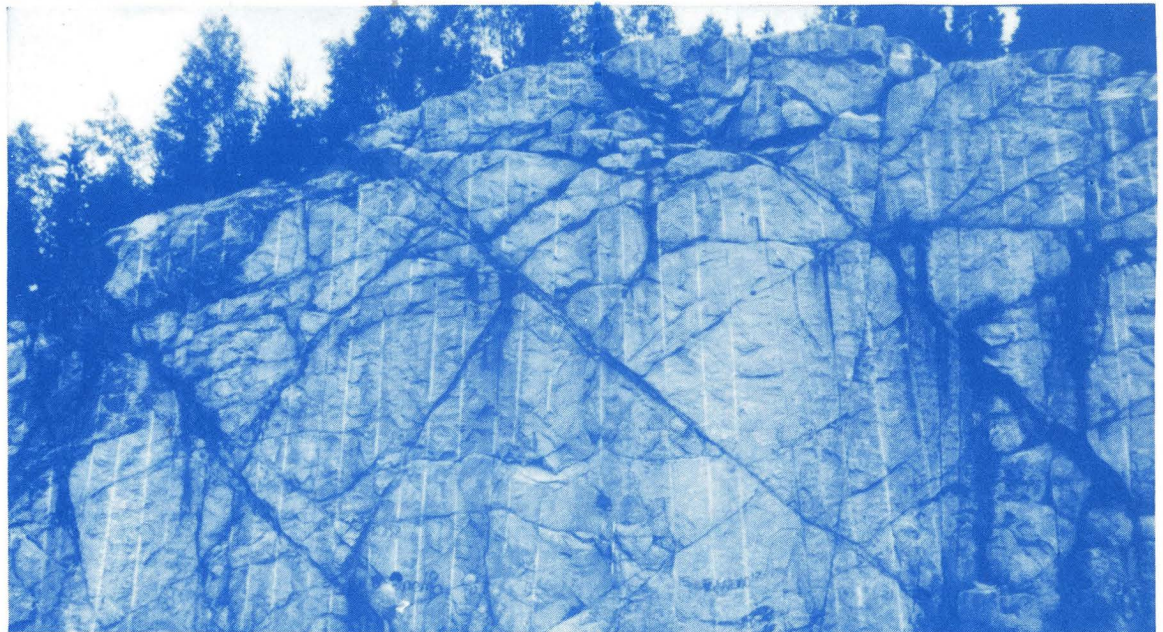


BeFo



Drill Hole Deviations Governed by the Rock Structure

How — Why — What to do

Thomson Sinkala

**Stiftelsen Bergteknisk Forskning — BeFo
Swedish Rock Engineering Research Foundation**

Drill Hole Deviations Governed by the Rock Structure

How — Why — What to do

Bergberoende borrhålsavvikelser Observationer och slutsatser

Thomson Sinkala, Technical University of Luleå

CONTENTS	PAGE
FÖRORD	
SUMMARY	
1 INTRODUCTION	1
2 THE HOLE DEVIATION PROBLEM	2
3 A FIELD STUDY ON SMOOTH BLASTED HOLES	4
3.1 Choice of field study method	4
3.2 Hole deviation measurements	5
3.2.1 Measurements using theodolites	5
3.2.2 Measurements using a tape and rods	6
3.2.3 Practical limitations	7
3.3 Evaluations of data obtained by theodolites	7
4 RESULTS	
4.1 Observations on results from example plots and photographs	9
4.1.1 Slant layered rocks	10
4.1.2 Horizontally layered rocks	15
4.1.3 Vertically layered rocks	15
4.1.4 Unlayered rocks, with or without joints	15
4.1.5 Other deductions	18
4.2 Comparing data obtained using rods and a tape with those obtained using theodolites	19
5 QUALITATIVE THEORY FOR DEVIATIONS IN SLANT BEDDED ROCKS	20
5.1 "Up-dip" hole deviations	21
5.2 "Down-dip" hole deviations	22
6 CONCLUDING REMARKS	28
Acknowledgements	31
References	31

FÖRORD

Borrhålen vid bergborrning hamnar inte alltid exakt i planerat läge, där de ur sprängningssynpunkt skulle göra bäst nytta. Skillnaden mellan verkligt och avsett läge kallas borrhålsavvikelse, ett begrepp som tyvärr är alltför välkänt inom branschen och betraktas som ett gissel sedan länge.

Egentligen är dock förekomsten av borrhålsavvikelser inte speciellt förvånande - bergborrhålens slankhetsgrad överträffar ofta med någon storleksordning allt vad motsvarande mått brukar uppgå till i t.ex. verkstadsindustrin. Hål med längder motsvarande 100, ja till och med 1.000 diametrar uppfattas som bekant inte som lätta att åstadkomma med precision ens i de mest homogena material.

Försök att minska dessa borrhålsavvikelser saknas då naturligtvis inte heller i bergborrbranschen - från praktikerns "knep" och yrkesskicklighet till maskinella hjälpmedel, från råd och anvisningar till vetenskapliga avhandlingar finns en del att studera om ämnet. Problemet kvarstår dock och ingalunda är alla fenomen kända.

Den i denna BeFo-rapport presenterade studien hade till mål att utröna om och i så fall hur borrhålsavvikelsema beror på bergartens struktur. En intelligent och samtidigt billig metod att skaffa sig statistiskt underlag tillämpades och resultaten blev mycket entydiga - om man tar hänsyn till hur oregelbundna bergarters naturliga struktur brukar vara.

Ett vid avdelningen för Bergmaskinteknik vid Högskolan i Luleå utfört och av BeFo finansierat licentiatarbete utgör bakgrunden till denna BeFo-rapport som i sammanfattning presenterar studiens huvuddrag och viktigaste slutsatser.

Stockholm i mars 1988.

Olaf Meyer

f.d. adj. prof. vid

Avd. för Bergmaskinteknik

Högskolan i Luleå

SUMMARY

Drill holes in rock are rarely straight. Rock, hole drilling equipment, drill operators, hole plans - are among the several contributing factors to hole deviations. Little is actually known about the hole deviation phenomena, but economic consequences in mining, oil, construction, and exploration industries are undoubtedly enormous.

In this thesis the results of a field study are presented, in an attempt to shed some light on one of the least understood phenomena, namely: rock dependent hole deviations. In order to reach a reasonable statistical conclusion and still keep the costs of the study limited, this study was carried out on holes that remain in rock walls after smooth blasting in road-cuts, open-pits, and quarries.

The phenomenal and statistical results of the study clearly indicate that rock structural properties do have an influence on the amount and direction of hole deviations in such a way that one can actually predict the future deviations if the rock structure, hole plans, and drilling conditions remain the same in the area.

Based on evidence from hole paths in layered and jointed rock structures, a qualitative theory is finally presented to explain the "up-dip" and "down-dip" hole deviations phenomena.

The BeFo publication hereby presented contains in essence a summary of a licentiate thesis at Luleå University with registration no 1986:07L (140 pages). Any reader who would be interested in further details, is kindly referred to this publication.

1. INTRODUCTION

For rock handling operations utilizing drilling and blasting to fragment rock, the main "external" limitations on the sizes of cycles of operations are, in general:

- * geology (configuration of the orebody)
- * rock mechanics problems (stability of rock mass)
- * hole deviations (inability to drill holes according to plan)

In many cases geology and rock mechanics are practically favourable. However, the obstacle remains hole deviations.

In surface construction works hole deviation problems give rise to e.g.:

- multiple bench drilling/blasting
- large boulders
- unevenly broken bench walls, in some cases leaving dangerously hanging rock pieces

As for underground operations, hole deviations result in, e.g.:

- excessive development due small stope sizes
- ore losses
- ore dilution
- minimized possibilities for automation

Drill hole deviation problems are also common in other fields such as exploration and oil-well drilling industries.

In all these operations the enormous economic impact is a daily ache.

2 THE HOLE DEVIATION PROBLEM

There are basically three operational causes of hole deviations in long hole drilling (Figure 1.), viz alignment, collaring and trajectory (path due to nature of rod/bit contact with rock).

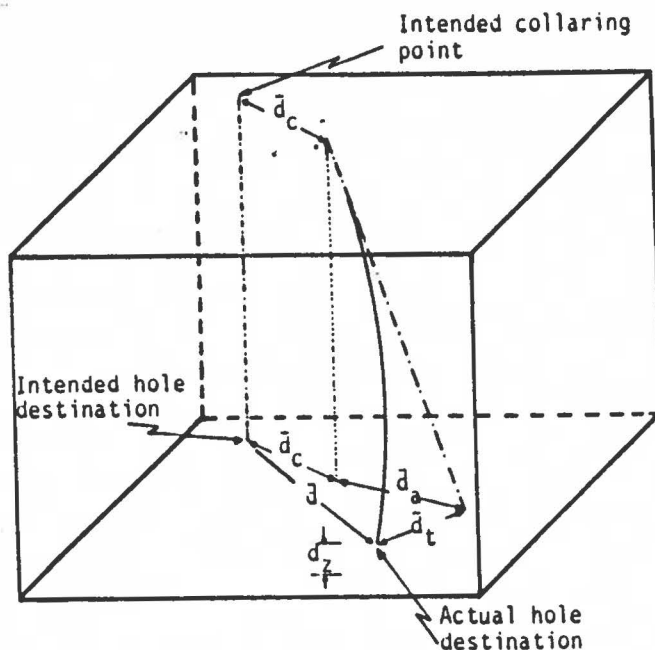


Figure 1. Diagrammatic representation of alignment ($\vec{d}_a$), collaring ($\vec{d}_c$), and trajectory ($\vec{d}_t$) deviations.

In this sense therefore, hole deviation can be defined as a departure of a hole from its designed starting point, its designed path, and its designed destination point.

Since the operator/machine dependent causes, namely, "alignment" and "collaring" are caused outside of holes and hence easier to investigate and understand, this study concentrates on the third problem, i.e. trajectory hole deviation - by far the most critical one, especially for long holes. The source categories of factors contributing to trajectory deviation include pattern of holes, drill forces, equipment components, and rock properties [Sinkala, April 1987].

Once again, the study presented here, picks mainly one aspect only, namely the question of whether one can learn more about the rock dependent part of trajectory deviation and to some extent, influence of hole patterns on the deviation.

Some authors have described regularities of such deviations as shown in figure 2. This study shall also investigate if such observations are true, and if so, why?

