretation

The analyses show significant differences between measured and calculated (theoretical) strains (Appendices A and B) for both boreholes. The longitudinal gauges exhibit consistently the largest relative differences compared to the theoretical values, whereas the tangential gauges display the smallest relative difference compared to theoretical strains. For the tangential, and to some degree the inclined gauges, the theoretical strains are larger than the measured strains. However, large deviations (theoretical vs measured) are found for both shallow and deep measurements, making it difficult to identify general trends.

During measurements, the final strain values were recorded once the core was on surface and not immediately after completed overcoring. Thus, potential strain changes induced during the recovery process are included in the strain differences. Our (SwedPower's) experience in stress measurements has shown that for measurements with stable strain response, good bonding, and little microcracking, the strain changes during core recovery are small (see e.g. /Sjöberg and Klasson, 2003; Hakala et al, 2003/). However, if extensive microcracking and/or damage to the core occurs during overcoring and/or if bonding is suboptimal, larger changes may occur. These changes often result in lower strains being recorded, i.e. the strain differences being underestimated. Underestimated strains also result in underestimated stress magnitudes. These possible effects are discussed further in Section 5.4 below.

The amount of unexplained strain varies relatively dramatically between the different measurements. This measurement of "error" is, however, relatively large for all measurements – often above 20% in borehole DBT-1 and generally above 15% in borehole DBT-3. Normally, values around 10% are found for experimentally successful measurements (it was only 5% for test 1:4:1 in KFM01B). This may indicate that the measurements in DBT-1 and DBT-3 were less successful. In borehole DBT-1, a trend with increasing amount of unexplained strain for more measurements at larger depths can be observed. This trend is much less obvious in borehole DBT-3 due to the limited hole depth, see Figure 5-1. At lower depths, there is some correlation between the values for both boreholes (e.g. at 135 metres depth).

With increasing depth, the maximum theoretical tensile stress that can develop during overcoring increases. This is particularly evident in borehole DBT-1 (Figure 5-2). With tensile stresses exceeding 30 MPa, there is almost certainly bound to be permanent damage in the overcore samples. This occurs for measurement depths of around 275 metres in borehole DBT-1. The tensile damages must, in turn, influence the strain readings and the resulting stresses. However, with no record of the transient strain response, it is not possible to judge the effect of this. For comparison, the maximum tensile stress for test 1:4:1 in KFM01B was 33 MPa, with clear signs of core discing at the end of the overcore sample. Transient strain analysis of this test verified that extensive tensile damage had occurred at the gauge position in the sample – even without causing core discing at this precise location.

The difference in measured vertical stress compared to the theoretical value corresponding to the overburden height, can be taken as an indicator of core damage in the axial direction. If core damage occurs, large axial strains are recorded, which, in turn, result in an overestimation of the vertical stress (in a vertical borehole). For boreholes DBT-1 and DBT-3, no obvious correlations exist for measurements above approximately 400 metres depth. For deeper measurement points, the measured vertical stress is overestimated for some of the measurement points, as shown in Figure 5-3.

The fact that the reported principal and horizontal stresses from DBT-1 are significantly higher below approximately 250 metres depth can be nicely correlated with the above observations of high tensile stresses and larger amount of unexplained strain at these depths. With the high values on the maximum theoretical tensile stresses that can develop during overcoring, there is no reason to believe that the cores should ***not*** be damaged in tension (even without signs of core discing), in a similar fashion to what has been observed and inferred for the currently on-going measurements in KFM01B.

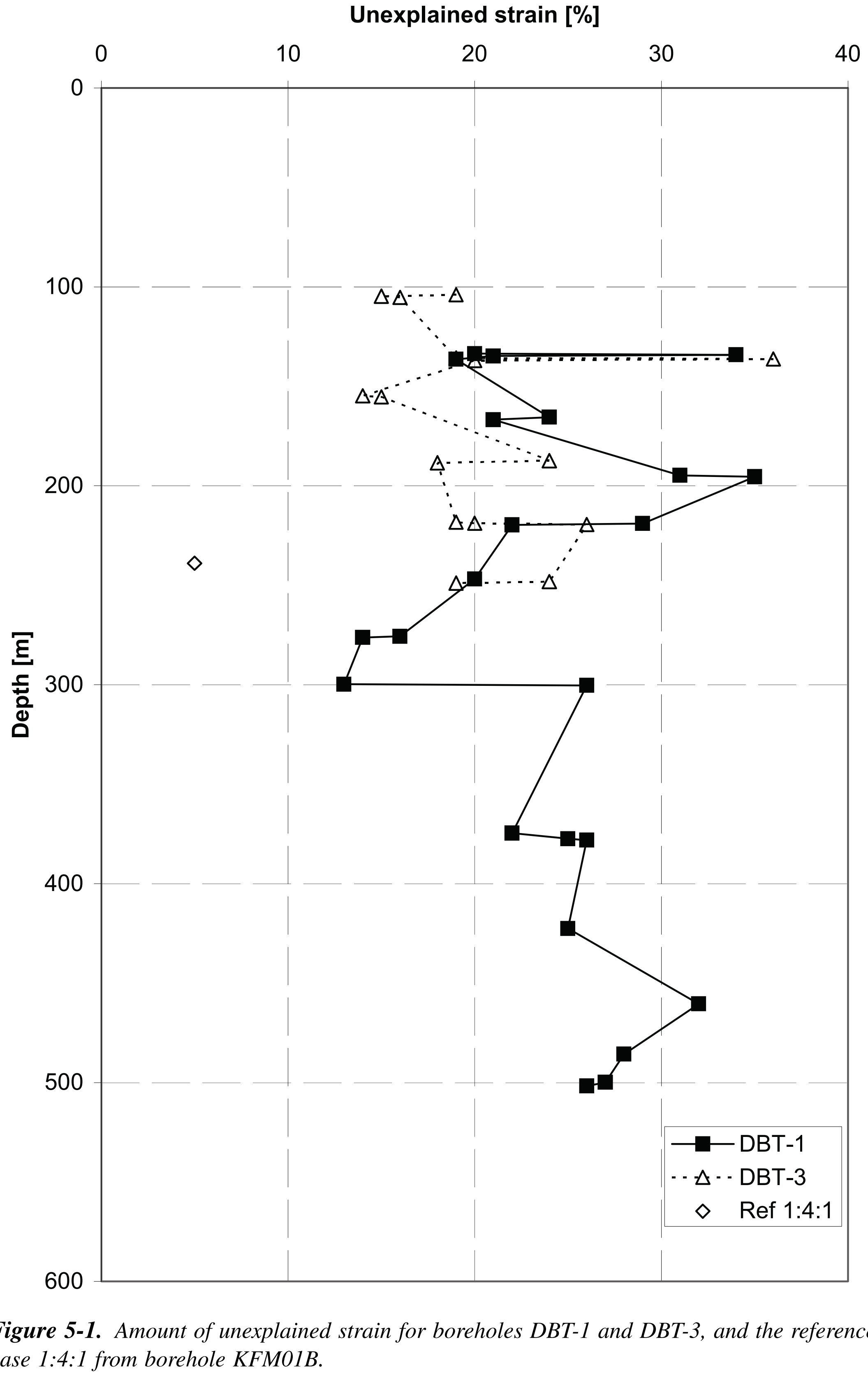

Figure 5-1. Amount of unexplained strain for boreholes DBT-1 and DBT-3, and the reference case 1:4:1 from borehole KFM01B.

