European Commission

Slope stability – design of slopes and embankments

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Outline of the talk

Slopes
- Scope and contents
- Ultimate limit state design of slopes
- Serviceability limit state design of slopes

Embankments
- Scope and contents
- Limit states
- Monitoring and maintenance

Summary of key points

Scope of EN 1997-1 Sections 11 and 12

- There is no separate section on slopes in EN 1997-1
- The provisions for the design of slopes and embankments are contained in Section 11: Overall stability
- The provisions in Section 11 apply to the overall stability of and movements in the ground, whether natural or fill, around foundations, retaining structures, natural slopes, embankments or excavations
- The provisions in Section 12 apply to embankments for small dams and for infrastructure

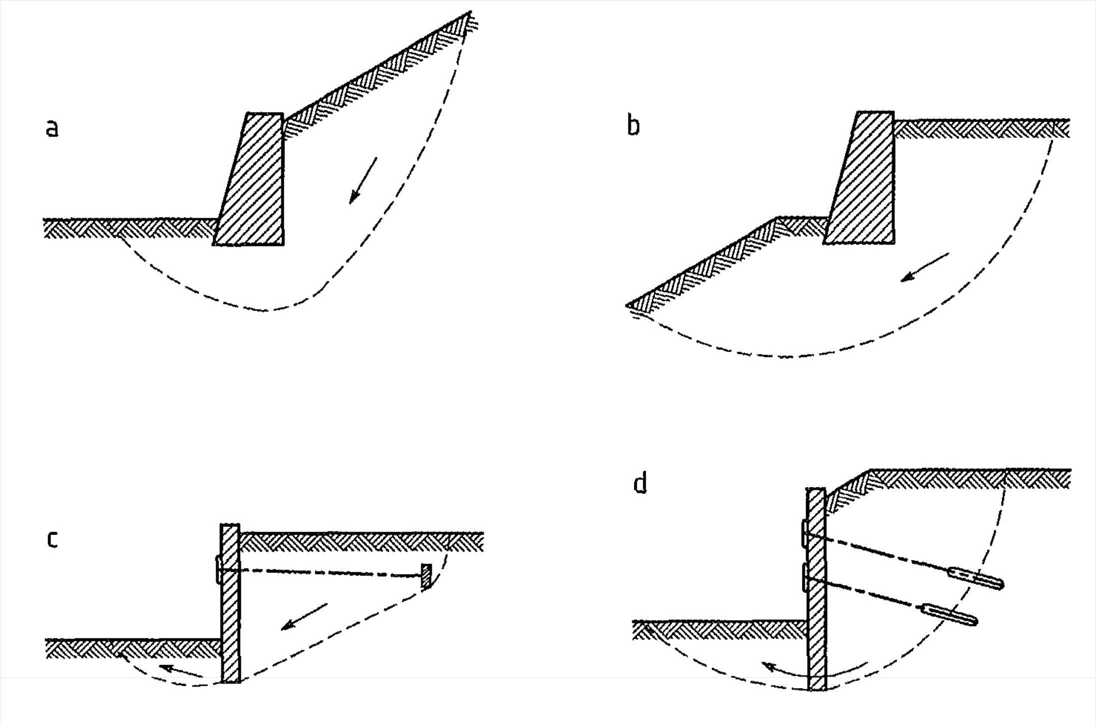
Slope stability – design of slopes

SCOPE AND CONTENTS

Overall stability

- An overall stability situation is where there is loss of overall stability of the ground and associated structures, i.e. slope stability, or where excessive movements in the ground cause damage or loss of serviceability in neighbouring structures, roads or services
- Typical structures for which an analysis of overall stability should be performed (and mentioned in relevant sections of Eurocode 7) are:
  - Retaining structures
  - Excavations, slopes and embankments
  - Foundations on sloping ground. natural slopes or embankments
  - Foundations near an excavation, cut or buried structure, or shore

Examples of overall stability



Examples of limit modes for overall stability of retaining structures presented in Section 9

Contents of EN 1997-1 Section 11 Overall stability

Section 11 has the following sub-sections:

§11.1 General (2 paragraphs)

§11.2 Limit states (2)

§11.3 Actions and design situations (6)

§11.4 Design methods and design considerations (11)

§11.5 Ultimate limit state design (26)

§11.6 Serviceability limit state design(3)

§12.7 Monitoring (2)