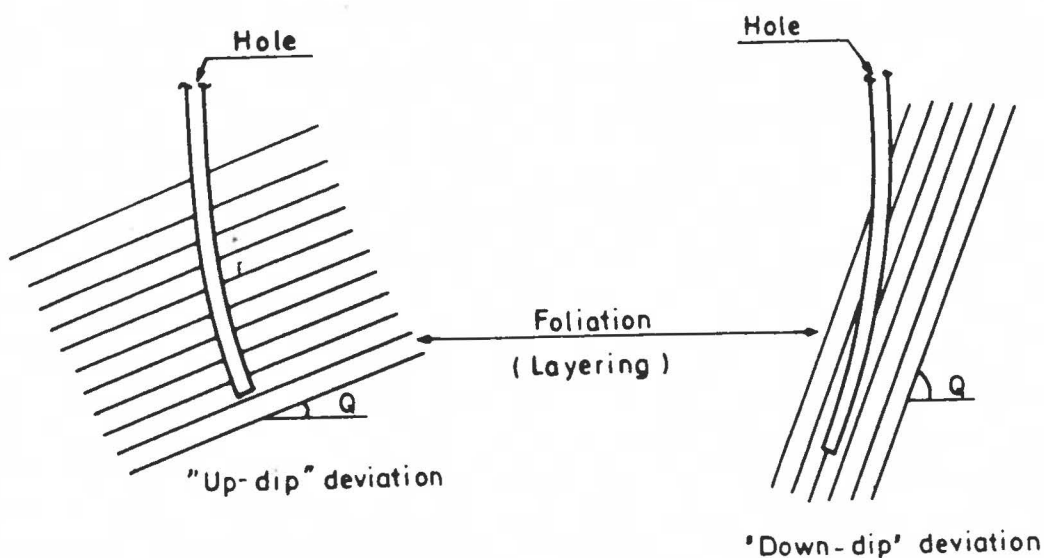


Figure 2. The observed hole deviation phenomena in layered rocks.

NOTE: In this report the following expressions are used:

"slant layered rocks:" this is used for those bedded rocks whose bedding planes are inclined obliquely to drill holes

"unidirectional:" this means common direction

3 A FIELD STUDY ON VISIBLE SMOOTH BLASTED HOLES

3.1 Choice of field study method

This study was carried out on holes done by percussive drilling. Economically, it was considered cheaper and quicker to study the holes that remain visible in the wall after blasting (photo 1) rather than trying to measure actual drill holes insitu. An approach to the study included a suitable choice of geological areas which would embrace both phenomenal and statistical evidence.



Photo 1: Illustrating the smooth blasted holes. Note the holes crossing one another. (See arrows)

Statistical sample variations were:

- DIRECT: - areas
- rock types

- INTRINSIC: - dates of drilling
- operators
- equipment

Phenomenological sampling involved:

- * photographing of the blasted rock faces
- * measurements of hole deviations using some suitable method(s)
- * rock hardness testing using a Schmidt hammer
- * visual examination of holes and geology of the respective rock faces
- * collection of rock samples for further examination

To fulfill these requirements several sites including road-cuts, open-pits, and quarries were visited and examined for the variables mentioned above. Most important was the requirement to cover a wide range of geological conditions and accordingly, a suitable route was chosen through Sweden and Norway. Even though machine parameters are missing in this study, correlating rock properties and patterns of holes with hole deviations can be deemed as not seriously violated.

3.2 Hole deviation measurements

3.2.1 Measurements using theodolites

Figure 3 illustrates the technique used to measure holes and their deviations. The following assumptions were made for the hole deviation measurements:

- * collar positions at which holes were found were regarded as according to intended plans
- * first straight portion from collar of a hole was considered as lying along an intended direction, and the first two measurement points were taken along this part
- * from the second measurement point onwards, it was considered that any deviation of a hole from the direction defined by the first two points were primarily due to rock influence

The procedure involved setting-up two theodolites (figure 3) and the distance between them measured. Reference angles along arrows LRA and RRA were taken. In order for the theodolites to measure common targets along holes a laser beam was used to indicate the points. For every hole a minimum of four points were measured, and at each of the points

both vertical and horizontal angles were noted. The data collected were later fed into a computer for various analysis.

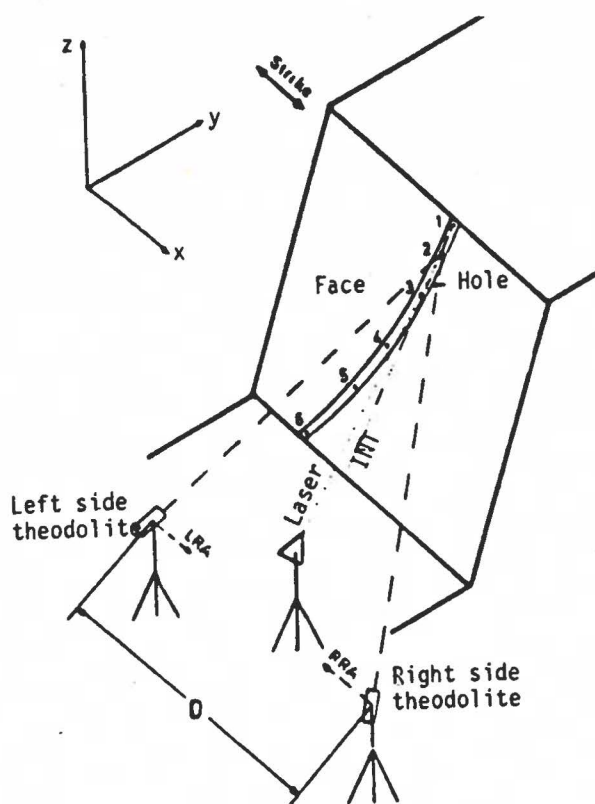


Figure 3. The field set-up used for measuring hole deviations.

With this method more than 350 holes from 36 rock faces in 25 different areas were actually measured. Eight more areas were examined and recorded by photographs only.

3.2.2 Measurements using a tape and rods

In certain rock faces where access was suitable, it was possible to manually measure hole deviations in planes approximately parallel to the rock faces.

The procedure involved linking the measuring rods together and aligning them along the first straight part of the beginning of a hole. A horizontal distance was then measured between bottom end of the hole and the rod string using a measuring tape to give a deviation. The method is only useful for holes that are severely deviated. It is also very easy and quick. However, results are approximate and are in one plane only. With this method 46 holes were measured, 11 of them for comparison with theodolite measurements as will be seen in section 4.2.

3.2.3 Practical limitations

One can always discuss how much more measurements should have been done, but practical limitations such as the following had to be accepted:

- * some holes were so broken as unmeasurable by theodolites. However their appearance still resembled the general behaviour of the rest of the holes in respective faces. Therefore the few that were recorded were deemed as representative of the faces
- * problems such as unconducive conditions for theodolite rigging, rain, traffic, etc., sometimes resulted in excessively long periods to measure each hole
- * the phenomena was so clear that it was decided as sufficient to take only a few holes and the rest taken in slides
- * the phenomena was so unique that even if a face had few holes it was considered worthwhile to make note of it

3.3 Evaluations of data obtained by theodolites

The calculations were done using the x, y, z cartesian coordinates. With the left side theodolite (fig. 3) as origin, the x-axis was taken as lying along the strike of rock face, the y-axis across rock face, while the z-axis vertical. This enabled locating hole deviations in three-dimensional space. Using this basis various sub-calculations were done for different analytical observations. The details of the collected data, mathematical derivation, computer programs and outputs can be found in Sinkala [1986, April 1987], and Easterling [1986].

The plots shown in the following chapter were performed by normalising all starting points of holes for each rock face studied, to examine the general behaviour of the deviations in the respective faces. The plots are of deviations in the X- or Y-axis versus hole length axis (e.g. fig. 4ii), and of plans showing the deviations in the x-y plane (e.g. fig. 4i). For the former plots the coordinate (0.00, 0.00) marks the starting point of holes. From this point intended directions of holes are made to run along (0.00, hole length). The plan plots are assumed self-explanatory.