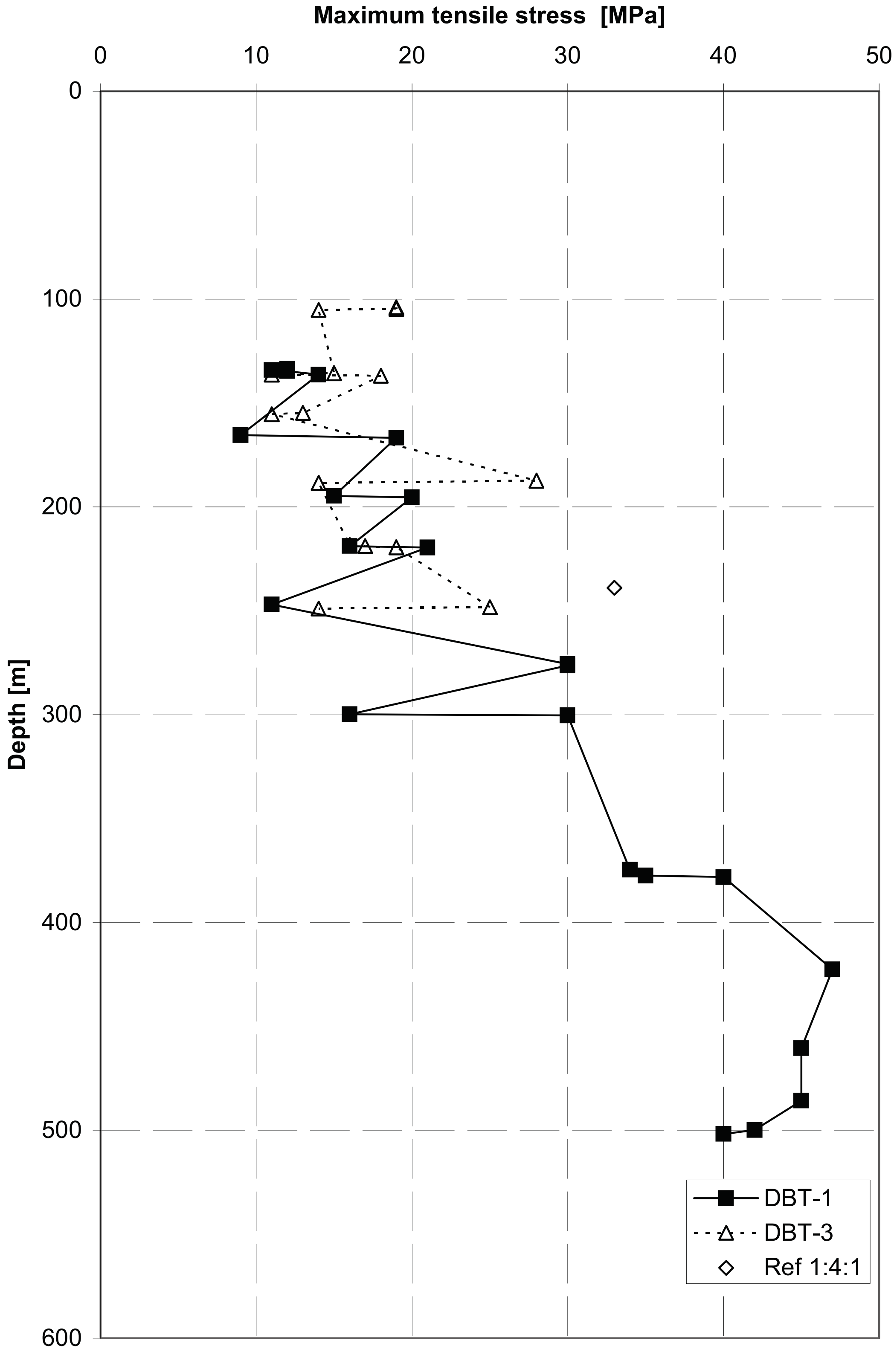

Figure 5-2. *Maximum tensile stress for boreholes DBT-1 and DBT-3, and the reference case 1:4:1 from borehole KFM01B.*

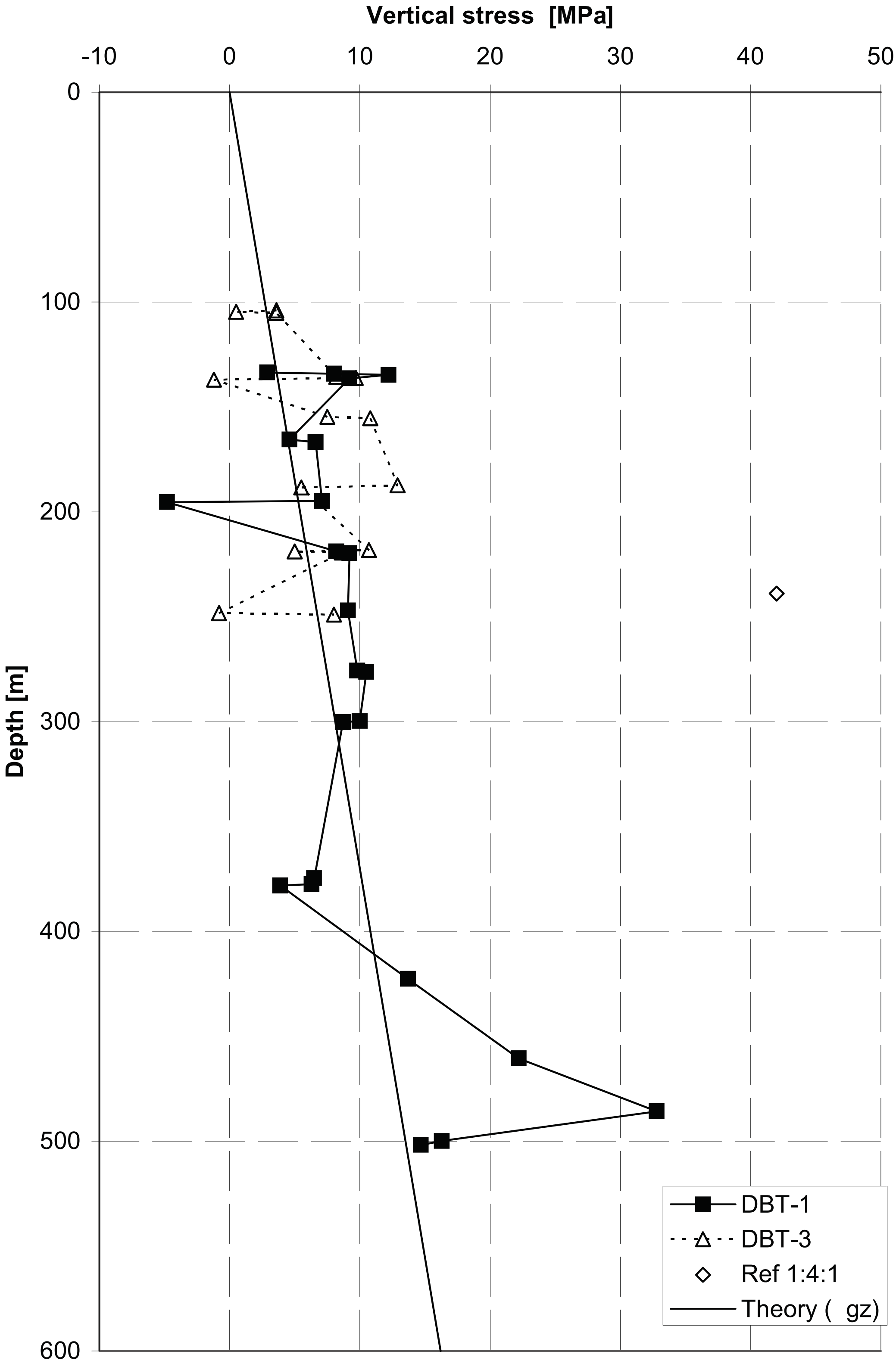

Figure 5-3. Measured vertical stress and theoretical vertical stress (overburden weight) for boreholes DBT-1 and DBT-3, and reference case 1:4:1 from borehole KFM01B.

5.4 Assessment of measured stresses

The measurements in DBT-1 and DBT-3 have, over the years, been considered fairly successful. The fact that many measurement results were reported is, however, ***not*** any proof that measurements were successful and reliable. It is difficult to state, with certainty, which of the reported measurements that are reliable based on the transient strain analysis. There are few clear trends in the data, even when cross-correlating the different analyzed parameters.