Slope stability –

design of slopes

ULTIMATE LIMIT STATE DESIGN OF SLOPES

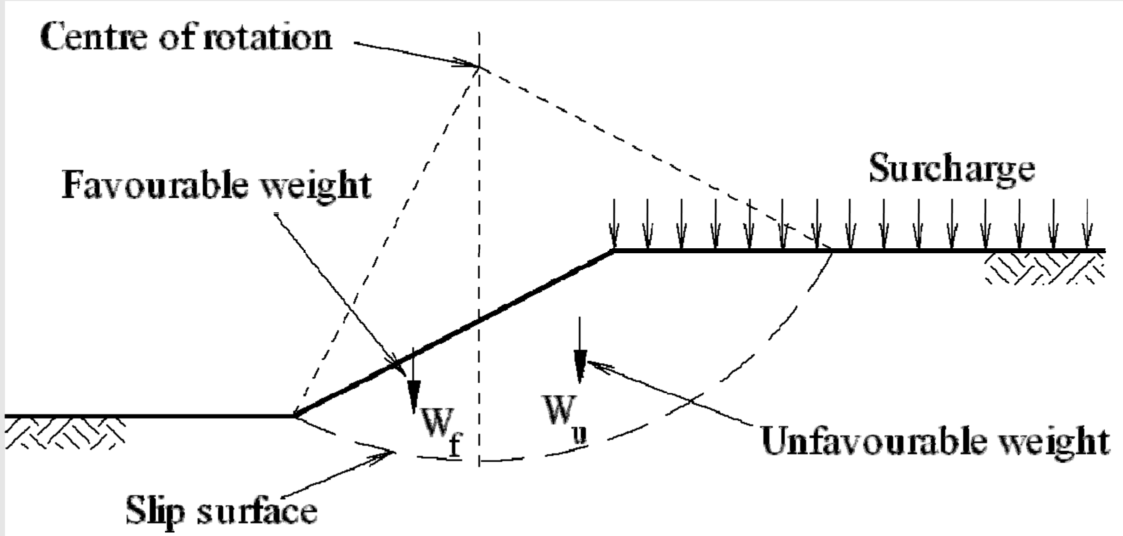
Stability analysis for slopes

- The overall stability of slopes shall be checked using the GEO/STR design values of actions, resistance and strengths with the appropriate values for the partial factors
- In analysing overall stability, all relevant modes of failure shall be taken into account
- No specific inequality to be satisfied for overall stability is given in Eurocode 7 and no calculation model is given
- The mass of soil or rock bounded by the failure surface should normally be treated as a rigid body or several rigid bodies moving simultaneously
- Stability may be checked by limit analysis or by the finite element method

Design Approaches for slope stability analyses

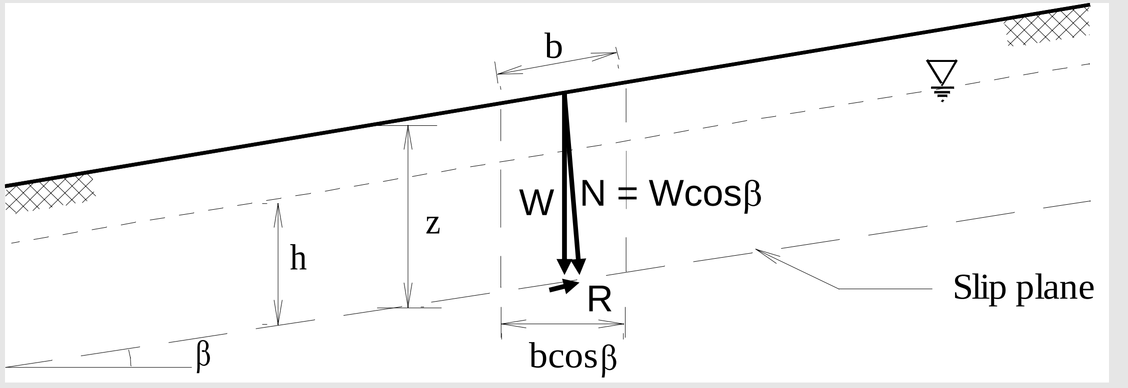
- DA3 is the same as DA1.C2 for the design of slopes as loads on the surface in DA3 are treated as geotechnical actions using the A2 set of partial factors on actions, as in DA1.C2
- In DA1, C1 and C2 should both be considered, but DA1.C2 normally controls
- Undrained condition:
  - DA1.C1 $\gamma_G = 1.35$, $\gamma_Q = 1.5$, $\gamma_{c_u} = 1.0$
  - DA1.C2 $\gamma_G = 1.0$, $\gamma_Q = 1.3$, $\gamma_{c_u} = 1.4$
- Drained condition
  - In DA1.C1 an increase in the vertical load increases the resistance since the resistance is a function of the normal stress so that the margin of safety is unchanged. Thus DA1.C1 does not usually govern.
  - Hence DA1.C2 governs, where $\gamma_G = 1.0$, $\gamma_Q = 1.3$, $\gamma_{c'} = \gamma_{\phi'} = 1.25$