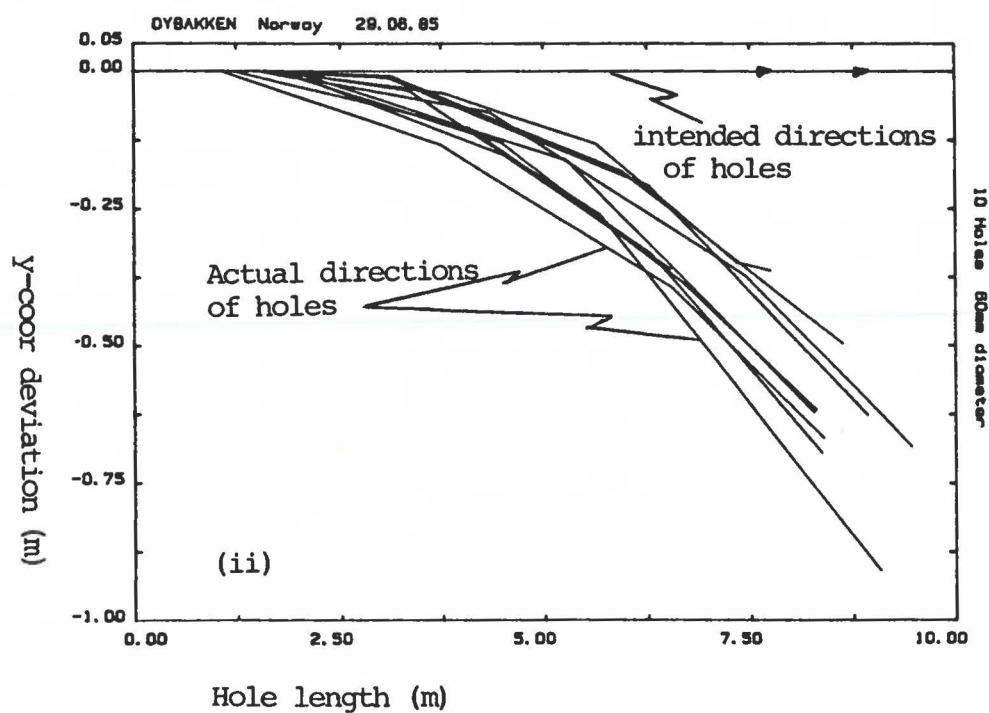
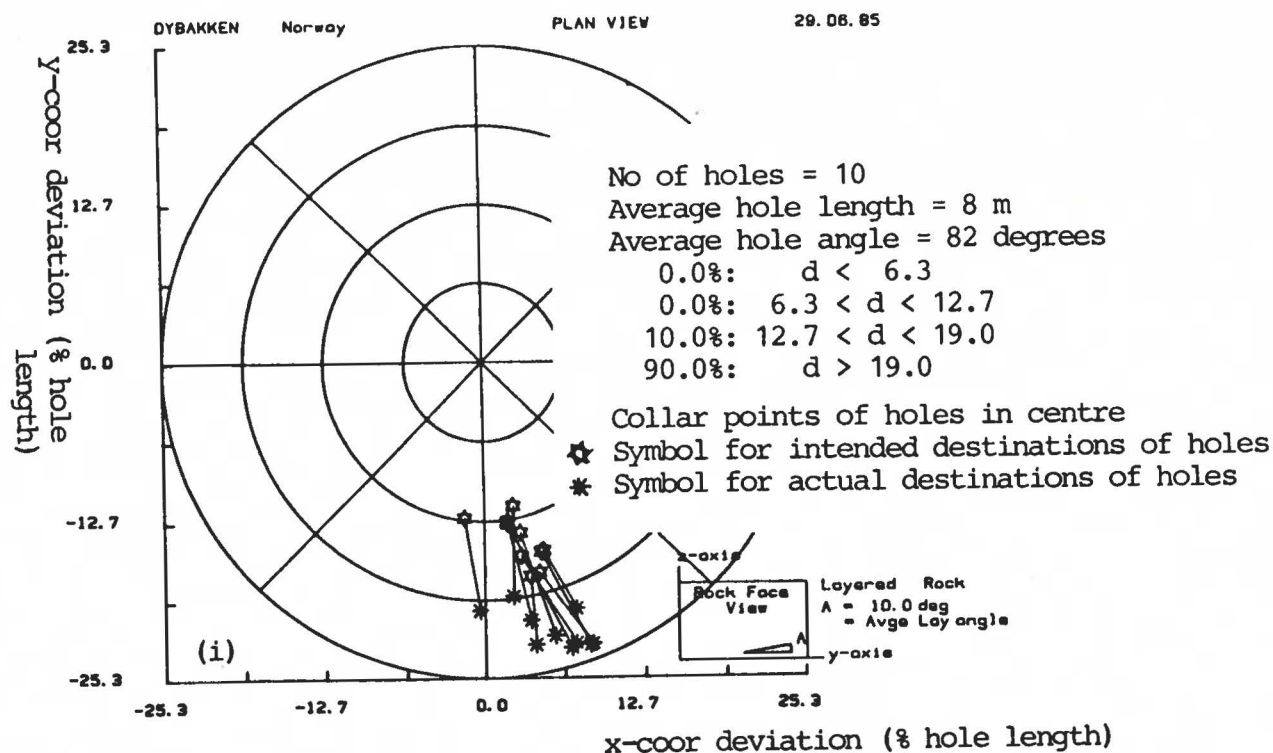


Figure 4. An example for interpreting data obtained by theodolites.

4 RESULTS

Results include direct observations in the field such as illustrated by photos, and observations from analysis as demonstrated by plots.

The rock formations examined along the route included igneous, metamorphic and sedimentary rocks. However most of them were metamorphosed sedimentary rocks. Norway has more geologically younger and layered rocks than Sweden. Most of the layered rocks examined outside mountain ranges in Sweden are geologically older and the boundaries between layers are smoother and much more strongly bonded.

Apart from Svappavaara (unlayered rock) whose hole inclinations lay between 59° and 63° to horizontal, all other holes studied were between 73° and 90° to the horizontal.

4.1 Observations on results from example plots and photographs

The hole deviation phenomena has been identified mainly in four characteristic rock structural groups (figure 5) for the downward drilled holes studied, namely:

- slant layered rocks
- horizontally layered rocks
- vertically layered rocks
- unlayered rocks, with or without joints

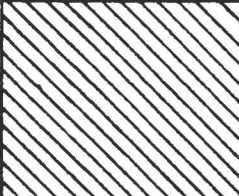
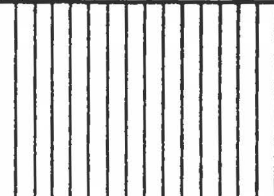
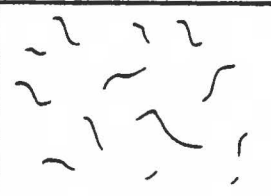
Slant Layered Rock	Horizontally Layered Rock	Vertically Layered Rock	Unlayered Rock - with or without joints
			

Figure 5. The four characteristic rock structural groups identified as giving unique hole deviation phenomena, for downward drilled holes.

The following sections describe the influence of these rock structures on hole deviations. Only one typical example of plots and photos is given for each typical rock structure discussed.

4.1.1 Slant layered rocks

In these rock types the following can be deduced:

- * the holes are observed to deviate unidirectionally (common direction), (figure 6 and photo 2), in a systematic manner
- * the unidirectional deviation generally appears to be up-dip when layering inclination is less than 40° - 50° to the horizontal, and down-dip when otherwise
- * the magnitudes of hole deviations are observed to decrease with increase of the following variables:
 - layer thickness
 - cohesion between layer boundaries
 - layer verticality
 - hole verticality (for steeply dipping layers)
 - hole diameter
 - rock hardness
- * the magnitudes of hole deviation are observed to increase with increase of:
 - hole length
 - grain fineness coupled with layer boundary weakness
- * for slant layered rocks which are heavily jointed, the hole deviations result mainly in unidirectional deviations, but with a wide range of severity
- * holes drilled through slant folded layers tend to deviate either randomly or unidirectionally, depending on the severity of the folds of the layers and the over-all average direction of the folds.



Photo 2. Bulken (Norway). Typical slant layered rock with up-dip unidirectional hole deviations. [Photo Thomson Sinkala]

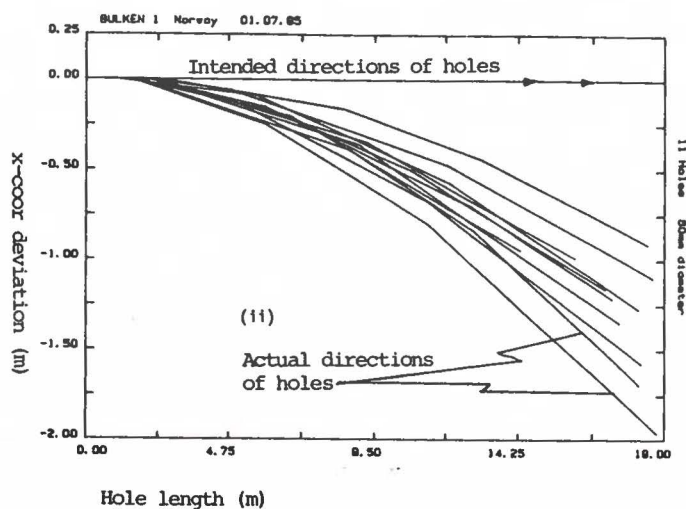
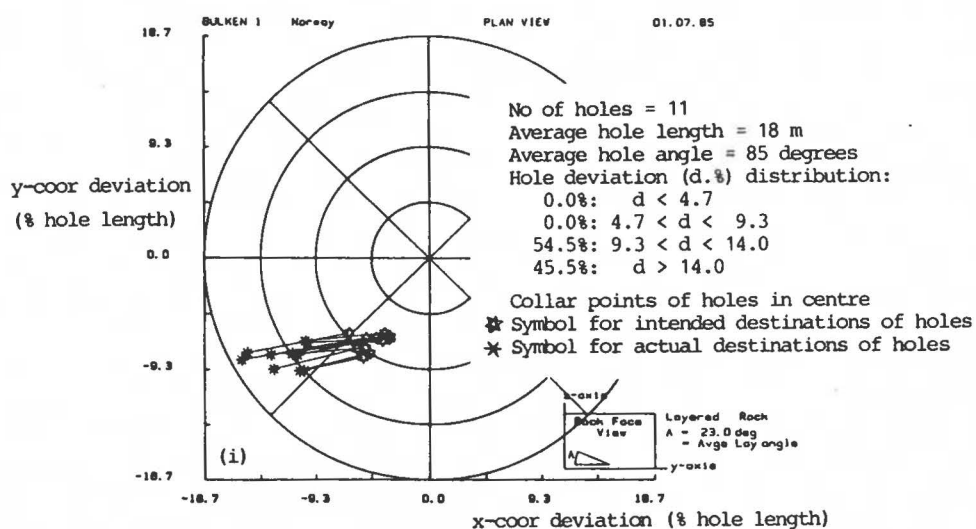


Figure 6. Plots showing unidirectional hole deviation behaviour in slant layered rocks.

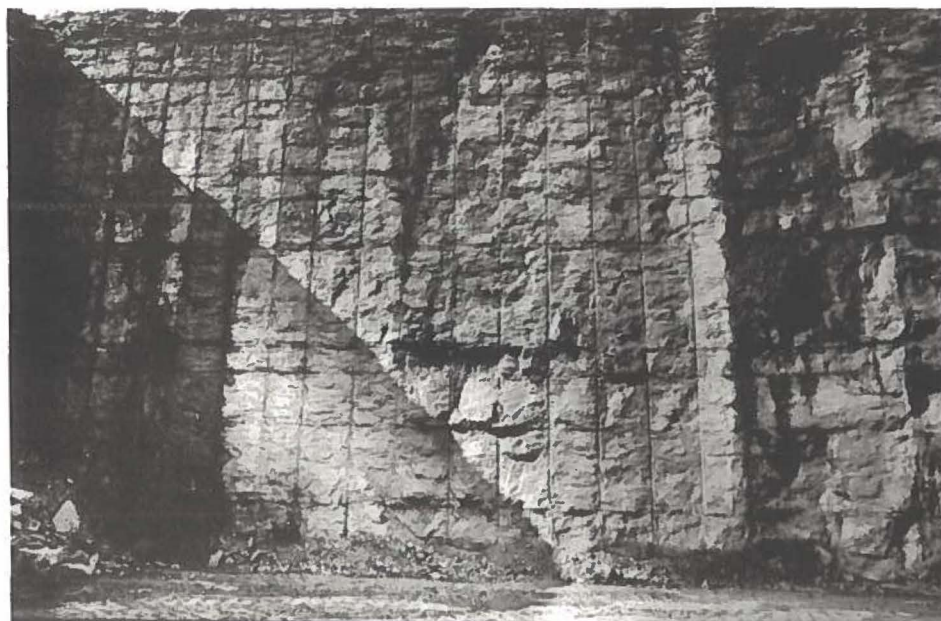


Photo 3. Slite F1 (Sweden). Typical horizontally layered rock showing virtually no hole deviations to the naked eye. [Photo: Thomson Sinkala]