An attempt has, however, been made to discard some of the measurements to arrive at probable estimates on the measured stress state. Only the vertical and horizontal stress components were considered in this task. The measured vertical stress for both boreholes is shown in Figure 5-3, whereas the maximum and minimum horizontal stresses are shown in Figure 5-4 and Figure 5-5. Measurements were discarded based on the following criteria and hypotheses:

- Large amount of unexplained strain (approximately above 30%).
- Apparently erroneous value on the vertical stress (negative values as well as largely overestimated values compared to the overburden weight).
- High values on tensile stress (approximately above 40 MPa).

The above criteria were combined, resulting in the following measurements being discarded:

- DBT-1: 3:3 (134.74 m), 5:2 (195.39 m), 10:1 (422.59 m), 10:2 (460.48 m), 10:3 (485.72 m).
- DBT-3: 5:2 (136.31 m), 5:3 (136.93 m), 7:1 (187.40 m), 9:1 (248.23).

The remaining measurement results are shown in Figure 5-6 through Figure 5-8, together with fitted linear trends to the data. A zero (0) intercept was assumed at the ground surface, in lieu of better alternatives. For the vertical stress, only the theoretical trend line corresponding to overburden weight is shown, as this is in fair agreement with measured stresses. The equations for these trend-lines are

$$\sigma_v = 0.027z,$$

$$\sigma_H = 0.113z,$$

$$\sigma_h = 0.069z,$$

where all stresses are in MPa and z is the depth below ground surface in metres. The obtained stress gradients are relatively high, but may be considered an upper limit to the stress gradient. If a different intercept is assumed, stress gradients would be lower. However, the present data do not support any assumptions regarding the intercept at the ground surface.

The high measured stresses below 320 metres depth in DBT-1 were previously interpreted as an effect of having passed the heavily fractured zone at 320 metres depth in DBT-1, thus moving into a different stress regime. The number of observations is, however, quite few, thus making this conclusion somewhat speculative. The above analysis shows that, by excluding some apparent outliers, a reasonably good fit can be obtained with a constant stress gradient with depth. It must also be recalled that the stresses measured at level 7 (≈ 275 metres depth) were almost as high as those at level 9 (≈ 375 metres depth). The fact that more core discing was observed below 320 metres depth can be explained as having passed the point where the induced stresses on the overcore sample exceed the damage threshold of the rock substance. The transient strain analysis confirms the higher possibility of induced tensile damage in the rock at these depths, but cannot be used to deduce the origin or cause of this damage.

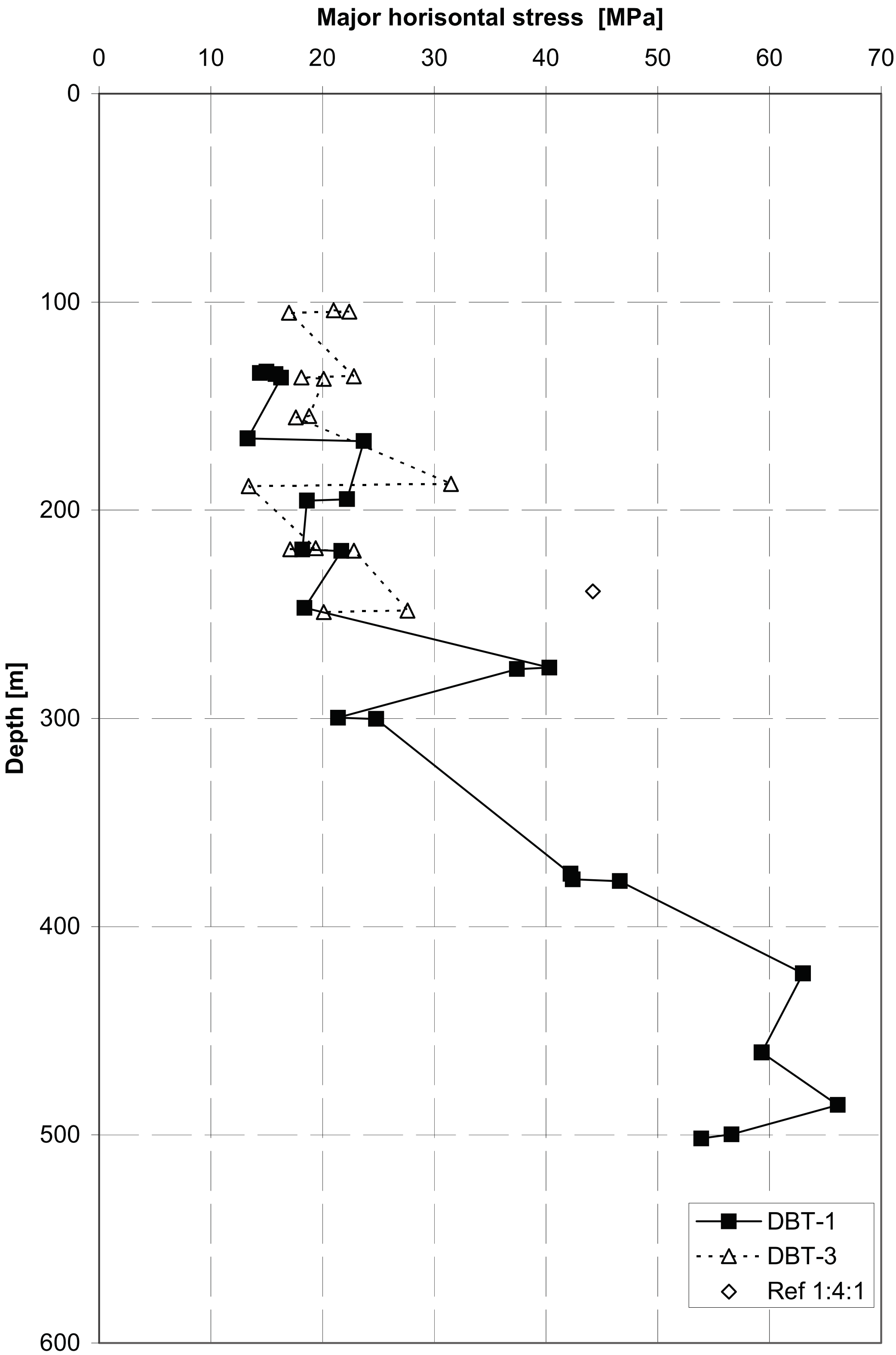

Figure 5-4. Measured major horizontal stress from boreholes DBT-1 and DBT-3, and reference case 1:4:1 from borehole KFM01B.

