The influence of joint orientation uncertainties on the stability of rock structures Do we need alternatives to partial factors?

Rainer Poisel

Vienna University of Technology, Institute for Geotechnics, Vienna, Austria

Nikolaus Hoedlmoser

Vienna University of Technology, Institute for Geotechnics, Vienna, Austria

Bernd Kolenprat

Federal Ministry of Labour, Social Affairs and Consumer Protection, Vienna, Austria

Robert Hofmann

Consulting Engineer, Perchtoldsdorf, Austria

Trunk, U. (1993): Probabilistic stability analysis for rock wedges. Proc. Eurock 1993, Balkema: Rotterdam, 227-232.

"The influence of the geometric rock mass parameters orientation and trace length is predominant. Thus, a better investigation for these parameters could lead to a better and more economic design of slopes and walls of underground openings.

Because of the great influence of the geometric parameters the values for partial safety factors shows a wide scatter for constant safety levels. Thus, the use of partial safety factors for wedge analysis is not recommended. "

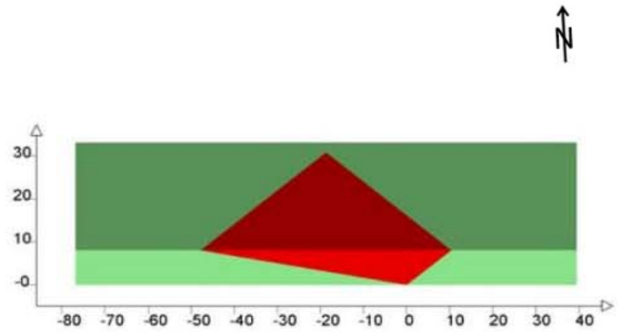
However,

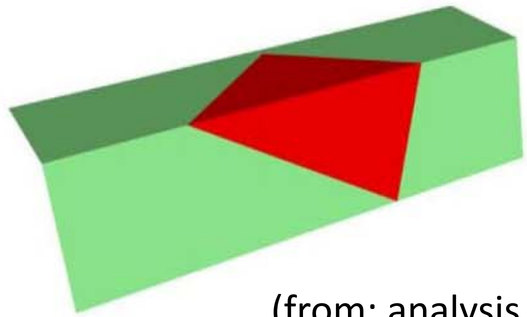
•EN 1990, Second draft from 30 April 2017, 1.1 Scope, (4) says:
"Design and verification in EN 1990 is based on the partial factor method."

•EN 1997-1, Draft April 2017, 4.3 Basic variables, 4.3.1 Geometrical data, says:
"Discontinuities within geotechnical units may be described in probabilistic terms."
The consideration of rock discontinuity uncertainties in rock stability analyses is missing completely.

EXAMPLE 1 – STABILITY OF A ROCK SLOPE

30 m high, dip direction = 185°, dip = 75°, upper slope surface horizontal





(from: analysis using swedge)

Discontinuity 1		Discontinuity 2	
mean dip direction [°]	147	mean dip direction [°]	223
mean dip [°]	40	mean dip [°]	67
mean cohesion [kPa]	23,4	mean cohesion [kPa]	123,5
mean angle of friction [°]	15,5	Mean angle of friction [°]	57

A deterministic analysis by a limit equilibrium approach yields a global factor of safety of 1,3.

Consideration of uncertainties of strength parameters

Trunk (1993) specified a mean variation coefficient (= standard deviation/mean value) of rock joint cohesion of 0,3 and a mean variation coefficient of rock joint angle of friction of 0,15.

discontinuity 1

mean cohesion [kPa]	23,4
mean angle of friction [°]	15,5

Standard deviation of cohesion [kPa] =
= mean cohesion [kPa] * 0,3 = 23,4 * 0,3 = 7