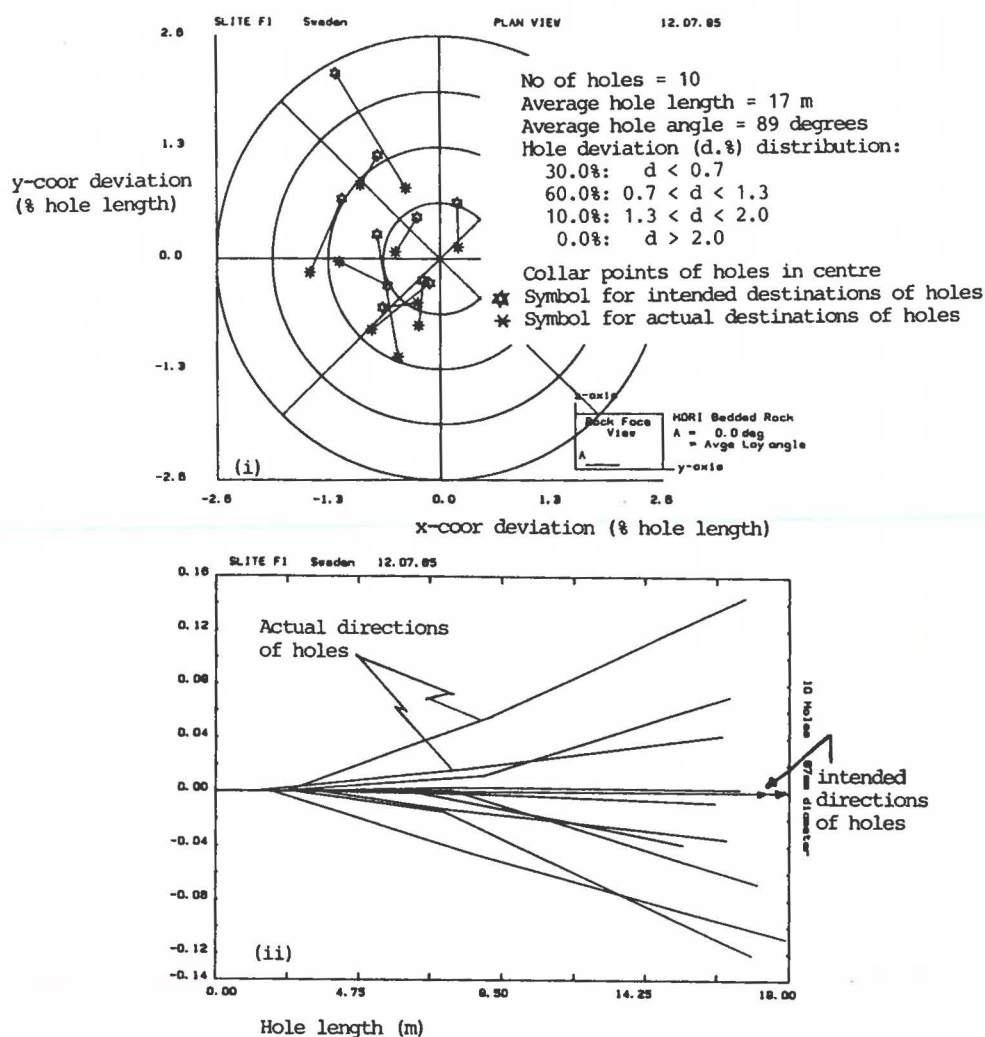


Figure 7. Plots showing random hole deviation behaviour in horizontally layered rocks.



Photo 4. Øvsteng (Norway). Typical vertically layered rock with holes (see arrows) following layer boundaries. [Photo: Thomson Sinkala]

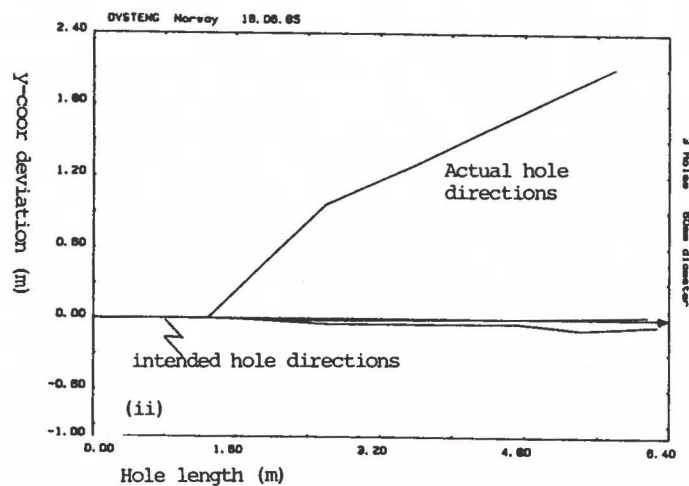
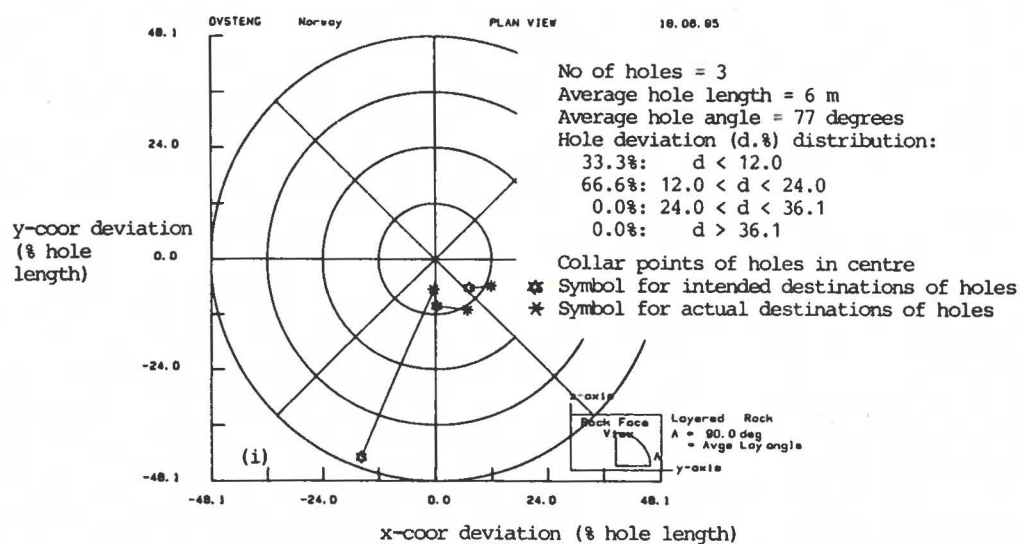


Figure 8. Plots showing the behaviour of holes in vertically layered rocks. The hole straightness depends on the straightness of the layer boundary.

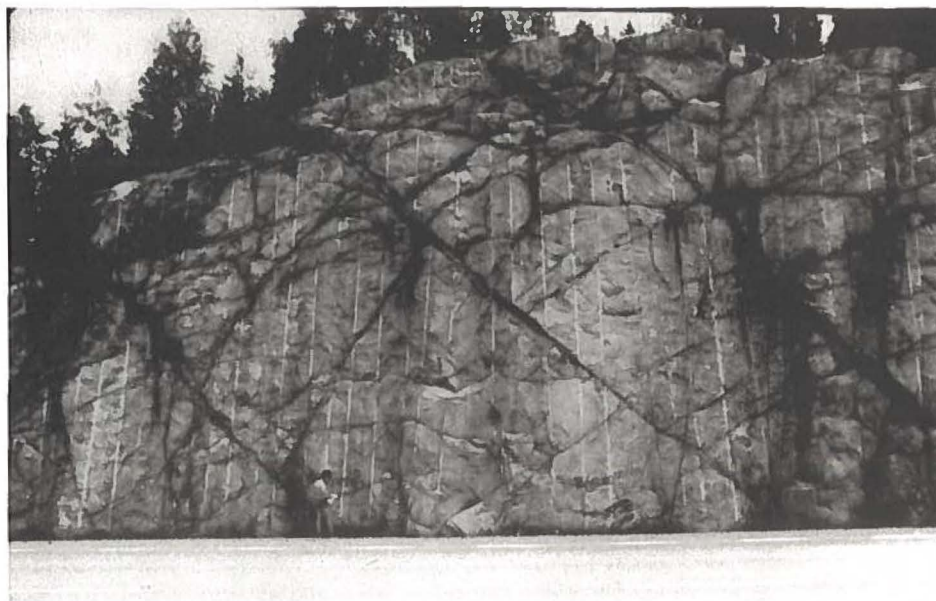


Photo 5. Tranemo (Sweden). Typical unlayered but jointed rock showing virtually no hole deviations to the naked eye. [Photo: Thomson Sinkala]