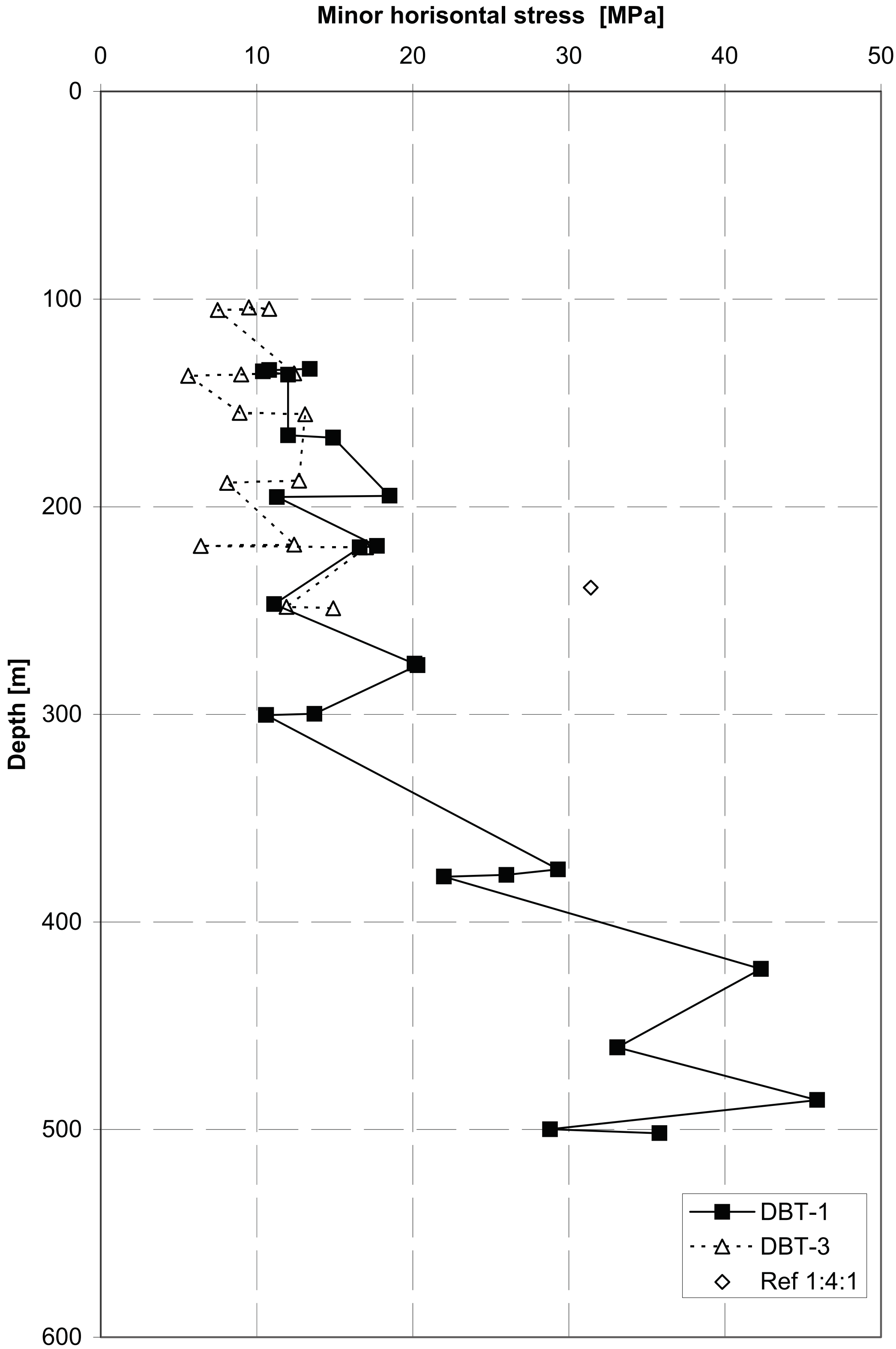

***Figure 5-5.** Measured minor horizontal stress from boreholes DBT-1 and DBT-3, and reference case 1:4:1 from borehole KFM01B.*

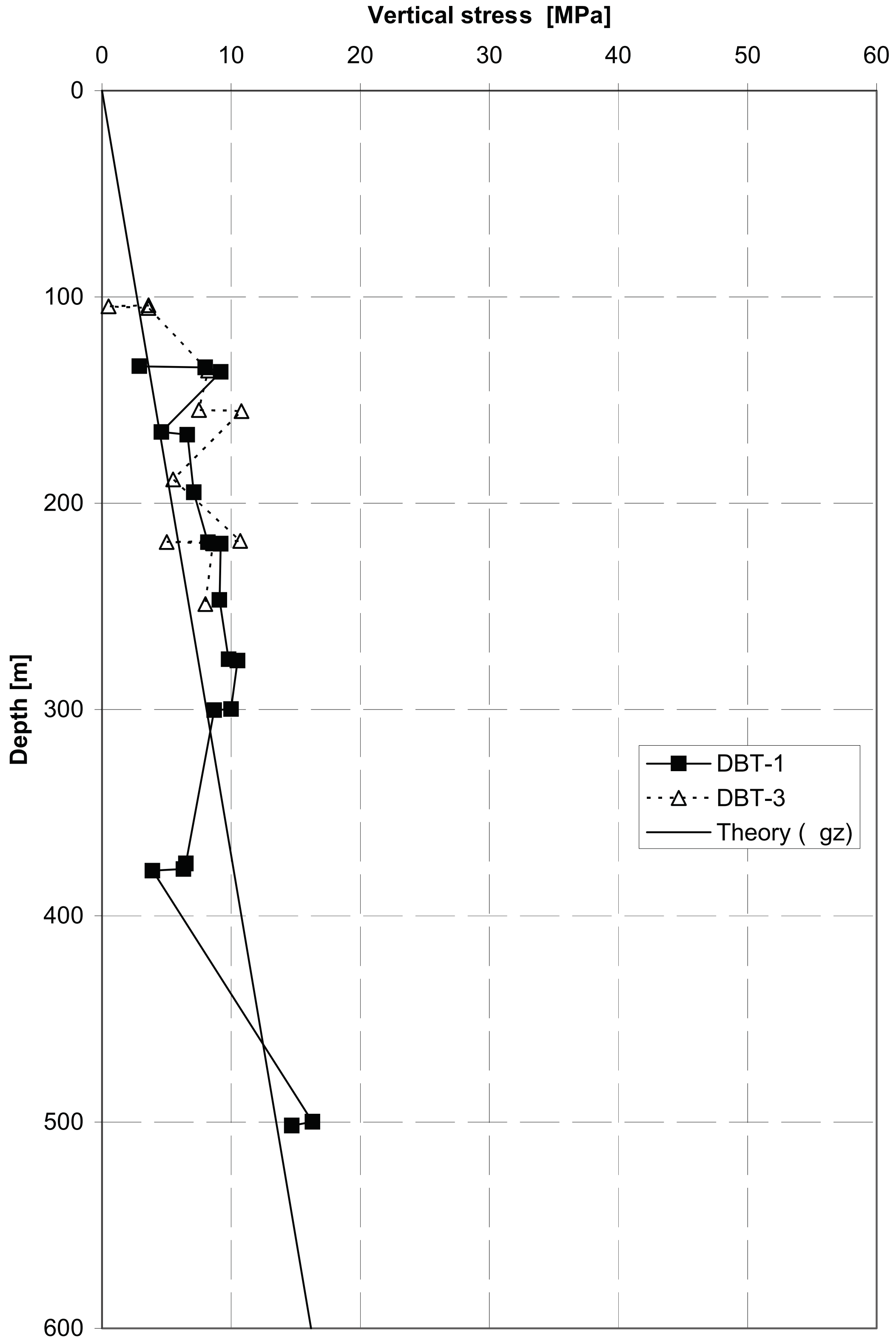

Figure 5-6. *Selected measurements of the vertical stress in boreholes DBT-1 and DBT-3.*