Standard deviation of angle of friction [°] =
= mean angle of friction [°] * 0,15 = 15,5 * 0,15 = 2,3

discontinuity 2

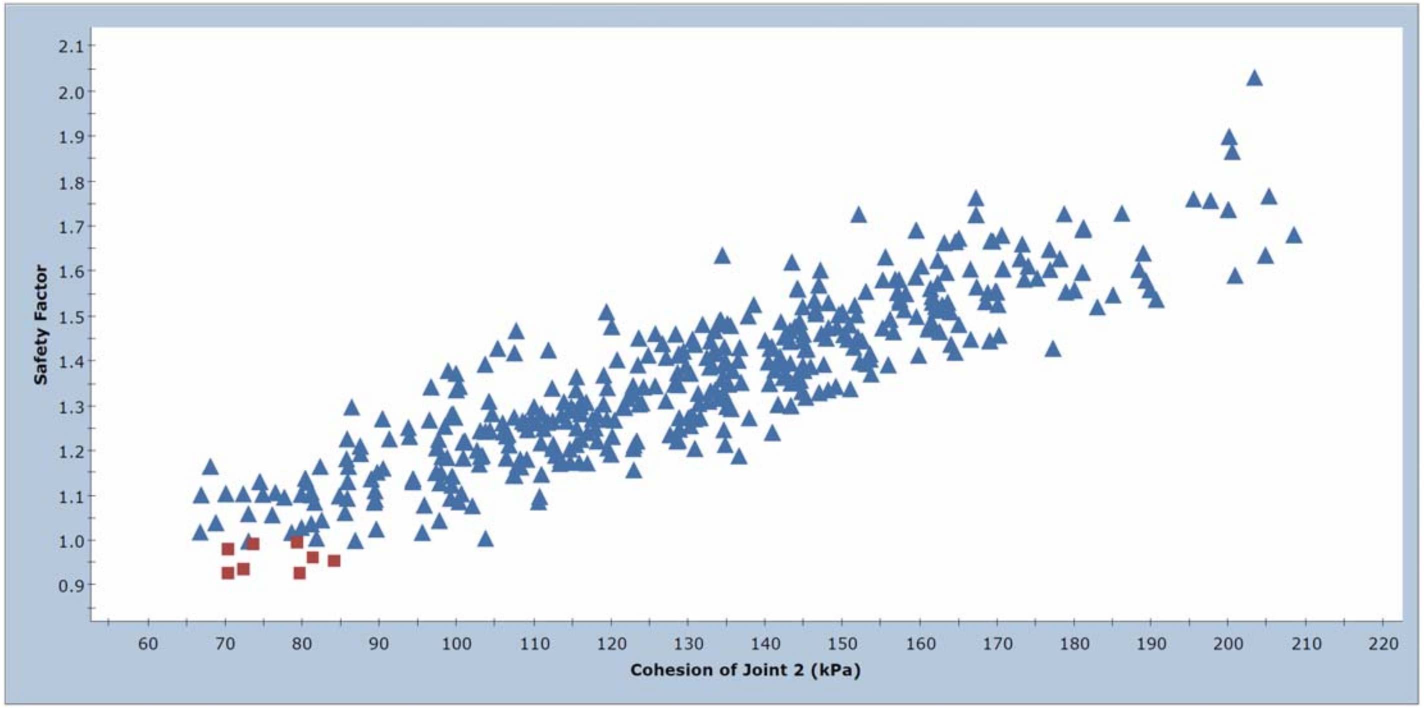
mean cohesion [kPa]	123,5
mean angle of friction [°]	57

Standard deviation of cohesion [kPa] =
= mean cohesion [kPa] * 0,3 = 123,5 * 0,3 = 37,1

Standard deviation of angle of friction [°] =
= mean angle of friction [°] * 0,15 = 57 * 0,15 = 8,6

A Monte-Carlo-Analysis (using swedge) taking these parameters into account yields

- a maximum global factor of safety of 2,0,
- a minimum global factor of safety of 0,9 and
- **a failure probability of 1,9 %**.



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Gibson (2011) recommends an (accepted) failure probability of 1 to 2 % for an overall slope in a mine. Regarding the consequences of a failure of an overall slope in a mine, we would choose a factor of safety of 1,3 for such a structure. Thus, the deterministic approach and the probabilistic approach (regarding uncertainties of strength parameters) yield analogue results.