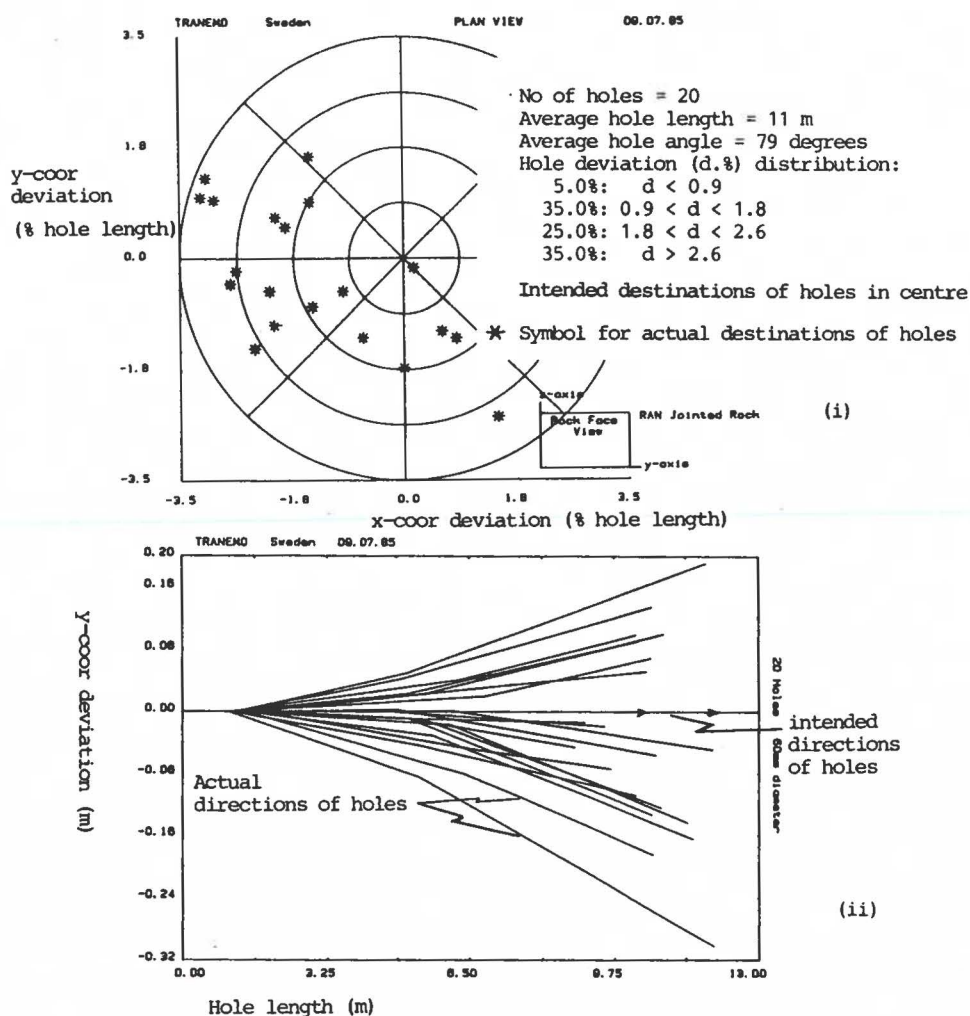


Figure 9. Plots showing random hole deviation behaviour in unlayered rocks. In the plan plot 9(i), intended hole destinations have been normalized in the centre of circles.

4.1.2 Horizontally Layered Rocks

The holes examined in these rock types were almost vertical (within 1° from vertical). The following can be observed:

- * the holes deviate randomly (figure 7) although to the naked eye they appear undeviated (photo 3)
- * the hole deviations have no dependence on layer thickness
- * the hole deviations generally increase with increase in hole length
- * the magnitudes of hole deviations decrease with increase in:
 - hole diameter
 - rock hardness

4.1.3 Vertically layered rocks

In these rocks (photo 4):

- * the holes are observed to follow layer boundaries (figure 8)
- * the hole deviation magnitudes decrease with increase in:
 - layer thickness
 - layer boundary bondage
 - hole diameter

4.1.4 Unlayered rocks, with or without joints

For vertical or nearly vertical holes, these rock types induce essentially random hole deviations (figure 9 and photo 5). However, the pattern of joints in the rocks play an important part and their effects are summarized in Table 1.

In general, the magnitudes of hole deviations decrease with an increase in the following parameters:

- rock hardness
- hole diameter
- hole verticality

Table 1. Influence of joint patterns on deviations in unbedded rocks.

Joint Pattern	Deviation Phenomena
(i) Slant, high frequency joints with parallel planes	Unidirectional hole deviation
(ii) Slant, low frequency joints with parallel or approx, parallel planes	Unidirectional to random hole deviations
(iii) Horizontal joint planes	Random hole deviations
(iv) Randomly oriented major or minor joint planes	Random hole deviations

The influence of hole length on the deviation magnitudes depends on the joint system in the rock, and the following have been observed (see table 1):

CASE (i): In all cases of holes plotted the magnitudes of hole deviations increase with increase in hole length, and the phenomena is similar to that of deviations in layered rocks.

CASE (ii): The deviation behaviour ranges from systematic to random, and some holes are almost undeviated. The deviation magnitudes are smaller than those observed in case (i).

CASE (iii): Random hole profiles with rather low deviation magnitudes are observed.

CASE (iv): Cross-sectional plots show gradual to random hole profiles. The deviation magnitudes are lower than for slant layered rocks.

For unlayered rocks a strong dependence of the deviation on hole inclination was also observed. For the rocks that do not have slant unidirectional joints, and when the inclination of holes lies along or approximately along the y-z plane (see figure 2) and are inclined at more than 10° from the vertical, the following observations can be made:

- * small diameter holes deviate upwards towards the viewer (fig 10 (i))
- * large diameter holes deviate downwards (away from the viewer) as in figure 10 (ii), and almost in the vertical plane. This observation seems to be in agreement with that by Medda et al cited in Sinkala [1986].

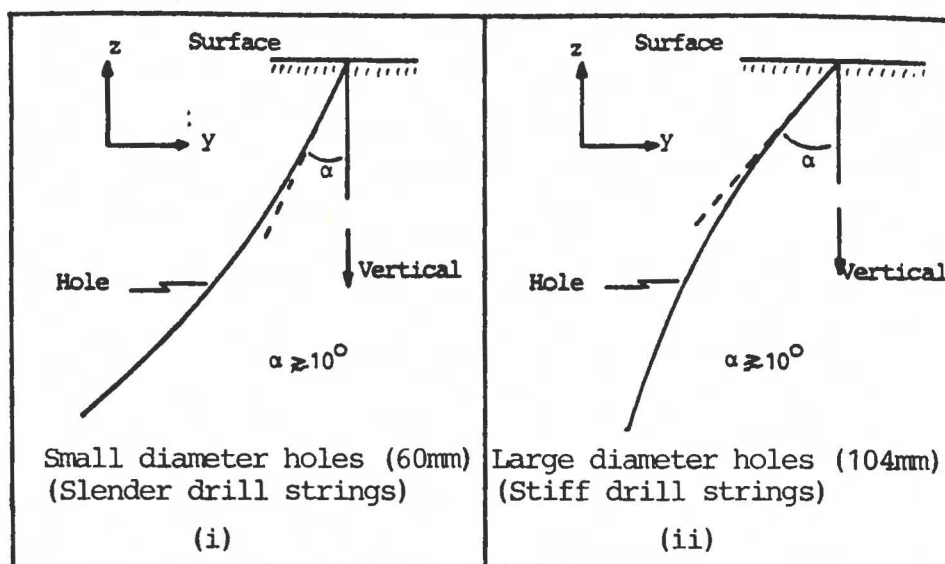


Figure 10. Illustrations showing the influence of hole inclinations on deviations for different sizes of holes in unlayered rocks.

A possible explanation for the two observations is that given the same hole length, the slender drill rods used in small diameter (57 mm) holes are likely to sag, therefore forming an upward concave shape along which the drill bit would be directed. On the other hand, weight of large bits used in large diameter (104 mm) holes would cause large drill rods to bend downwards due to increased gravity effects.

It has also been observed that practically all holes with this phenomena have larger deviations along the y-axis than in the x-axis. (See coordinate definition in figure 3).

Due to hole inclination alone, the phenomena just described does not seem well defined for rocks with slant beddings.

4.1.5 Other deductions

As the hole becomes longer, the trajectory deviation d_t is observed to be the greatest of the three hole deviation source components defined earlier in the introductory section. The general relation is illustrated in figure 11.

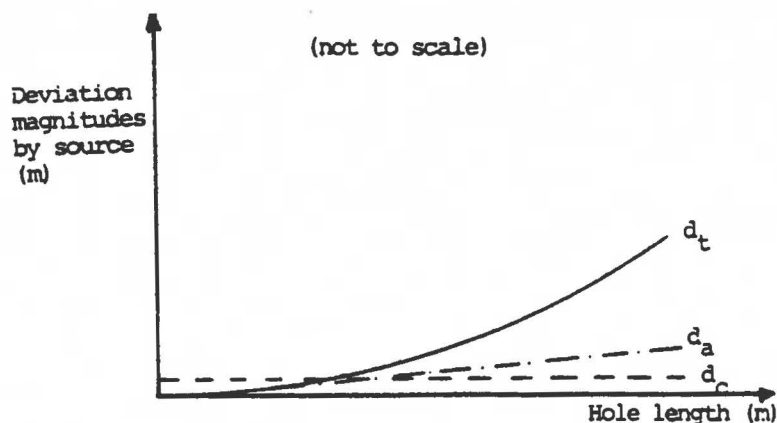


Figure 11. The general comparison of the magnitudes of source deviations in relation to hole length.

Figure 12 is a comparison of hole deviation magnitudes from the three basic rock structures defined in figure 5. Clearly, slant layered rocks induce higher magnitudes of deviations than other rock types.

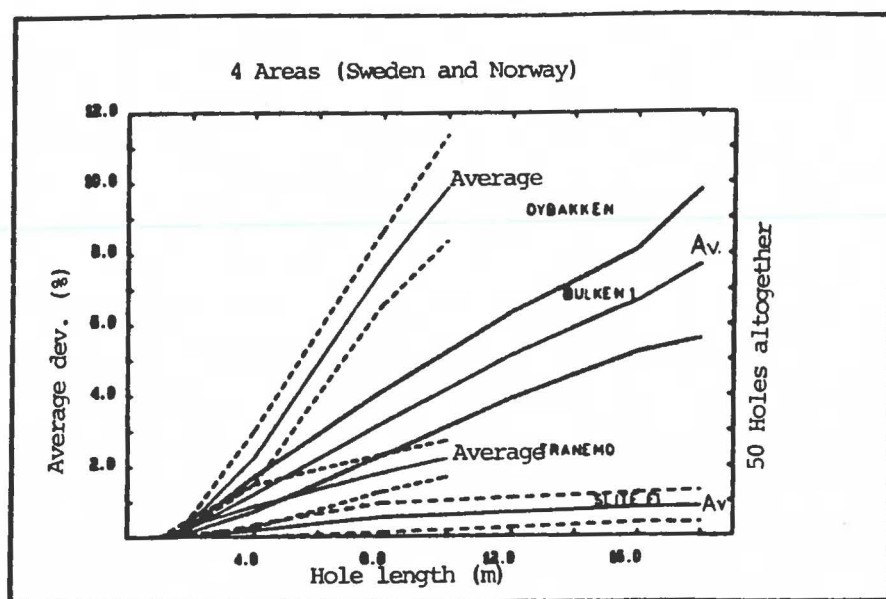


Figure 12. An illustration comparing hole deviations in different rock types: Øybakken (slant layers), Bulken 1 (slant layers), Tranemo (unlayered), and Slite F1 (horizontal layers). (Average percentage deviation versus hole length).