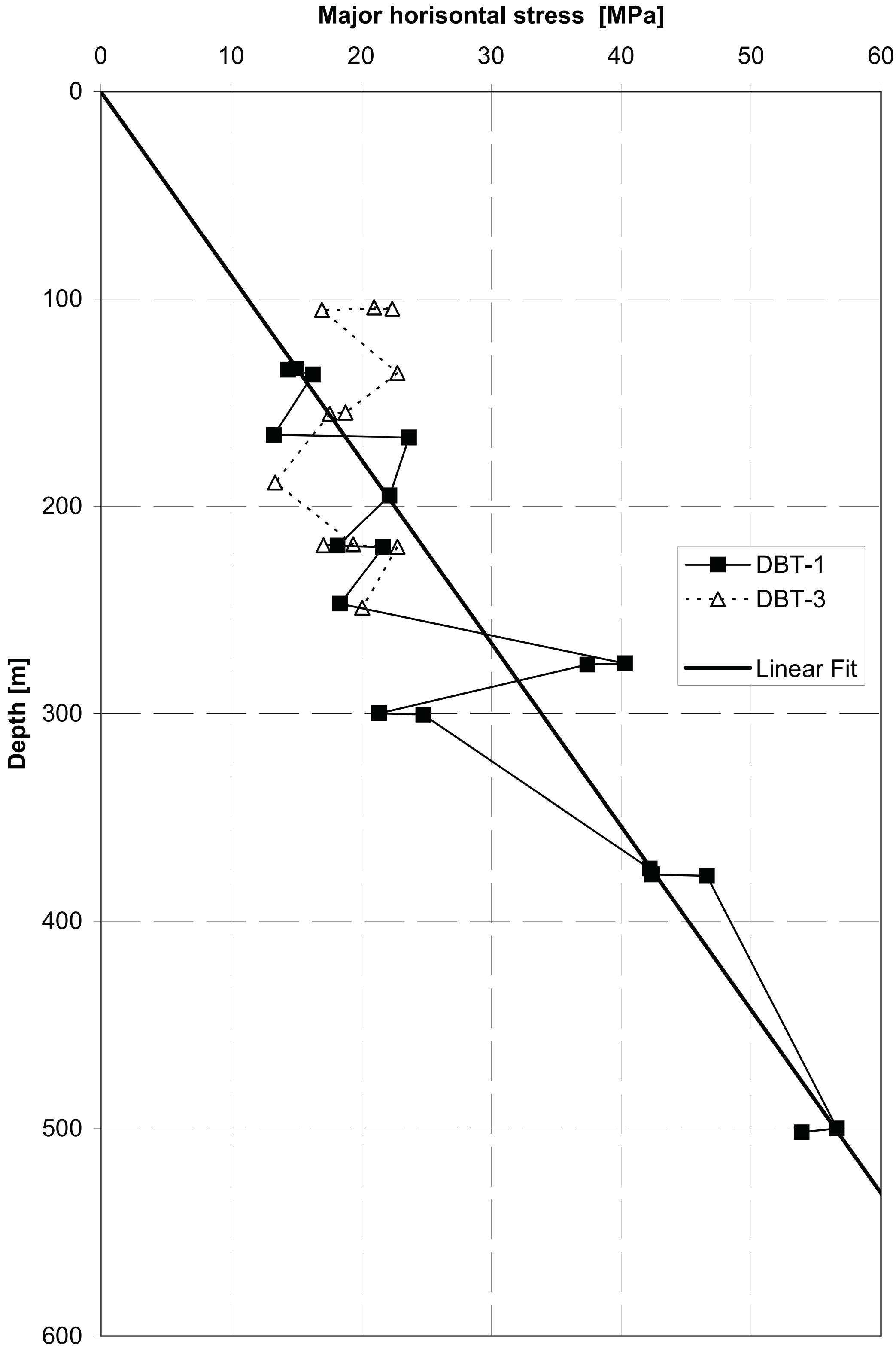

Figure 5-7. Selected measurements of the major horizontal stress in boreholes DBT-1 and DBT-3.

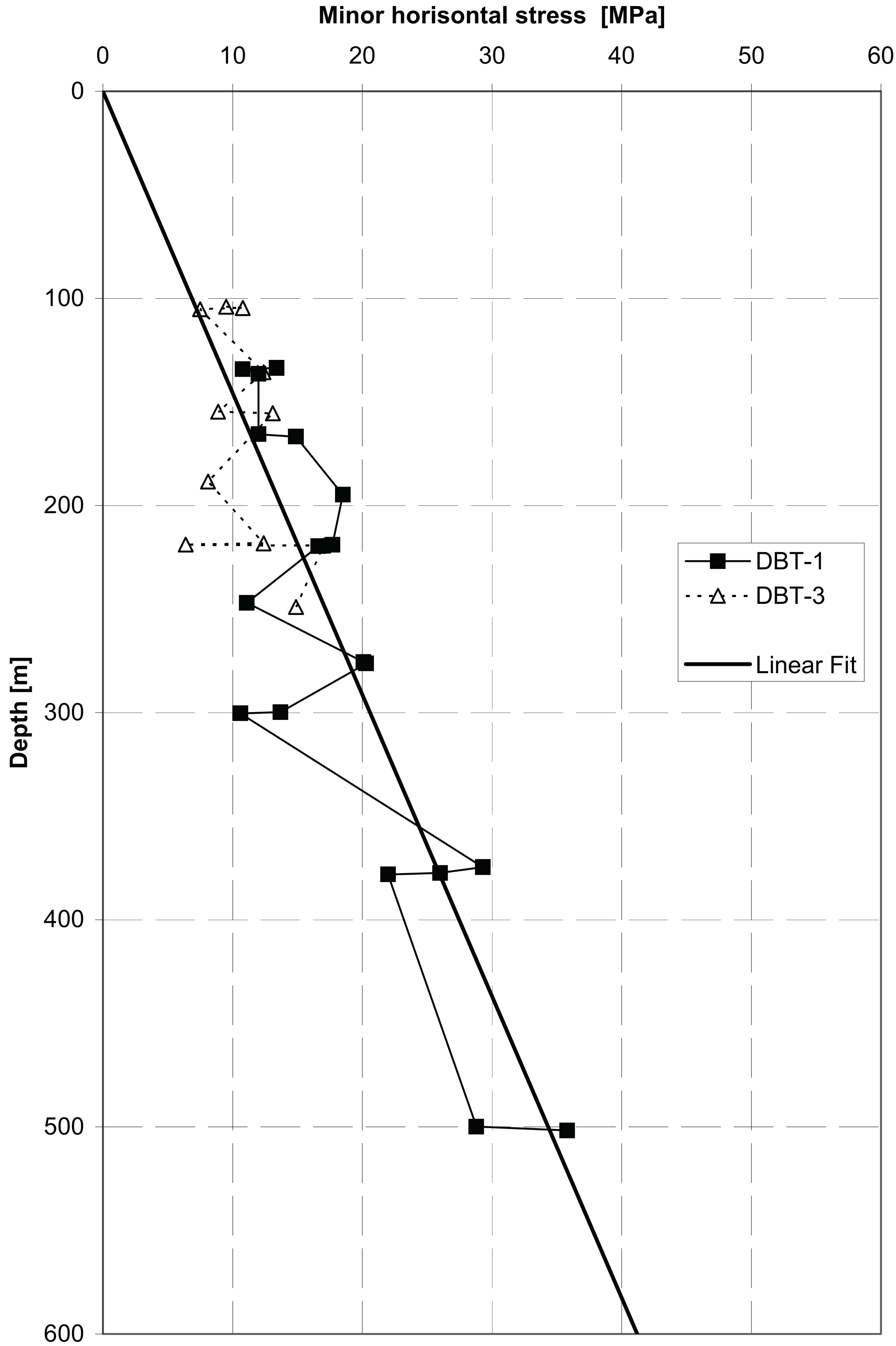

__Figure 5-8.__ Selected measurements of the minor horizontal stress in boreholes DBT-1 and DBT-3.

5.5 Conclusions

The following conclusions can be stated:

- The amount of unexplained strain is high for nearly all measurements in DBT-1 and DBT-3. The error value is particularly high for measurements below 250 metres depth.
- Stress calculation was, as far as can be ascertained, performed with different values on the elastic constants for different strain gauges/orientations. This may have resulted in larger amounts of unexplained strain (since this is calculated by the computer program assuming completely isotropic conditions).
- High tensile stresses are noted with increasing measurement depths, in particular below 250 metres depth in the boreholes. This is a strong indicator of tensile damage being done to the overcore samples, which, in turn, most likely influence the test results.
- High tensile stress and large amount of unexplained strain correlates with reported higher stress magnitudes below 250 metres depth.
- Given the lack of clear trends, it is difficult to state which of the measurements that are less reliable. Nevertheless, an attempt was made to discard apparent outliers in the data. The remaining stress results were analyzed and linear trends fitted to the data, resulting in the following relations for the vertical and horizontal stress components:

  $$\sigma_v = 0.027z,$$

  $$\sigma_H = 0.113z,$$

  $$\sigma_h = 0.069z,$$

  where all stresses are in MPa and z is the depth below ground surface in metres. The fit is reasonably good, using a constant stress gradient with depth. Thus, the previous interpretation /SSPB, 1982/ regarding different stress regimes above and below 320 metres depth may be questioned.