Comments on slope stability



- Part of soil weight is favourable while another part is unfavourable
- All the soil weight components are treated as coming from a “single source” and the same partial factor is applied to the unfavourable and favourable components of the soil weight
- It is difficult to analyse slope stability using a resistance factor with the method of slices
- Hence DA2 is generally not used for slope stability analyses

Infinite slope analysis (Water table at surface)



DA1.C2

Design sliding force, S_d

$S_d = \gamma_G W \sin\beta = \gamma_G \gamma z b \cos\beta \sin\beta$

Design resistance, R_d

$R_d = \gamma_G (W\cos\beta - ub\cos\beta)\tan(\tan^{-1}(\tan\phi'_k/\gamma_M))$

$= \gamma_G(\gamma zb\cos^2\beta - \gamma_w zb\cos^2\beta)\tan(\tan^{-1}(\tan\phi'_k/\gamma_M))$

$S_d \leq R_d$

$\gamma_G \gamma zb \cos\beta \sin\beta \leq \gamma_G \gamma' zb \cos^2\beta \tan(\tan^{-1}(\tan\phi'_k/1.25))$

$\gamma \tan\beta \leq \gamma' (\tan\phi'_k/1.25)$

Traditional design

$$FOS = \frac{\gamma' \tan\phi'}{\gamma \tan\beta}$$

If FOS = 1.25:

$\gamma \tan\beta = \gamma' (\tan\phi'/1.25)$

i.e. Eurocode 7 design is same as traditional design

General stability analyses for slopes

- It is stated that a slope analysis should verify the overall moment and vertical equilibrium of the sliding mass (Clause 11.5.1(10))
- But no specific inequality to be satisfied is given in Eurocode 7
- If horizontal equilibrium is not checked, the interslice forces should be assumed to be horizontal if a method of slices is used (Clause 11.5.1(10))
    - This means that some slope stability analysis methods are not acceptable
- Finite elements can be used, but no guidance given

Details of different methods of slices from SLOPE/W

Note:

- Acceptable methods
- Not acceptable methods

Table 2-1 Equations of Statics Satisfied

Method	Moment Equilibrium	Force Equilibrium
Ordinary or Fellenius	Yes	No
Bishop's Simplified	Yes	No
Janbu's Simplified	No	Yes
Spencer	Yes	Yes
Morgenstern-Price	Yes	Yes
Corps of Engineers – 1	No	Yes
Corps of Engineers – 2	No	Yes
Lowe-Karafiath	No	Yes
Janbu Generalized	Yes (by slice)	Yes
Sarma – vertical slices	Yes	Yes

Table 2-2 Interslice force characteristics and relationships

Method	Interslice Normal (E)	Interslice Shear (X)	Inclination of X/E Resultant, and X-E Relationship
Ordinary or Fellenius	No	No	No interslice forces
Bishop's Simplified	Yes	No	Horizontal
Janbu's Simplified	Yes	No	Horizontal
Spencer	Yes	Yes	Constant
Morgenstern-Price	Yes	Yes	Variable; user function
Corps of Engineers – 1	Yes	Yes	Inclination of a line from crest to
Corps of Engineers – 2	Yes	Yes	Inclination of ground surface at top of slice
Lowe-Karafiath	Yes	Yes	Average of ground surface and slice base inclination
Janbu Generalized	Yes	Yes	Applied line of thrust and moment equilibrium of slice
Sarma – vertical slices	Yes	Yes	$X = C + E \tan \phi$

Bishop's simplified method of slices

The global factor of safety F in Bishop's simplified method of slices is equivalent to a partial factor on the soil strength parameters with appropriate partial factors on the actions

$$\tau_{mob} = \frac{c'}{F} + \sigma_n' \frac{\tan\phi'}{F} = \frac{c'}{\gamma_{M;mob}} + \sigma_n' \frac{\tan\phi'_k}{\gamma_{M;mob}}$$

$$\gamma_{M;mob} = \frac{1}{\sum \gamma_G W \sin\alpha} \sum \frac{[c'_k b + (\gamma_G W - \gamma_G u b)\tan\phi'_k]\sec\alpha}{1 + \frac{\tan\alpha \tan\phi'_k}{\gamma_{M;mob}}}$$