Design Element	Sjoberg	Schellman	Pothitos	Kirsten	Recommended
Bench	10	12	10 – 50	20 to 50	15 to 30
Inter-ramp	1 to 2	8 to 10	1 to 3 <1*	5 to 10	2 to 5 <1*
Overall Slope	0.3	<8	1 to 3 <1*	1.5 to 5	1 to 2 <1*

* Overall or inter-ramp including haul road or key infrastructure

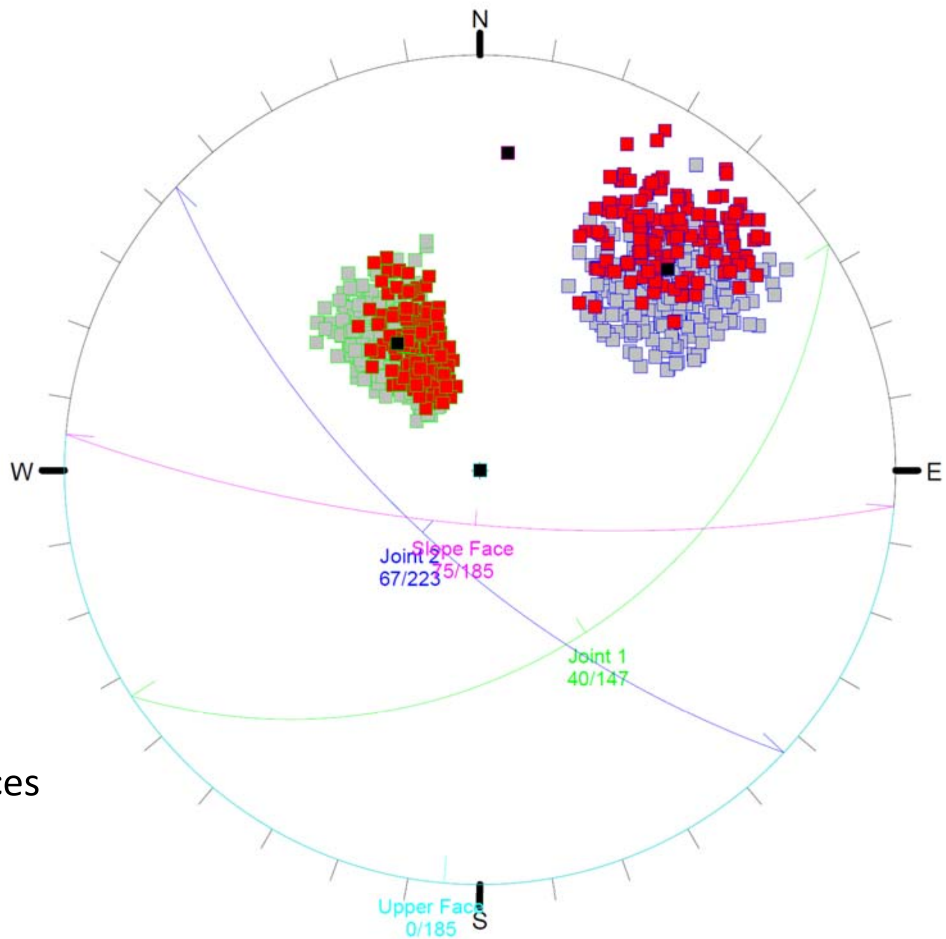
in percentage

(partial) safety factors
1,1
1,2
1,3 (1,5)

From: Gibson 2011

Consideration of uncertainties of discontinuity orientations

standard deviation of dip direction and of dip of the discontinuities:
10° (often observed value)



Stereographic projection of the slope faces
and the discontinuity uncertainties
from: analysis using swedge

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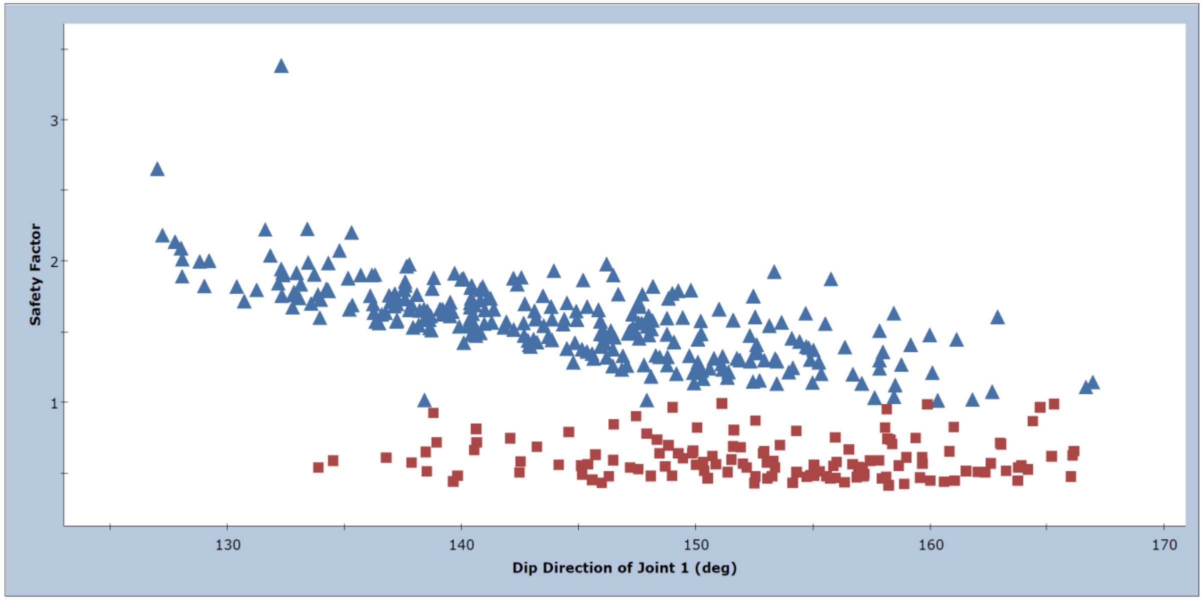
A Monte-Carlo-Analysis taking a standard deviation of 10° of dip direction and of dip of the discontinuities and mean values of the discontinuities´ strength parameters into account yields