6 References

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Appendix A

Analysis of measurements in borehole DBT-1 and reference case 1:4:1 from borehole KFM01B

Table A-1. Measurement results from borehole DBT-1.

Step	Depth [m]	Test	E [GPa]	ν	Probe bearing [°]	Measured stresses												
						σ_H [MPa]	σ_h [MPa]	Bearing σ_H [°]	σ_v [MPa]	σ_1 [MPa]	Dip σ_1 [°]	Bearing σ_1 [°]	σ_2 [MPa]	Dip σ_2 [°]	Bearing σ_2 [°]	σ_3 [MPa]	Dip σ_3 [°]	Bearing σ_3 [°]
3	133.61	3:1	76.3	0.18	249	15.0	13.4	148.3	2.9	15.1	5.8	155.2	13.8	9.7	246.2	2.5	78.7	34.9
1	134.18	3:2	80.9	0.20	293	14.4	10.8	118.9	8.0	15.4	20.7	305.3	11.2	13.5	40.5	6.6	64.9	161.4
1	134.74	3:3	78.4	0.20	48	15.8	10.4	94.2	12.2	19.0	44	324.4	15.2	15.8	70.2	4.2	41.7	174.8
1	136.41	3:4	75.6	0.21	323	16.3	12.0	99.9	9.2	18.5	25.9	284.9	12.2	8.6	19.1	6.9	62.5	125.9
3	165.54	4:1	75.4	0.17	304	13.3	12.0	49.9	4.6	13.3	5.7	48.7	12.0	2.1	318.4	4.5	83.9	208.4
3	166.80	4:2	75.1	0.19	177	23.7	14.9	90.7	6.6	24.2	9.9	275.3	16.6	21	9.1	4.4	66.6	161.6
3	194.77	5:1	71.9	0.19	18	22.2	18.5	96.3	7.1	22.2	1.9	275.1	19.0	10.7	184.7	6.7	79.1	14.8
3	195.39	5:2	77.6	0.20	312	18.6	11.3	102.7	-4.8	19.2	9.0	283.1	11.3	1.2	13.3	-5.4	81.0	111.0
1	218.90	6:1	75.7	0.22	302	18.2	17.7	31.2	8.2	20.6	25.5	328.8	18.1	1.8	237.9	5.4	64.4	144.1
1	219.63	6:2	75.0	0.20	273	21.7	16.6	13.9	9.2	25.8	26.9	180.5	17.4	10.2	85.2	4.4	60.9	336.4
2	246.94	6:3	86.5	0.20	45	18.4	11.1	44.7	9.1	18.4	0.7	44.8	11.1	11.9	134.9	9.0	78.1	311.2
2	75.65	7:1	72.1	0.18	202	40.3	20.1	142.6	9.8	40.5	3.7	323.3	21.4	18.4	54.6	8.4	71.2	222.2
2	276.31	7:2	75.6	0.20	112	37.4	20.3	90.0	10.5	38.0	8.3	270.2	20.3	1.7	0.4	9.9	81.5	102.1
2	299.71	8:1	80.3	0.23	340	21.4	13.7	129.1	10.0	21.8	11.3	310.6	13.9	12.4	43.1	9.3	73.2	179.5
1	300.34	8:2	79.6	0.23	235	24.8	10.6	152.7	8.7	32.0	29.1	332.1	10.6	1.5	241.3	1.5	60.8	148.5
2	374.63	9:1	75.0	0.19	248	42.2	29.3	149.1	6.5	42.5	5.6	147.7	29.7	7.4	57.0	5.8	80.6	274.6
2	377.37	9:2	75.0	0.19	328	42.4	26.0	165.0	6.3	42.8	6.5	162.4	28.0	16.5	70.5	3.8	72.2	273.0
2	378.16	9:3	75.0	0.19	107	46.6	22.0	122.3	3.9	47.2	6.5	122.0	22.1	3.3	31.6	3.3	82.7	275.2
2	422.59	10:1	75.0	0.19	80	63.0	42.3	129.1	13.7	63.1	2.7	128.4	43.2	10.1	37.9	12.7	79.5	233.4
2	460.48	10:2	75.0	0.19	244	59.3	33.1	139.1	22.2	60.4	9.5	139.1	33.1	0.0	229.1	21.2	80.5	319.2
2	485.72	11:1	75.0	0.19	12	66.1	45.9	118.6	32.8	67.0	9.4	301.8	48.7	21.9	35.6	29.0	66.0	189.9
2	499.87	11:2	75.0	0.19	227	56.6	28.8	158.5	16.3	56.9	4.4	158.6	28.8	1.2	248.7	16.1	85.4	353.7
2	501.76	11:3	75.0	0.19	263	53.9	35.8	154.6	14.7	54.1	4.4	153.6	36.6	10.8	62.8	13.7	78.3	265.5

Table A-2. Analysis of measurements in borehole DBT-1 for step 1-3 and reference case 1:4:1 from borehole KFM01B.

Step	Depth [m]	Test	Measured strains									Calculated strains									Unexplained strain [%]	Maximum tensile stress [MPa]
			ε_{L1}	ε_{T1}	ε_{45_1}	ε_{L2}	ε_{T2}	ε_{45_2}	ε_{L3}	ε_{T3}	ε_{45_3}	ε_{L1}	ε_{T1}	ε_{45_1}	ε_{L2}	ε_{T2}	ε_{45_2}	ε_{L3}	ε_{T3}	ε_{45_3}		
3	133.61	3:1	-1	338	204	-49	288	249	-23	305	189	-26	398	146	-26	333	225	-25	359	142	20	12
1	134.18	3:2	-44	193	94	-2	276	151	138	273	110	36	212	172	38	317	222	37	346	104	34	11
1	134.74	3:3	5	276	37	74	158	335	146	338	305	88	308	5	88	189	330	90	412	259	21	12
1	136.41	3:4	-14	301	92	52	376	345	72	212	84	44	342	125	45	446	398	46	258	74	19	14
3	165.54	4:1	-71	311	155	28	272	150	53	243	146	6	348	208	6	323	154	6	294	134	24	9
3	166.80	4:2	-45	619	337	-1	347	21	20	300	215	-6	715	441	-8	411	40	-9	361	261	21	19
3	194.77	5:1	-92	556	163	32	390	85	38	446	228	-4	633	320	-5	468	166	-5	533	334	31	15
3	195.39	5:2	-306	295	-51	87	450	362	-135	267	1	-136	303	35	-134	374	344	-134	308	17	35	20
1	218.90	6:1	36	384	203	-34	384	203	9	375	-39	6	461	312	8	441	344	7	442	35	29	16
1	219.63	6:2	17	516	-6	17	397	211	17	326	299	24	603	49	21	466	307	24	382	413	22	21
2	246.94	6:3	-14	142	83	88	329	215	21	340	182	38	157	108	39	398	219	39	396	212	20	11
2	75.65	7:1	-23	913	444	5	925	372	-19	230	222	-9	1066	526	-10	1088	431	-11	275	258	16	30
2	276.31	7:2	-46	365	227	0	975	417	11	530	379	-9	421	242	-9	1145	453	-10	629	402	14	30
2	299.71	8:1	4	277	161	36	495	355	21	265	119	26	321	165	27	581	384	27	312	106	13	16
1	300.34	8:2	13	630	784	58	271	88	-52	165	42	10	738	787	12	335	-65	6	182	-73	26	30
2	374.63	9:1	-46	924	426	-93	518	229	-70	644	453	-86	1239	494	-88	689	246	-87	861	541	22	34
2	377.37	9:2	-81	408	289	-42	638	119	-77	948	487	-82	545	402	-83	858	150	-85	1264	673	25	35
2	378.16	9:3	-120	274	81	-105	670	381	-47	1073	405	-116	365	128	-114	893	530	-114	1440	536	26	40
2	422.59	10:1	-62	1072	500	-9	639	484	-115	1337	555	-75	1436	633	-74	874	580	-72	1766	740	25	47
2	460.48	10:2	87	1299	519	20	446	243	332	873	529	70	1740	724	67	598	381	70	1165	773	32	45
2	485.72	11:1	130	1367	639	126	1066	764	85	707	224	158	1831	951	160	1434	1089	161	946	357	28	45
2	499.87	11:2	37	1196	563	-27	940	531	-8	309	168	8	1605	731	8	1252	726	8	417	212	27	42
2	501.76	11:3	-6	1133	529	-39	545	169	-23	900	557	-22	1518	714	-25	731	236	-24	1203	763	26	40
Ref	238.94	1:4:1	167	1049	1001	187	1648	730	269	836	514	225	1058	967	227	1642	695	221	851	470	5	33