DA1.C1: Apply γ_G = 1.35 to permanent actions, incl. soil weight force via the soil weight density and γ_Q = 1.5 to variable actions and check that $\gamma_{M;mob}$ = F ≥ 1.0

DA1.C2: Apply γ_G= 1.0 to permanent actions, incl. soil weight force via the soil weight density and γ_Q=1.3 to variable actions and check that $\gamma_{M;mob}$ = F ≥ 1.25

Slope stability –
design of slopes

SERVICEABILITY LIMIT STATE DESIGN OF SLOPES

Serviceability limit state design of slopes

- Eurocode 7 states the design of slopes shall show that the deformations of the ground will not cause a serviceability limit state in structures and infrastructure on or near the particular ground
- Since the analytical and numerical methods available at present do not usually provide reliable predictions of the deformations of a natural slope, the occurrence of serviceability limit states should be avoided by one of the following:
  - Limiting the mobilised shear strength
  - Observing the movements and specifying actions to reduce or stop them, if necessary (i.e. use the Observational Method)

Slope stability –
design of embankments

SCOPE AND CONTENTS

Design of embankments

- Paragraph 12.1(1)P states that the provisions in Section 12 shall apply to embankments for small dams and for infrastructure
- However, no definition is given for the word “small”
- Frank et al. state that it may be appropriate to assume “small dams” include dams (and embankments for infrastructure) up to a height of approximately 10m

Contents of EN 1997-1 Section 12 Embankments

Section 12 Embankments is the shortest Section on EN 1997-1

It has the following sub-sections:

§12.1 General (2 paragraphs)

§12.2 Limit states (2)

§12.3 Actions and design situations (8)

§12.4 Design methods and design considerations (13)

§12.5 Ultimate limit state design (7)

§12.6 Serviceability limit state design(4)

§12.7 Supervision and monitoring (6)

Special features of embankment design

- Since embankments are constructed by placing fill and sometimes involve ground improvement, the provisions on fill in Section 5 should be applied
- For embankments on ground with low strength and high compressibility, Clause 12.4(4)P states that *the construction process shall be specified*, i.e. in the Geotechnical Design Report, to ensure that the bearing resistance is not exceeded or excessive movements do not occur during construction

Slope stability –
design of embankments
LIMIT STATES

Limit states to be checked

A long list of possible limit states, both ultimate, including GEO and HYD types, and serviceability limit states, that should be checked for embankments is provided including:

- Loss of overall stability
- Failure in the embankment slope or crest
- Failure by internal erosion
- Failure by surface erosion or scour
- Excessive deformation

Limit states involving adjacent structures, roads and services are also included in the list

Ultimate and serviceability limit state analyses

- All possible failure modes of an embankment shall be considered, as stated in Section 11
- Since embankments are often constructed in different phases, with different load conditions, analyses should be carried out phase by phase and in accordance with the Geotechnical Design Report
- The design should show that settlement of the embankment will not cause a serviceability limit state in the embankment or nearby structures or services
- The settlement of the embankment should be calculated using the principles of Section 6.6.1 – settlement of foundations

Slope stability –
design of embankments

MONITORING AND MAINTENANCE

Monitoring and maintenance

- Since the behaviour of embankments on soft ground during construction is usually monitored to ensure failure does not occur, it is often appropriate to use the Observational Method for design
- The importance of both supervision and monitoring in the case of embankments is demonstrated by the fact that in Section 12 there is a separate sub-section, 12.7, with specific provisions for the supervision of the construction of embankments and the monitoring of embankments during and after construction
- The only other section of Eurocode 7 that has specific provisions for both supervision and monitoring is the section on ground anchorages

Slope stability –

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SUMMARY OF KEY POINTS

Summary of key points

- Sections 11 and 12 set out the provisions for the design of slopes and embankments
- The focus is on the relevant limit states to be checked
- No calculation models are provided
- When using method of slices for slope stability, some simplified methods not acceptable
- The relevance and importance of other sections of EN 1997-1 in the design of embankments is noted, for example:
  - The section on Fill and Ground Improvement
  - The sub-section on the Observational Method
  - The sub-section on the Geotechnical Design Report
  - The section on Supervision and Monitoring

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Geotechnical design with worked examples

eurocodes.jrc.ec.europa.eu