Refurbishment of Road Infrastructure – FE Analysis in Steep Slopes

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Need for FEM Analysis?

- **classical domain of 2D limit-equilibrium models:**
  ULS checks of the internal equilibrium in supporting structures and the external stability (sliding, overturning), e.g. LARIX, DC-WINKEL / DC-BÖSCHUNG or similar

- **investigation of 3D stress redistribution** (if needed to verify existing reinforcement for higher loads):
  shell structure models under surface tractions for earth pressure, e.g. AXISVM or similar

- **FE geotechnical analysis (2D or 3D):**
  only warranted for more complicated soil-structure interaction
  → how to find the ‘initial stress’ state?
  → how to incorporate partial safety factors?
Rem: Standard FEM Assumptions

- **Slope stability analysis:**
  - initial stress state is elastic (no plastic zones)
    - i.e. sloping angle << angle of internal friction
  - global FoS computed with \((\tan)\varphi-c\) reduction method

- **Pit excavation analysis:**
  - initial stress state in horizontal terrain, \(\lambda_x = 1 - \sin \varphi\)
  - staged excavation with characteristic material properties
    (convergence achieved by employing unloading functions)
  - dimensioning of retaining wall with factorized sectional forces
  - separate check against buckling of props etc.

→ how to achieve convergence in staged backfilling?
Ex. Double Cantilever Retaining Wall

Hand calculation of earth pressure:

Assumption 1: horizontal component acting on common ‘backface’

Assumption 2: stabilizing weight of soil column on rear cantilever
Ex. Double Cantilever Retaining Wall

Issues to be investigated:

#1: Effect of hinge between walls on earth pressure?

#2: Failure of anchor with subsequent overstressing of rock toe?

(#3:) Influence of the rock surface location on the backfill pressure?
Ex. Double Cantilever Retaining Wall

Backfill in stages: → internal load function on earth weight

→ smaller backfill space tends to reduce earth pressure

note: 10 kPa cohesion added in all cases to ease convergence
Ex. Double Cantilever Retaining Wall

ULS: → increasing earth weight and/or reducing soil strength

development of failure mechanism due to wall rotation in opposite directions
Ex. Road on Unstable Slope

**Project:** widening of road to accommodate heavier traffic

typical construction works with piling («Lehnenviadukt»)
Ex. Road in Instable Slope

Initial State: \( \rightarrow \) internal load function on earth weight (no tension) with artificial cohesion

rock debris \( \varphi = 38^\circ, c \rightarrow 10 \text{kPa} \)

moraine \( \varphi = 36^\circ, c \rightarrow 20 \text{kPa} \)

resid. FoS = 1.16 (\( \cong \) model factor)

level of existing road

strength mobilisation (without existing road)
Ex. Road in Instable Slope

Concept of model factor:

\[ R_d = 1 / \gamma_M \cdot \eta R_k \]  

where \( R_k \) = characteristic resistance (e.g. by back analysis)  
\( \eta \) = reduction for lack of mobilisation of strength  
\( \gamma_M \) = model factor for uncertainty as to conservativeness

Application to initial state:

- convergence for \( \{\phi', c'\} \) near instability is very slow *)
- not practicable to afford in every new analysis of road structure
  (as copying in Z_Soil is not possible)

→ compute with «affordable» \( \{\phi', c'\} \)
→ treat remaining FoS as \( \gamma_M \)

*) beware of Gremlins: a programming error was detected in handling internal load factors upon restart
Ex. Road in Instable Slope

Existing Road: → reduced traffic assumptions ($\alpha_{Q,\text{act}} = 0.7$), $\gamma_F = 1.3$

vertical stress [kPa]
(referenced to initial state)
Ex. Road in Instable Slope

Existing Road: \(\rightarrow\) determining FoS (for reduced traffic, \(\gamma_F = 1.3\))

\[ \text{abs. displacement [m] (referenced to initial state)} \]

\[ \text{incremental deviatoric strain} \]

\[ \text{FoS}_{\varphi-c} = 1.31 \] (independent of slope stiffness)

\[
\begin{align*}
\text{for } & E_{\text{moraine}} = 20 \text{ kPa} \\
E_{\text{rock debris}} & = 10 \text{ kPa}
\end{align*}
\]
Ex. Road in Instable Slope

Road widening: → upgrading with full traffic loads [SIA 261]

view uphill: with lane for slow traffic
Ex. Road in Instable Slope

Road widening: Solution with shallow foundation

\[ \text{FoS}_\varphi-c = 1.34 \] (with upgraded traffic loads)
Ex. Road in Instable Slope

Road widening: Solution with pile foundation

\[ \text{abs. displacement [m] (referenced to initial state)} \]

\[ \text{dito. with anchoring} \]

\[ \text{FoS}_{\varphi-c} = 1.45 \text{ (with upgraded traffic loads)} \]
Conclusions

- **Analysis of retaining walls:**
  - staged backfilling can be modelled by increasing earth weight
  - \( \varphi - c \) reduction \( \{ \varphi_k \to \varphi_d, c_k \to c_d \} \) at final stage leads to the same result as backfilling with \( \{ \varphi_d, c_d \} \)
  - \( \to \) be careful: \( \gamma_\varphi = 1.2 \), but \( \gamma_c = 1.5 \) ! [cf. Table 1 of SIA 267:2013]

- **Analysis in steep slopes:**
  - back analysis with Geologist’s data nearly always leads to instable slopes (\( c' = 0 \ldots 10 \text{ kPa} \) ?)
  - increment earth weight with fictitious \( c' \), then reduce \( c' \)
  - accept as initial state some fictitious \( c' \), assign \( \text{resid. } FoS = \gamma_M \)
  - evaluate all analysis results with \( t_{\text{initial}} \) as reference time step
  - in practice, increasing the \( FoS \) is often more important than knowing its true value (but mind \( \gamma_M \))