- a maximum global factor of safety of 3,4,
- a minimum global factor of safety of 0,4 and
- **a failure probability of 32,2 %.**



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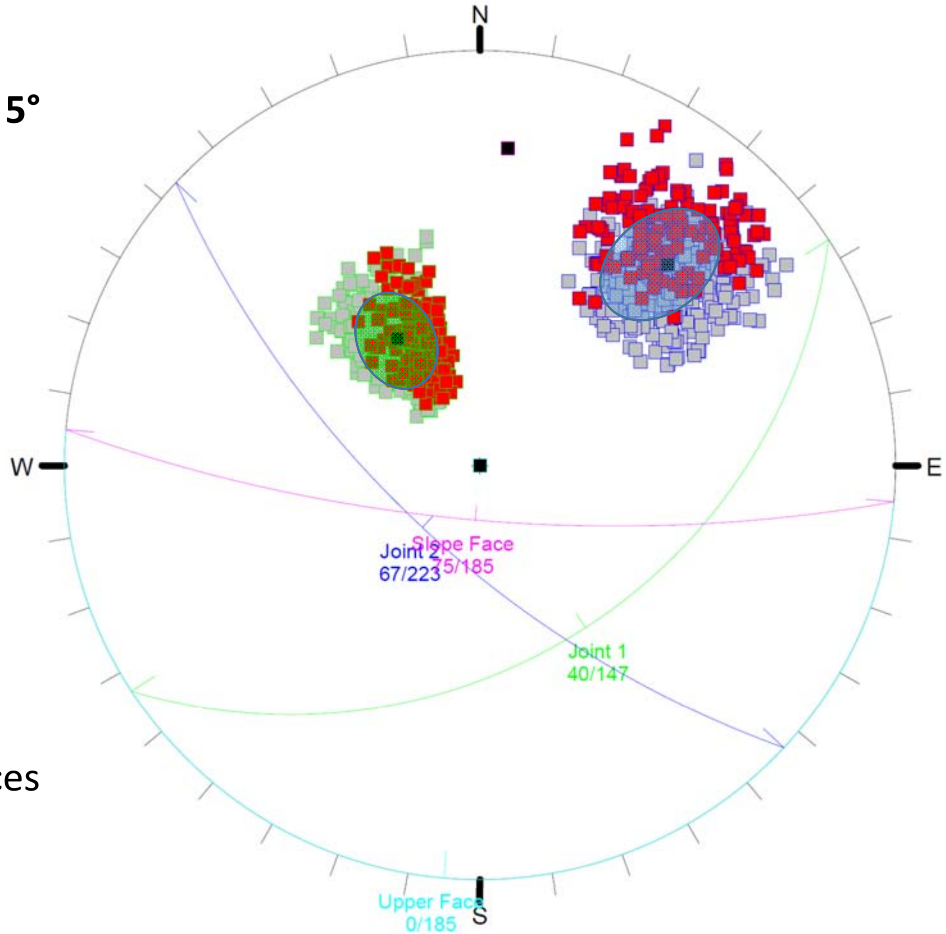
Consideration of uncertainties of discontinuity orientations

