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SECTION DE GÉNIE CIVIL

Numerical back-analysis and future risk assessment of the Hirschigraben Landslide(s)

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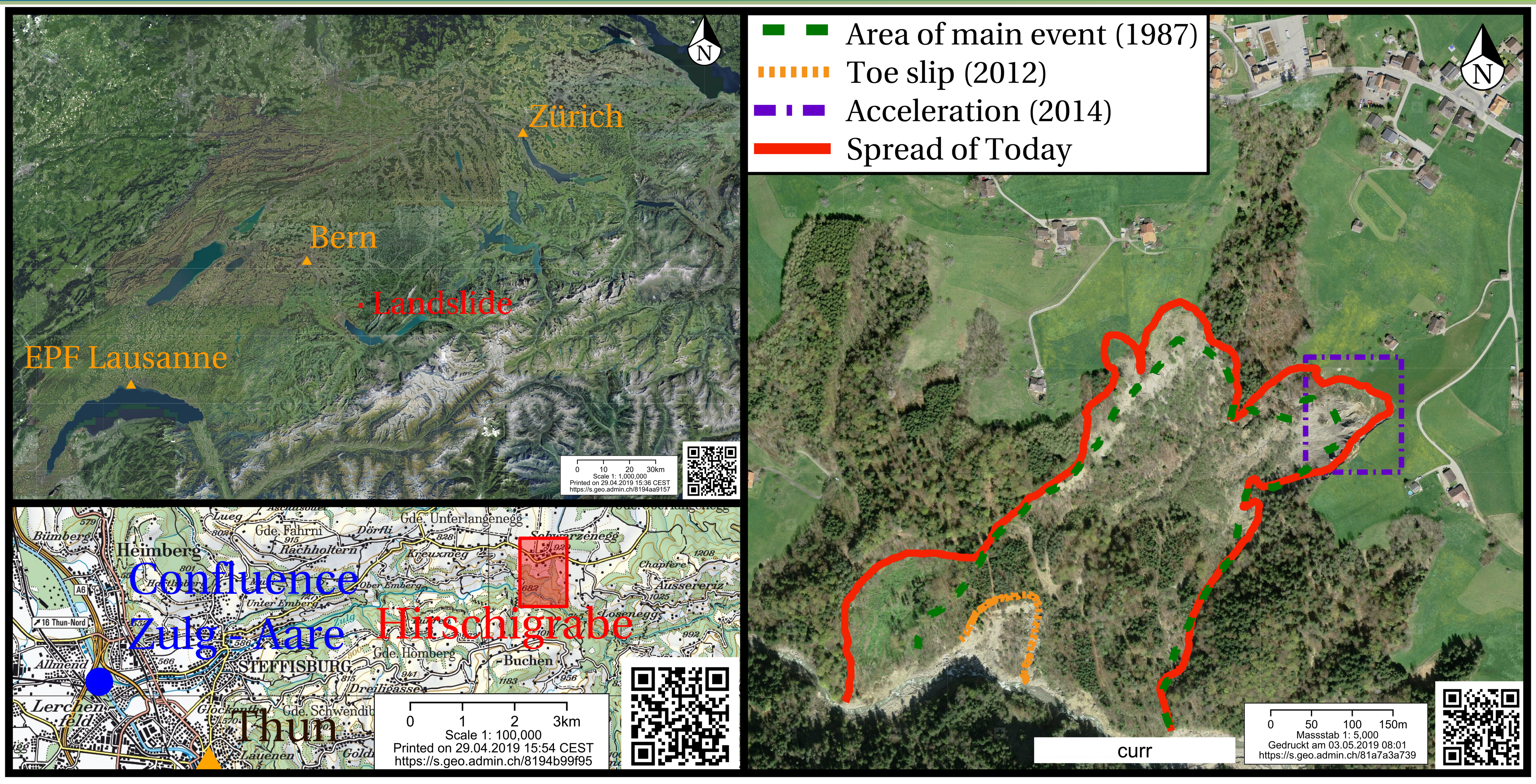
1. Landslide