4.2 Comparing data obtained using rods and a tape with those obtained using theodolites

Hole deviation measurement using a tape and rods can be a very useful, quick and inexpensive way of getting rough estimates of trajectory hole deviations in an area, provided conditions mentioned in section 3.2.2 prevail. Results can be reasonably accurate when greatest deviations lie along a rock face. This is illustrated in table 2 where manual and theodolite measurements are compared. Remember that the x-axis lies approximately along the rock face (figure 3).

Table 2. Comparison of manual and theodolite hole deviation measurements. See Sinkala [1986] for more results.

Area	Hole No	Manual deviation measurements (along face)	Theodolite deviation measurements		
			x-axis	y-axis	Total
B U L K E N 1	6	1,9	1,69	0,22	1,72
	7	2,2	1,96	0,35	2,01
	8	0,97	1,10	0,28	1,14
	9	1,6	1,58	0,30	1,62
	10	1,36	0,91	0,21	0,94
	11	1,5	1,27	0,32	1,32
	1	1,14	1,17	0,09	1,18
	2	1,1	1,07	1,12	1,56
	3	1,16	1,10	0,17	1,12
	4	1,1	1,08	0,16	1,09
N 2	5	1,6	1,47	0,27	1,49

It is observed that results of manual measurements are almost equal to those of absolute total deviations measured by theodolites.

Discrepancies for some holes such as 2 and 10 may be due to any or all of the following:

- * planes along which manual measurements were done may not have been the same planes containing total absolute deviations
- * manual measurements were not as precise as measurements by theodolites, with help of laser

5 QUALITATIVE THEORY FOR DEVIATIONS IN SLANT BEDDED ROCKS

The regularity of hole deviations with rock layering - obviously observed in the field, raises a question of whether there would be some reasonable explanation of this occurrence. The following, is an attempt to find such explanation by qualitative reasoning rather than quantitative analysis.

An attempt is made to explain the progressive damage of rock material across oblique boundaries, based on clues from field study observations on holes through oblique joints and slant layers. Exaggerated figures are used in order to clarify the point.

Referring to figures 13 to 22, let:

- F_A = axial drill resultant force, initially along drill bit axis
- B_H, B_W = height and diameter of bit body (plus insert button) respectively
- C = the first crack length to the boundary
- H_C = length between initiation point of first crack from A and its hit of boundary
- H_L = the length to a point on the boundary where edge A of the bit first touches the bottom layer of the boundary
- H_{UR}, H_{DR} = vertical length travelled by edge B of bit before touching bottom layer of boundary in up-dip and down-dip cases respectively
- A = the edge close to the bit where the first crack C to the boundary will be formed
- B = the other side of the bit opposite to edge A

Φ_U, Φ_D = layering angles inducing "up-dip" and "down-dip" hole deviations, respectively

α_U, α_D = angles formed between the bit and original axes, in an "up-dip" and "down-dip" hole deviations cases, respectively

β_U, β_D = angle between hole curvature and original axis in "up-dip" and "down-dip" cases, respectively

Assumptions: The beds have slant layering angle and their boundaries are smooth. The layer fabrics have uniform grain sizes or grain aggregates. The propagation of cracks is uniform and proportional to the applied force. The aperture of the joint or boundary is less than the bit height. The boundary is free, or the material filling the boundary is weaker than the main rock forming the layers.

5.1 "Up-dip" hole deviation

Field observations show that the first crack C will run normal to the boundary, and that the region in the vicinity of the crack under the bit at A will be much more damaged than that away from it (at B)

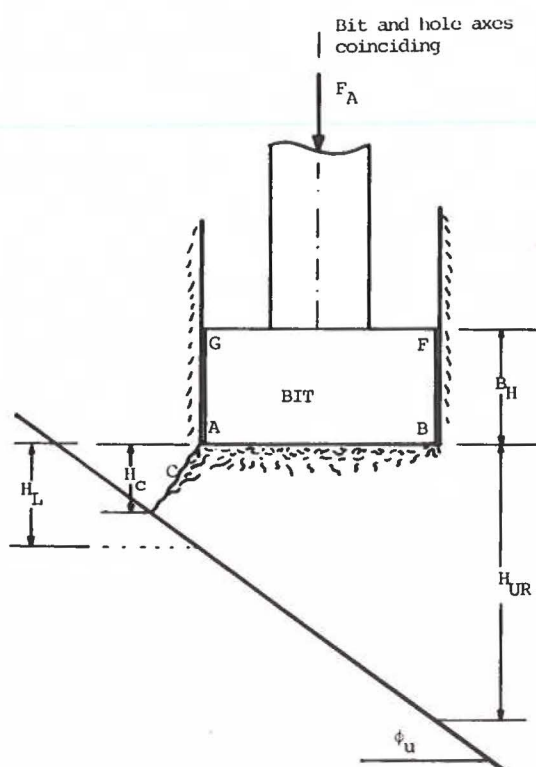


Figure 13. Initiation of first crack in the vicinity of a boundary.

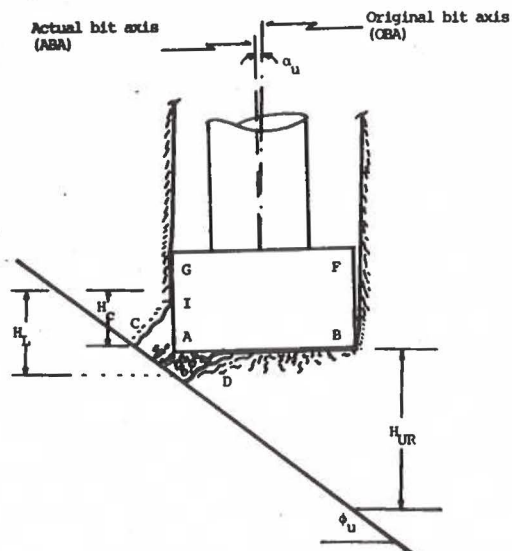


Figure 14. Bit tilt with α_U on left OBA.

- * edge A has no reacting force and the area is completely damaged
- * region D is chipping off much quicker and is more damaged, therefore reducing strength of material for the region
- * thrust will force bit axis to the left side of the original axis

Before edge A touches the boundary two cases can occur

- * for $B_H < H_C$ the bit will continue to move towards edge A after edge G of the bit passes I
- * for $B_H > H_C$ edge A of the bit will touch the boundary before edge G passes I (see figure 15)

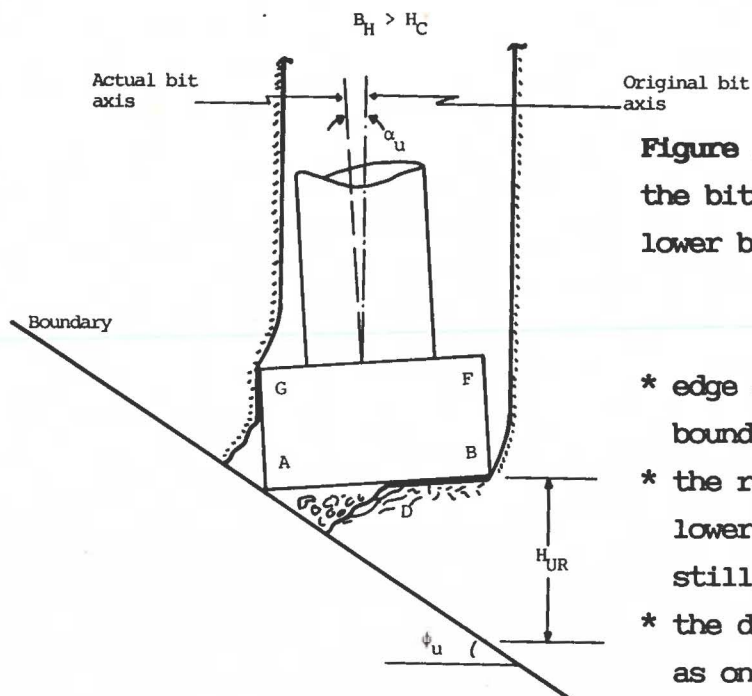


Figure 15. Configuration of the bit at first touch of the lower boundary.

- * edge A just touches the layer boundary
- * the rock material in the lower bed below edge A is still intact
- * the damage extent increases as one moves from edge B towards region D

Because of these conditions and because the rock material below edge A is just starting to get damaged, the bit axis will begin to regain its original direction.

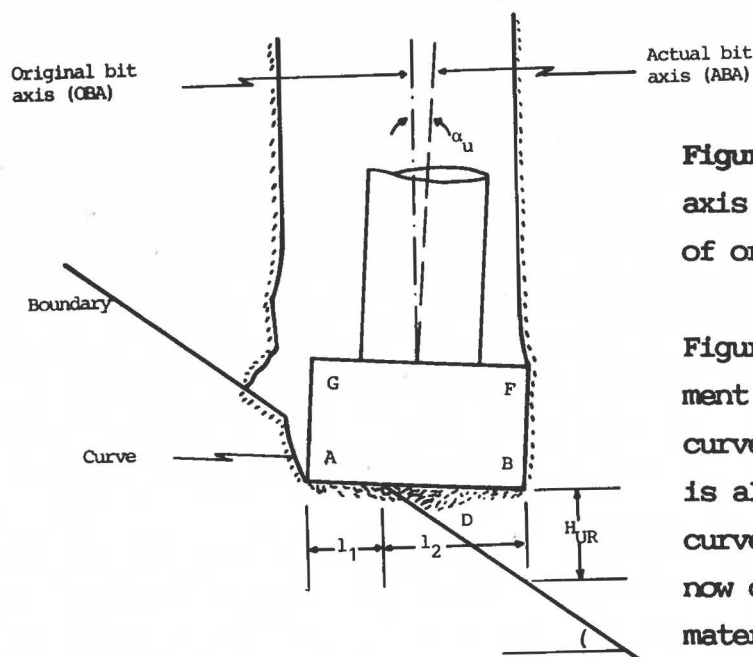


Figure 16. Change of bit axis with α_u on right side of original bit axis (OBA).

Figure 16 shows the bit movement towards B in form of a curved path. Note that edge F is also enlarging the hole in a curved path. The condition is now created where the rock material trapped between the bit and the lower boundary will

always be much more damaged than that in the lower bed, thus making the bit continue to move towards B. Consequently the bit axis will shift to the right side of the original axis.