standard deviation of dip direction and of dip of the discontinuities: **5°**

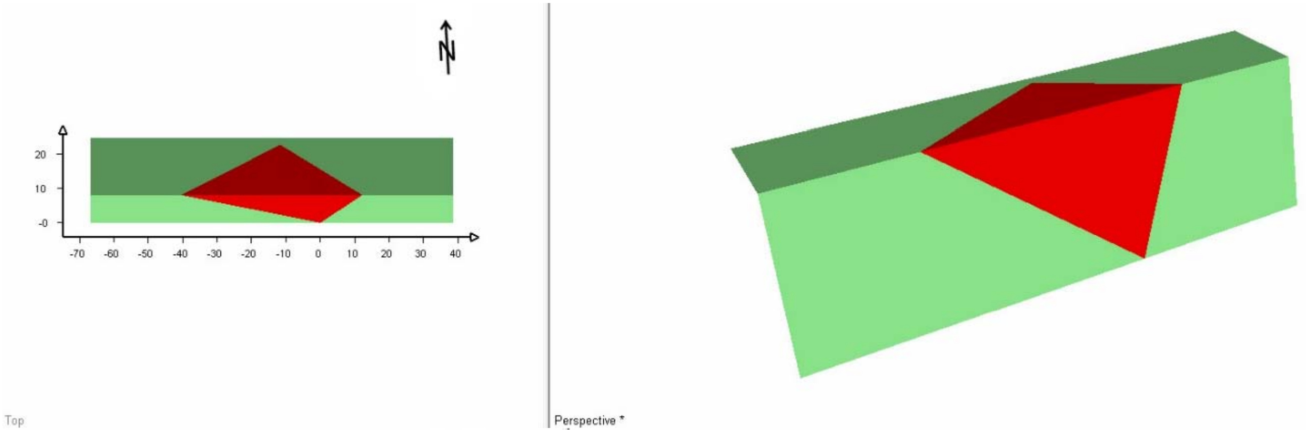
➡ **failure probability 20 %**



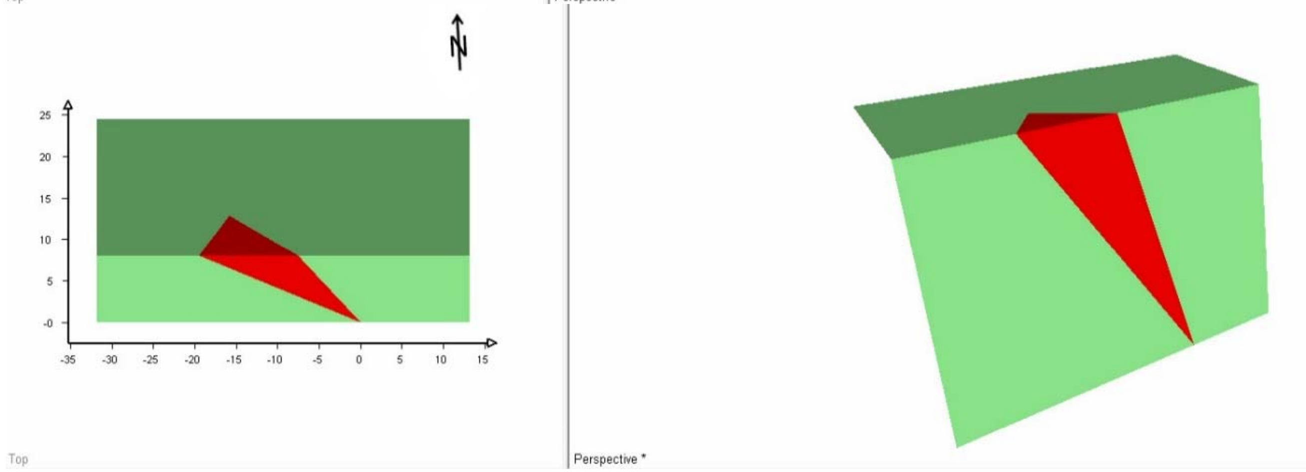
Stereographic projection of the slope faces and the discontinuity uncertainties
from: analysis using swedge

standard deviation of dip direction and of dip of the discontinuities: **10°**

Block with minimum global factor of safety (sliding on discontinuitiy 1 only!)