Table A-3. Absolute and relative difference between calculated and measured strains, theoretical (ρ*gz*) and measured (σ_v) vertical stress, for borehole DBT-1 and reference case 1:4:1 from borehole KFM01B.

Step	Depth [m]	Test	Absolute difference									Relative difference									ρgz [MPa]	σ_v [MPa]	Diff. [MPa]
			ε_{L1}	ε_{T1}	ε_{45_1}	ε_{L2}	ε_{T2}	ε_{45_2}	ε_{L3}	ε_{T3}	ε_{45_3}	ε_{L1}	ε_{T1}	ε_{45_1}	ε_{L2}	ε_{T2}	ε_{45_2}	ε_{L3}	ε_{T3}	ε_{45_3}			
3	133.61	3:1	-25	60	-58	23	45	-24	-2	54	-47	-2500%	18%	-28%	47%	16%	-10%	-9%	18%	-25%	3.6	2.9	-0.7
1	134.18	3:2	80	19	78	40	41	71	-101	73	-6	182%	10%	83%	2000%	15%	47%	-73%	27%	-5%	3.6	8.0	4.4
1	134.74	3:3	83	32	-32	14	31	-5	-56	74	-46	1660%	12%	-86%	19%	20%	-1%	-38%	22%	-15%	3.6	12.2	8.6
1	136.41	3:4	58	41	33	-7	70	53	-26	46	-10	414%	14%	36%	-13%	19%	15%	-36%	22%	-12%	3.7	9.2	5.5
3	165.54	4:1	77	37	53	-22	51	4	-47	51	-12	108%	12%	34%	-79%	19%	3%	-89%	21%	-8%	4.5	4.6	0.1
3	166.80	4:2	39	96	104	-7	64	19	-29	61	46	87%	16%	31%	-700%	18%	90%	-145%	20%	21%	4.5	6.6	2.1
3	194.77	5:1	88	77	157	-37	78	81	-43	87	106	96%	14%	96%	-116%	20%	95%	-113%	20%	46%	5.3	7.1	1.8
3	195.39	5:2	170	8	86	-221	-76	-18	1	41	16	56%	3%	169%	-254%	-17%	-5%	1%	15%	1600%	5.3	-4.8	-10.1
1	218.90	6:1	-30	77	109	42	57	141	-2	67	74	-83%	20%	54%	124%	15%	69%	-22%	18%	190%	5.9	8.2	2.3
1	219.63	6:2	7	87	55	4	69	96	7	56	114	41%	17%	917%	24%	17%	45%	41%	17%	38%	5.9	9.2	3.3
2	246.94	6:3	52	15	25	-49	69	4	18	56	30	371%	11%	30%	-56%	21%	2%	86%	16%	16%	6.7	9.1	2.4
2	75.65	7:1	14	153	82	-15	163	59	8	45	36	61%	17%	18%	-300%	18%	16%	42%	20%	16%	7.4	9.8	2.4
2	276.31	7:2	37	56	15	-9	170	36	-21	99	23	80%	15%	7%	-	17%	9%	-191%	19%	6%	7.5	10.5	3.0
2	299.71	8:1	22	44	4	-9	86	29	6	47	-13	550%	16%	2%	-25%	17%	8%	29%	18%	-11%	8.1	10.0	1.9
1	300.34	8:2	-3	108	3	-46	64	-153	58	17	-115	-23%	17%	0%	-79%	24%	-174%	112%	10%	-274%	8.1	8.7	0.6
2	374.63	9:1	-40	315	68	5	171	17	-17	217	88	-87%	34%	16%	5%	33%	7%	-24%	34%	19%	10.1	6.5	-3.6
2	377.37	9:2	-1	137	113	-41	220	31	-8	316	186	-1%	34%	39%	-98%	34%	26%	-10%	33%	38%	10.2	6.3	-3.9
2	378.16	9:3	4	91	47	-9	223	149	-67	367	131	3%	33%	58%	-9%	33%	39%	-143%	34%	32%	10.2	3.9	-6.3
2	422.59	10:1	-13	364	133	-65	235	96	43	429	185	-21%	34%	27%	-722%	37%	20%	37%	32%	33%	11.4	13.7	2.3
2	460.48	10:2	-17	441	205	47	152	138	-262	292	244	-20%	34%	39%	235%	34%	57%	-79%	33%	46%	12.4	22.2	9.8
2	485.72	11:1	28	464	312	34	368	325	76	239	133	22%	34%	49%	27%	35%	43%	89%	34%	59%	13.1	32.8	19.7
2	499.87	11:2	-29	409	168	35	312	195	16	108	44	-78%	34%	30%	130%	33%	37%	200%	35%	26%	13.5	16.3	2.8
2	501.76	11:3	-16	385	185	14	186	67	-1	303	206	-267%	34%	35%	36%	34%	40%	-4%	34%	37%	13.5	14.7	1.2
Ref	238.94	1:4:1	58	9	-34	40	-6	-35	-48	15	-44	35%	1%	-3%	21%	0%	-5%	-18%	2%	-9%	6.5	42	35.5

Appendix B

Analysis of measurements in borehole DBT-3 and reference case 1:4:1 from borehole KFM01B

Table B-1. Measurement results from borehole DBT-3.

Step	Depth [m]	Test	E [GPa]	ν	Probe bearing [°]	Measured stresses σ_H [MPa]	σ_h [MPa]	Bearing σ_H [°]	σ_v [MPa]	σ_1 [MPa]	Dip σ_1 [°]	Bearing σ_1 [°]	σ_2 [MPa]	Dip σ_2 [°]	Bearing σ_2 [°]	σ_3 [MPa]	Dip σ_3 [°]	Bearing σ_3 [°]
3	133.61	4:1	66.2	0.19	100	21.0	9.5	132.9	3.6	22.0	12.8	132.6	9.5	2.4	42.0	2.7	77.0	301.6
3	134.18	4:2	68.3	0.18	312	22.4	10.8	161.8	0.5	22.5	4.5	341.7	10.8	1.2	251.6	0.4	85.4	147.1
3	134.74	4:3	70.4	0.20	353	17.0	7.5	133.1	3.6	17.1	5.2	133.2	7.5	3.9	223.6	3.5	83.5	350.1
3	136.41	5:1	63.3	0.14	129	22.8	12.4	136.9	8.2	22.8	1.1	316.6	14.0	27.9	226.0	6.6	62.1	48.7
3	165.54	5:2	64.8	0.17	151	18.1	9.0	140.1	9.7	18.1	3.6	141.1	11.8	48.7	235.2	7.0	41.0	47.9
3	166.80	5:3	69.1	0.19	69	20.1	5.6	134.1	-1.2	20.1	3.3	314.2	5.7	3.2	44.4	-1.3	85.4	178.5
3	194.77	6:1	60.6	0.16	151	18.8	8.9	1.7	7.5	19.1	8.6	2.6	9.4	25.8	96.8	6.8	62.6	255.7
3	195.39	6:2	62.7	0.17	164	17.6	13.1	145.9	10.8	18.2	15.9	325.7	13.1	0.9	235.4	10.0	74.0	142.1
3	218.90	7:1	69.2	0.20	285	31.5	12.7	141.0	12.9	34.3	19.8	322.1	13.1	18.3	58.9	9.7	62.5	188.4
1	219.63	7:2	61.4	0.17	245	13.4	8.1	22.1	5.5	17.0	29.3	21.5	8.1	1.0	291.0	1.9	60.7	199.3
1	246.94	8:1	70.6	0.18	211	19.4	12.4	176.9	10.7	21.6	24.5	2.5	13.1	17.7	100.9	7.9	59.0	223.1
1	75.65	8:2	71.6	0.16	198	17.1	6.4	162.4	5.0	20.3	25.0	349.3	10.1	13.4	85.7	1.1	61.2	201.4
3	276.31	8:3	71.5	0.19	148	22.8	17.0	11.3	8.6	24.1	16.6	183.6	17.8	13.8	89.4	6.5	68.1	321.7
2	299.71	9:1	66.8	0.14	308	27.6	11.9	174.8	-0.8	28.8	11.3	354.2	12.0	3.4	263.5	-2.0	78.2	156.8
2	300.34	9:2	60.9	0.15	0	20.1	14.9	147.8	8.0	20.5	10.1	325.8	15.1	8.1	234.3	7.5	77.0	106.3