Figure 16 also shows that eventually the bit will tilt, creating an α_u towards the right. This will continue as long as $l_1 < l_2$, and as long as the area marked by l_2 has more damage than that marked by l_1 . Meanwhile the area in the lower bed in the l_2 region will experience very little or no damage. When l_1 is greater than l_2 the damage zone in l_1 will tend to be symmetric. This condition, in addition to the stiffness of the drill rod, will begin to recover the bit axis towards the original one (i.e. leftwards).

From figure 17 we learn the following:

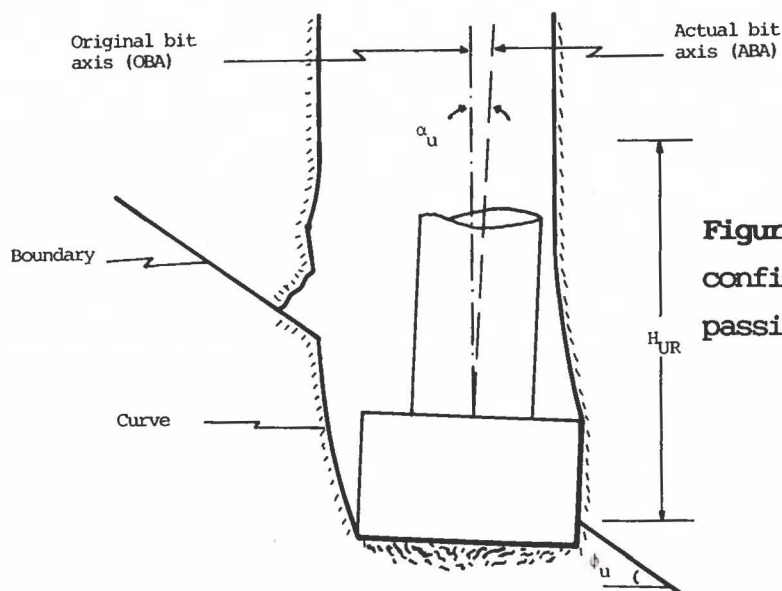


Figure 17. A look of bit configuration just after passing the boundary.

- * the bit has finally got into the lower bed
- * the bit axis is at an angle α on the right side of the original axis

This condition would result in the following:

- a) If there would be no other boundary below the bit there would be a tendency to recover the original bit axis due to the stiffness of the drill rod.
- b) On the other hand, if the bit encountered another boundary before recovering its original axis, the same process of bit trajectory would be repeated, this time increasing α even more on the right side of the original axis. This tilt would create the "up-dip" hole deviation. The successive process would be as shown in figure 18.

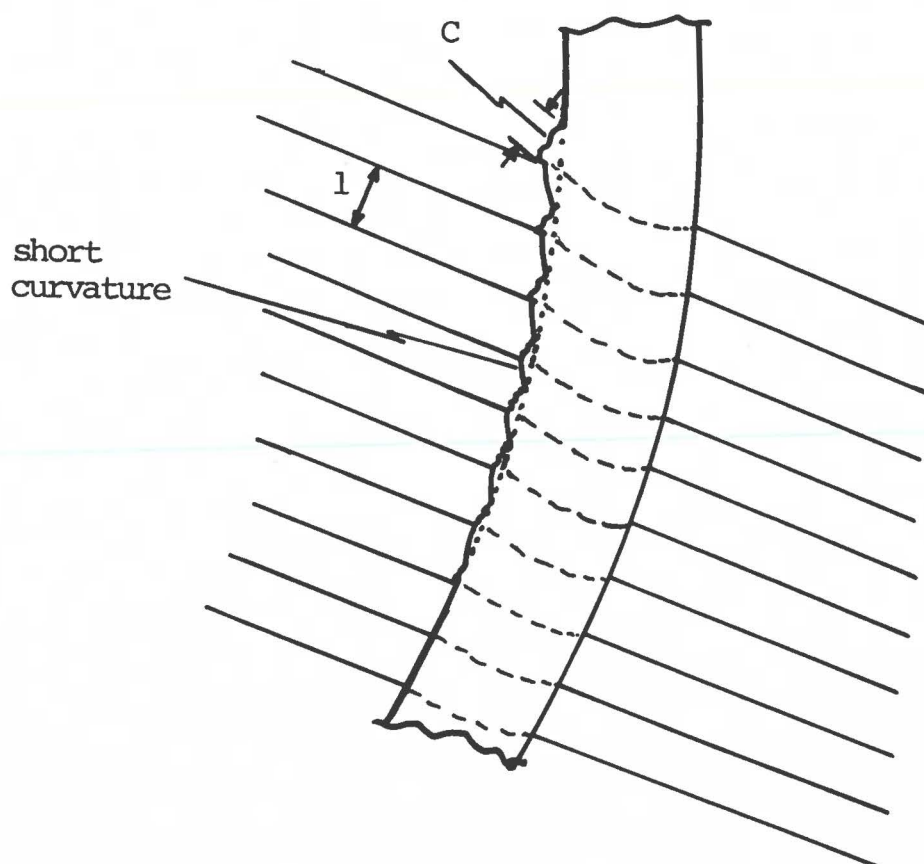


Figure 18. The up-dip deviation in a layered rock where layer thickness "1" is greater than the first crack length "c". (Emphasis only on up-dip side).

5.2 "Down-dip" hole deviation

Most of the failure process is as described for the "up-dip" hole deviation case and the explanation will not be repeated. In this section, only major differences are described.

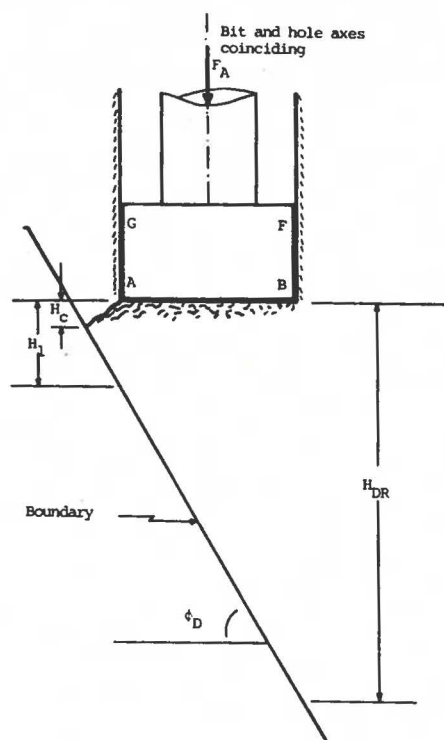


Figure 19. Initiation of a crack tip in the vicinity of a boundary. (Steep boundary angle).

Figure 19 shows the initial condition of the drill bit, just as in the "up-dip" case. The main differences are significantly larger ϕ_D and H_{DR} as against ϕ_U and H_{UR} , respectively.

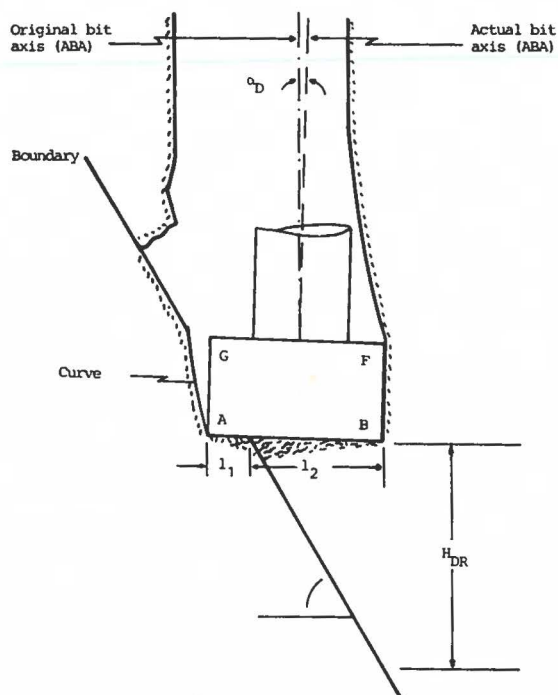


Figure 20. Passage of a bit across a steep boundary.

Because H_{DR} is long, figure 20 shows that the more damaged and therefore weaker area marked l_2 will be greater than the less damaged area l_1 in the lower bed, over a longer distance, than was the case in the "up-dip" path. Because of this the curvature of the hole marked "curve" will also continue over a long distance.

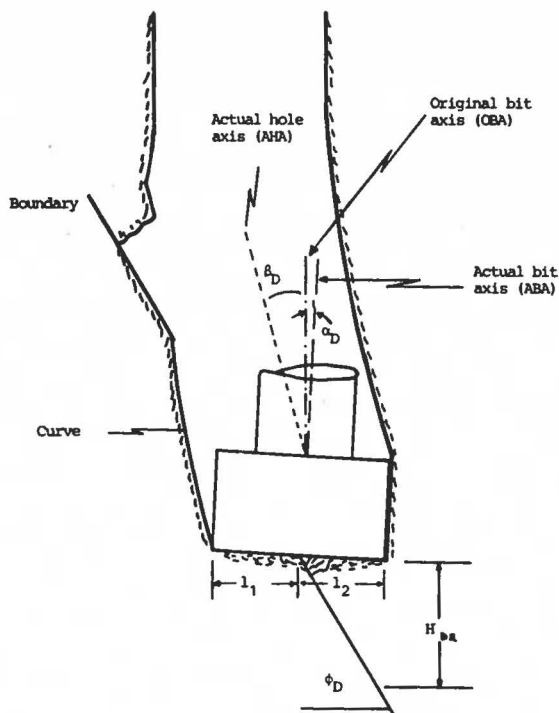


Figure 21. Illustration showing that $\beta_D > \alpha_D$.

Because of drill rod stiffness, it is shown in figure 21 that the bit is gaining more area (l_1) in the lower bed. Even though the bit axis has α_D on the right side of the original axis, it is seen that the axis of the curved hole is on the left side of the original axis, and $\beta_D > \alpha_D$.