Block with maximum global factor of safety (sliding on both discontinuities)



Kinematic changes (e.g. sliding on one discontinuity – sliding on two discontinuities) cause abrupt changes of the effects of actions and of resistances and therefore abrupt changes in stability. Thus, rock discontinuity orientation uncertainties cannot be considered by partial factors.

Moreover, kinematic changes cause discontinuous distribution functions of effects of actions, of resistances and of safety factors. Consequently the Monte Carlo method should be applied when using probabilistic methods for assessment of discontinuity orientation uncertainties .

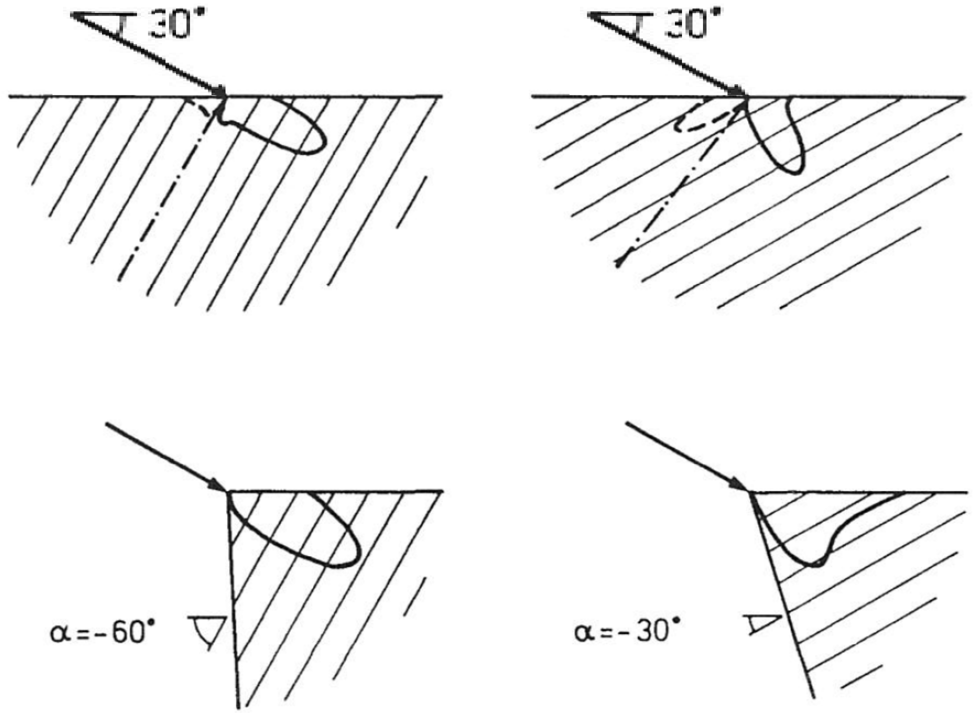
	maximum global factor of safety	minimum global factor of safety	failure probability
strength uncertainties	2,0	0,9	1,9 %
orientation uncertainties	2,2	0,4	32,2 %

Thus, uncertainties of discontinuity orientations influence rock slope stability (at least) in the same way as uncertainties of rock joint strength parameters do. While uncertainties of rock joint strength parameters are considered by partial factors dealt with in detail, the consideration of uncertainties of discontinuity orientations is missing completely in EN 1990 and in EN 1997-1.

lines of equal stress in a foundation on rock with one joint set and with elastic, transversal isotropic behaviour

tension unlimited

tension cut-off



left case: the direction of maximum stress is normal to the discontinuities and points directly into the ground
right case: direction of maximum stress is oblique to the discontinuities and parallel to the ground surface