Table B-2. Analysis of measurements in borehole DBT-3 for step 1-3 and reference case 1:4:1 from borehole KFM01B.

Step	Depth [m]	Test	Measured strains									Calculated strains									Unexplained strain [%]	Maximum tensile stress [MPa]
			ε_{L1}	ε_{T1}	ε_{45_1}	ε_{L2}	ε_{T2}	ε_{45_2}	ε_{L3}	ε_{T3}	ε_{45_3}	ε_{L1}	ε_{T1}	ε_{45_1}	ε_{L2}	ε_{T2}	ε_{45_2}	ε_{L3}	ε_{T3}	ε_{45_3}		
3	133.61	4:1	-57	269	157	0	207	160	-30	675	180	-30	313	214	-28	253	191	-29	774	230	19	19
3	134.18	4:2	-63	266	115	-76	272	123	-70	699	256	-76	318	146	-75	321	159	-75	804	312	15	19
3	134.74	4:3	-26	247	130	-11	498	208	-11	110	72	-15	291	160	-15	574	242	-16	140	83	16	14
3	136.41	5:1	-39	198	229	26	528	265	149	644	422	54	230	249	55	613	264	54	760	380	19	15
3	165.54	5:2	-59	132	96	16	525	249	250	333	219	80	147	194	81	599	334	80	429	187	36	11
3	166.80	5:3	-53	537	275	-70	-33	35	-108	440	261	-85	626	232	-85	-13	-38	-84	505	244	20	18
3	194.77	6:1	45	233	98	37	222	150	53	644	424	54	284	100	53	271	163	54	751	478	14	13
3	195.39	6:2	46	295	240	129	488	287	57	377	308	91	348	247	90	583	264	90	445	321	15	11
3	218.90	7:1	-2	377	302	54	200	140	100	944	244	59	444	443	63	256	230	61	1099	328	24	28
1	219.63	7:2	24	263	359	23	405	72	32	152	215	33	324	355	32	482	21	30	194	178	18	14
1	246.94	8:1	122	275	248	61	514	162	2	255	260	74	351	249	72	610	181	71	605	319	19	16
1	75.65	8:2	-15	236	197	-15	476	70	59	162	303	14	289	209	12	563	60	11	221	293	20	17
3	276.31	8:3	-56	449	176	25	327	263	69	557	134	16	522	290	18	401	356	18	668	185	26	19
2	299.71	9:1	-115	524	261	-38	128	58	-95	829	138	-91	621	394	-89	182	120	-90	970	247	24	25
2	300.34	9:2	-12	405	174	130	591	478	2	384	240	48	481	186	48	715	470	49	462	257	19	14
Ref	238.94	1:4:1	167	1049	1001	187	1648	730	269	836	514	225	1058	967	227	1642	695	221	851	470	5	33

Table B-3. Absolute and relative difference between calculated and measured strains, theoretical (ρgz) and measured (σ_v) vertical stress, for borehole DBT-3 and reference case 1:4:1 from borehole KFM01B.

Step	Depth [m]	Test	Absolute difference									Relative difference									ρgz [MPa]	σ_v [MPa]	Diff. [MPa]
			ε_{L1}	ε_{T1}	ε_{45_1}	ε_{L2}	ε_{T2}	ε_{45_2}	ε_{L3}	ε_{T3}	ε_{45_3}	ε_{L1}	ε_{T1}	ε_{45_1}	ε_{L2}	ε_{T2}	ε_{45_2}	ε_{L3}	ε_{T3}	ε_{45_3}			
3	133.61	4:1	27	44	57	-28	46	31	1	99	50	47%	16%	36%	-	22%	19%	3%	15%	28%	2.8	3.6	0.8
3	134.18	4:2	-13	52	31	1	49	36	-5	105	56	-21%	20%	27%	1%	18%	29%	-7%	15%	22%	2.8	0.5	-2.3
3	134.74	4:3	11	44	30	-4	76	34	-5	30	11	42%	18%	23%	-36%	15%	16%	-45%	27%	15%	2.8	3.6	0.8
3	136.41	5:1	93	32	20	29	85	-1	-95	116	-42	238%	16%	9%	112%	16%	0%	-64%	18%	-10%	3.7	8.2	4.5
3	165.54	5:2	139	15	98	65	74	85	-170	96	-32	236%	11%	102%	406%	14%	34%	-68%	29%	-15%	3.7	9.7	6.0
3	166.80	5:3	-32	89	-43	-15	20	-73	24	65	-17	-60%	17%	-16%	-21%	61%	-209%	22%	15%	-7%	3.7	-1.2	-4.9
3	194.77	6:1	9	51	2	16	49	13	1	107	54	20%	22%	2%	43%	22%	9%	2%	17%	13%	4.2	7.5	3.3
3	195.39	6:2	45	53	7	-39	95	-23	33	68	13	98%	18%	3%	-30%	19%	-8%	58%	18%	4%	4.2	10.8	6.6
3	218.90	7:1	61	67	141	9	56	90	-39	155	84	3050%	18%	47%	17%	28%	64%	-39%	16%	34%	5.1	12.9	7.8
1	219.63	7:2	9	61	-4	9	77	-51	-2	42	-37	38%	23%	-1%	39%	19%	-71%	-6%	28%	-17%	5.1	5.5	0.4
1	246.94	8:1	-48	76	1	11	96	19	69	350	59	-39%	28%	0%	18%	19%	12%	3450%	137%	23%	5.9	10.7	4.8
1	75.65	8:2	29	53	12	27	87	-10	-48	59	-10	193%	22%	6%	180%	18%	-14%	-81%	36%	-3%	5.9	5.0	-0.9
3	276.31	8:3	72	73	114	-7	74	93	-51	111	51	129%	16%	65%	-28%	23%	35%	-74%	20%	38%	5.9	8.6	2.7
2	299.71	9:1	24	97	133	-51	54	62	5	141	109	21%	19%	51%	-134%	42%	107%	5%	17%	79%	6.7	-0.8	-7.5
2	300.34	9:2	60	76	12	-82	124	-8	47	78	17	500%	19%	7%	-63%	21%	-2%	2350%	20%	7%	6.7	8.0	1.3
Ref	238.94	1:4:1	58	9	-34	40	-6	-35	-48	15	-44	35%	1%	-3%	21%	0%	-5%	-18%	2%	-9%	6.5	42	35.5