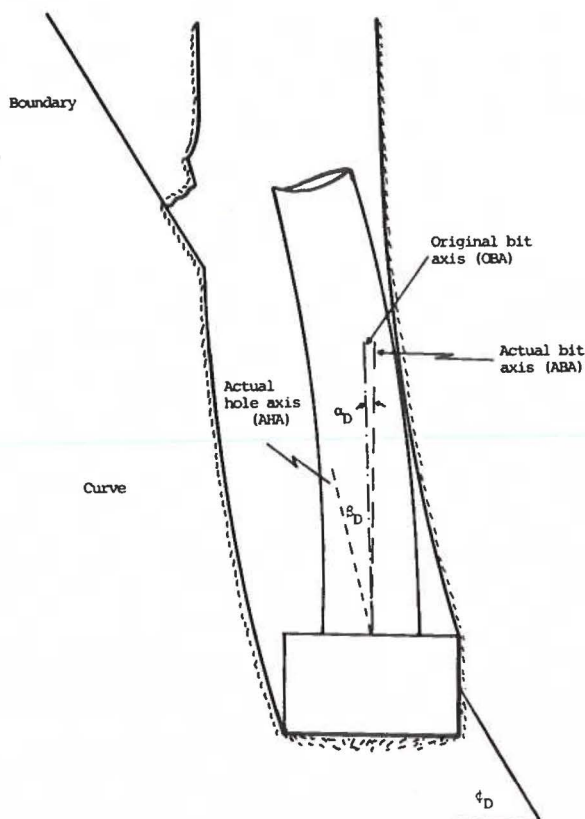


Figure 22. Illustration showing that $\beta_D > \alpha_D$, and that the "curve" is longer.

From figure 22 we note the following:

- * the bit is finally completely in the lower bed
- * the axis of the hole and the original axis of the bit are both on the left side of the prevailing bit axis

This condition will give rise to the following:

- a) There will be a tendency for the bit to recover its original axis because of the stiffness of the drill rod, if no other boundary is encountered

- b) If the bit gets to another boundary before the hole recovers its original axis, the bit trajectory process as described above will repeat, therefore increasing β_D on the left side of the original hole axis. This process will give rise to the "down-dip" hole deviation. The appearance of the trajectory will be as shown in figure 23.

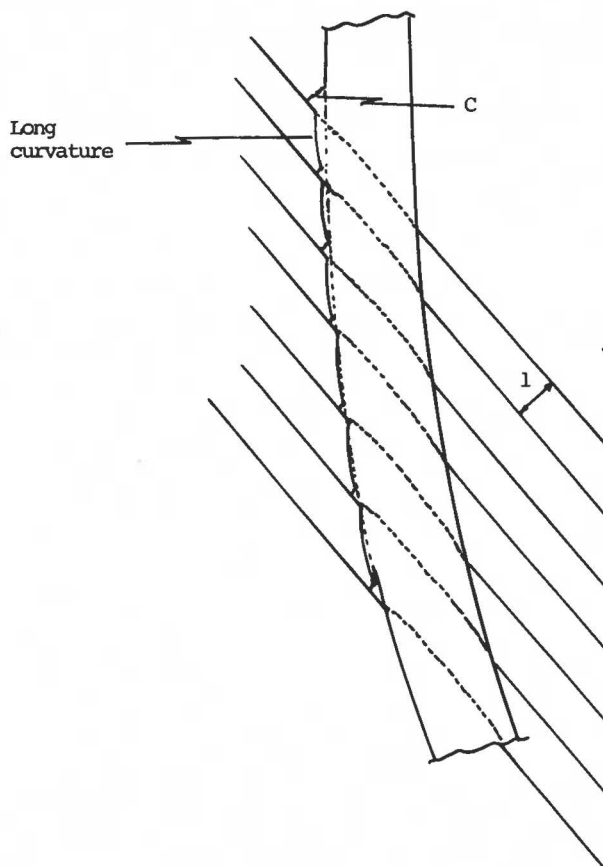


Figure 23. Down-dip hole deviation in steeply layered rocks. (Emphasis only on up-dip side).

Once again the thickness of layers is a big factor. Infact, it appears that when the layer thickness is very thin an "up-dip" hole deviation case is likely to occur for even fairly steep angles of rock layers. This is especially so in rocks with weak bonding between layers.

This is because the first crack propagation normal to the lower bed would be longer than the layer thickness, and therefore in general, no downward curve in region 1_1 (figure 21) would occur.

In the theory above, slip effects in both up-dip and down-dip cases were ignored. Events were observed where holes which were initially deviating up-dip, for instance, suddenly changed courses to down-dip because of surface characteristics of layered fabrics.

6 CONCLUDING REMARKS

Hole deviations are serious. They have always been a hassle and limitation to progress, usage of blasting possibilities, (larger openings, etc). Furthermore, deviations give rise to ore losses, dilution, excessive bending/breakage/jamming of drill stems, uneven toe burdens in quarries, ugly road-cuts or openings, boulders, etc. Much has been done to improve machines, automation, education, etc, but rock is rock and not man-made.

It is clearly seen, both from field observations and statistically, that the observations of unidirectional (common direction) hole deviations earlier reported for rotary drilling in layered rocks are the same for percussive drilling. However, this study has further identified the deviation phenomena as falling under four main rock structures, namely; slant layered, horizontally layered, vertically layered, and unlayered rocks.

For given machine parameters, hole pattern, and drill forces, the magnitude and severity of hole deviations have a strong dependence on rock structure.

Because of the complexity of rock structure and its interaction with other drilling parameters, a simple and universal mathematical theory for predicting hole deviations does not immediately seem likely, and more studies which simultaneously include data on all drilling parameters are sought. Based on the damage process of rock in the vicinity of layer boundaries, the author has so far given a qualitative theory explaining why holes are deviated up-dip or down-dip in layered (bedded) rocks.

This less costly but reasonably effective study has revealed some interesting results. However, future drilling operations would be desired to concurrently record all drilling conditions and parameters if hole deviation interpretations are to be more reliable, and hence possibly predictive.

Inspite of obvious limitations one can discuss if the findings of this study are applicable in their present form. If so, how can a "driller in distress" utilize this knowledge in practice?

Looking at the results of this study, the relations of hole deviations to the various hole patterns and rock conditions can be used in the design of the drilling operations to reduce the severities of hole deviation.

For some operations such as open-pits and road-cuts, the following could be a worthwhile procedure:

- (i) drill the first few holes and blast them
- (ii) observe the pattern of deviations due to influence of rock

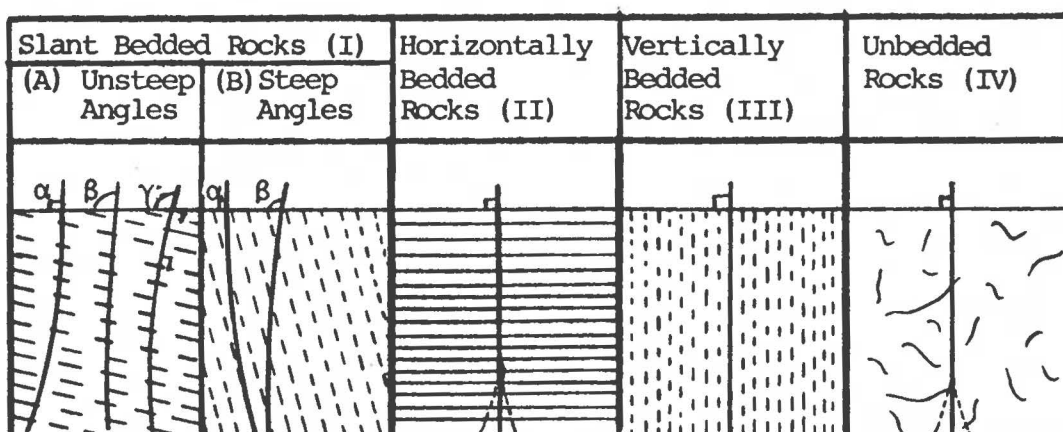


Figure 24. Planning of hole inclinations with consideration to rock structure influence on hole deviations.

- (iii) adjust the drill pattern in the following manner (refer to figure 24):

* Assumption: no or minimal deviations due to drill forces alone, e.g. by not over-thrusting drill strings.

IA. UNSTEEP BEDDED ROCKS

If holes were drilled vertical ($\alpha=90^\circ$) downwards, up-dip deviations would occur. On the other hand if holes were drilled normal to beddings ($\gamma > \alpha$), "practically" no deviations would be expected due to layering alone. Rather, weight of the drill string would

initially induce downward deviations. After drilling for some length of hole the downward deviation would eventually orient holes to some angle such that holes would begin to gain up-dip deviations.

If so, it would be reasonable to drill holes at some angle β between the two cases discussed above (i.e. $\alpha < \beta < \gamma$) at which hole deviations would break even (or closer), to give minimal hole crookedness.

IB. STEEP BEDDED ROCKS

Holes drilled vertical ($\alpha=90^\circ$) downward would deviate down-dip. To reduce hole deviations, it would be advisable to drill holes at some angle (β) greater than α (i.e. $\alpha < \beta$). This is because the more oblique to beddings the holes are, the longer it would take before the holes can orient themselves along beddings.

II. HORIZONTALLY BEDDED ROCKS

Drill holes as vertical as possible

III. VERTICALLY BEDDED ROCKS

Drill holes as vertical as possible

IV. UNBEDDED ROCKS

Drill holes as vertical as possible

Note however that any change of hole pattern should moreover consider the over-all economic, technical, and safety consequences of the resulting operation for the change to be effective.

Other measures for minimizing hole deviations include use of stiff rods and large diameter drill strings.

Acknowledgements

Thanks are due to Professor/Director Olaf Meyer (Swedish Industrial Fund), for the great help in sketching and summarizing this report from the Licentiate thesis, to Edward Easterling (M.Sc.) for assisting with field collection of data, to Professor Sven Granholm for supervision, to Secretaries Maria Fredriksson and Ingeborg Rova for typing the manuscript, and finally to the Swedish Rock Engineering Research Foundation (BeFo) for financing the project.

References

1. Easterling, E. 1986. A measuring technique for rock dependent hole deviations - a field study on visible smooth blasted holes. M.Sc. thesis. University of Luleå, Sweden.
2. Sinkala, T. 1986. Phenomena of Rock Dependent Drill Hole Deviations - A Field Study. Licentiate thesis. University of Luleå, Sweden. (See also references in this report).
3. Sinkala, T. April 1987. Rock and Hole Pattern Influences on Percussion Hole Deviations - A Field Study. International Conference "Drillex '87", 7-10 April, Stoneleigh, Warwickshire, England.
4. Sinkala, T. June 1987. Hole Deviations and Measurement Problems. Technical Report 1987:52T, G 2000:87:10. University of Luleå, Sweden.