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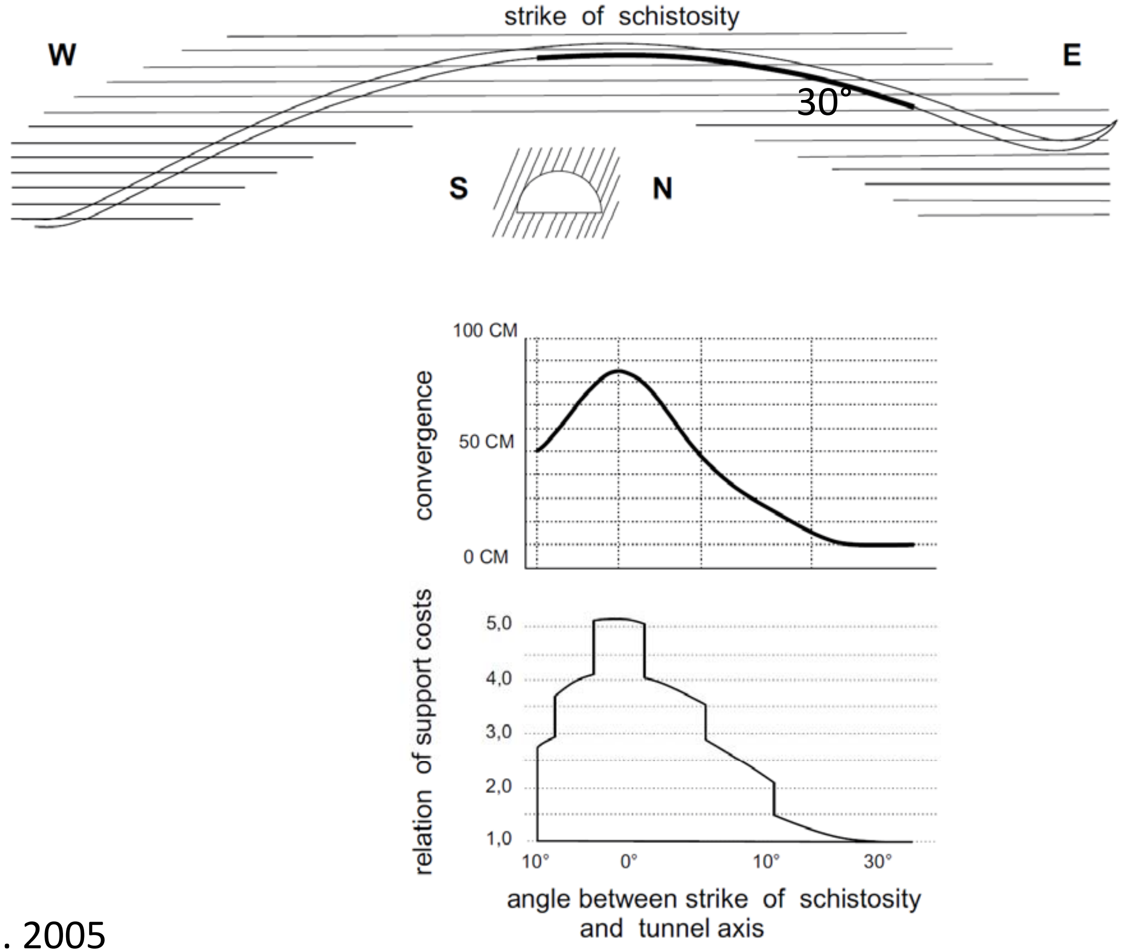
plan

displacements

Support costs

after: Huber et al. 2005



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Summary:

- The influence of discontinuity orientation uncertainties on rock engineering is eminent. However, the present drafts of EN 1990 as well as of EN1997-1 do not consider these effects.
- Consideration of discontinuity orientation uncertainties is only possible when using probabilistic methods.

Proposed supplements of EN 1990 and EN 1997-1:

EN 1990, Second draft from 30 April 2017, Annex C1 (informative), Paragraph C1.6.1.1 "Criterion for reliability based design and assessment" says, "When it is stated in the Eurocodes that a design and assessment situation is not covered by the partial safety factor design format of the Eurocodes, target reliability values should be defined.". In this paragraph target reliability values are given related to a one-year reference period. However, mostly only relative probabilities can be calculated in geotechnics. Probabilistic software in geotechnics (e.g. swedge) as well often gives relative probability as shown in the rock slope example. Thus, paragraph C1.6.1.1 should also include relative (accepted) probabilities.

EN 1997-1 (e.g. in 8.3 Verification by the partial factor method) should state that the effects of rock discontinuity orientation uncertainties must be considered by probabilistic methods.
EN 1997-1 should also enable an approach according to the methodologically sound procedure of swedge.

Based on a suggestion by Luis Lamas, John Harrison proposed, that EN 1990, 6.3.6 "Design values of geometrical data" should have a further note saying:
"For geotechnical design, deviation of excavation profiles from nominal values may be catered for by equation 6.23 ($a_d = a_{nom} \pm \Delta a$). Geometrical data associated with properties of the ground, such as boundaries between geotechnical units or the orientation of discontinuities within geotechnical units, should be treated as ground properties and catered for in a probabilistic way, as specified in EN 1997."