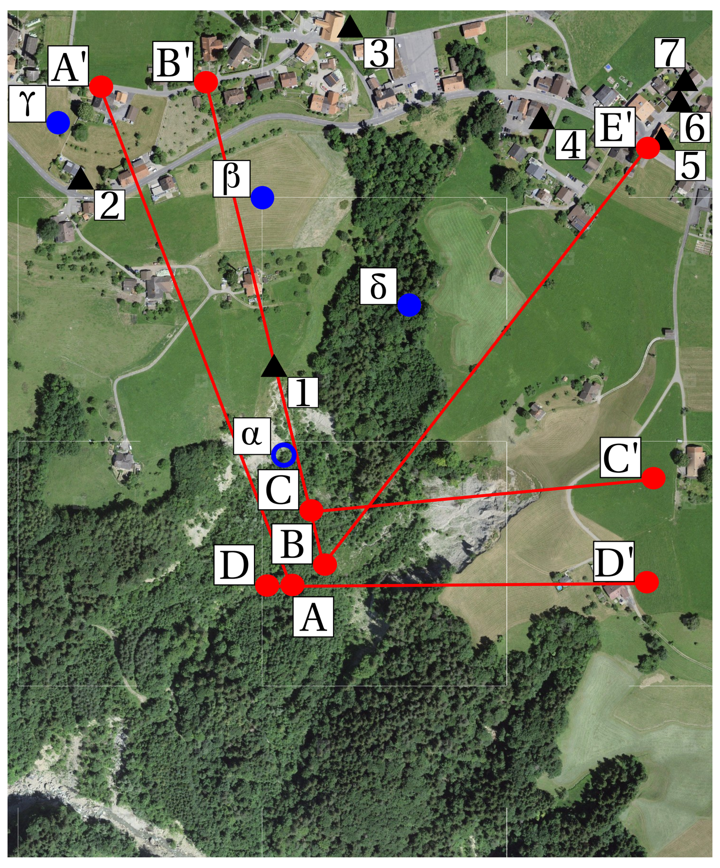


Situation of the landslide and landmarks of important phenomenons related to the event. Focus will be on the main event in 1987 (green dashed line) which has been used for the back analysis.

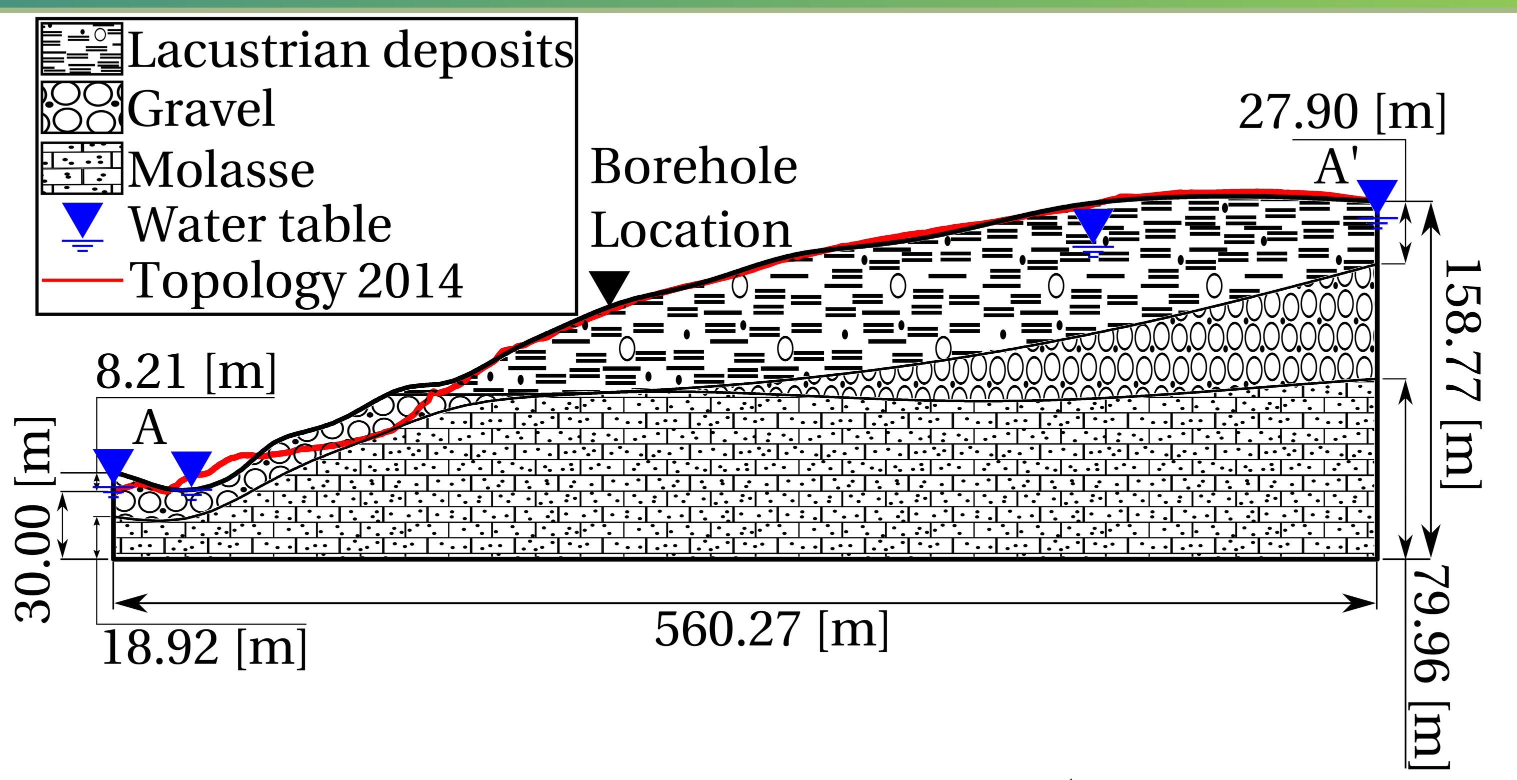
2. Motivation and objective

Motivation: The 1987 *Hirschigraben* landslide (2 to 3 Mio m^3, 10 to 12ha) was a spontaneous event. Ongoing settlements, terrain adjustment and the fear of another spontaneous event, require observation and a regular risk assessment (geodetic measurement points) of the situation.
Objectives: Generate a numerical, geological model and a setup to assess the risk for the residential buildings within the settlement cone, based on the resolution of an inverse problem with finite element limit analysis.

3. Model generation



Modelled section: indicated are borehole logs (1 - 7), sections for 2D analysis (A - A' to B - E'), springs (α to δ)



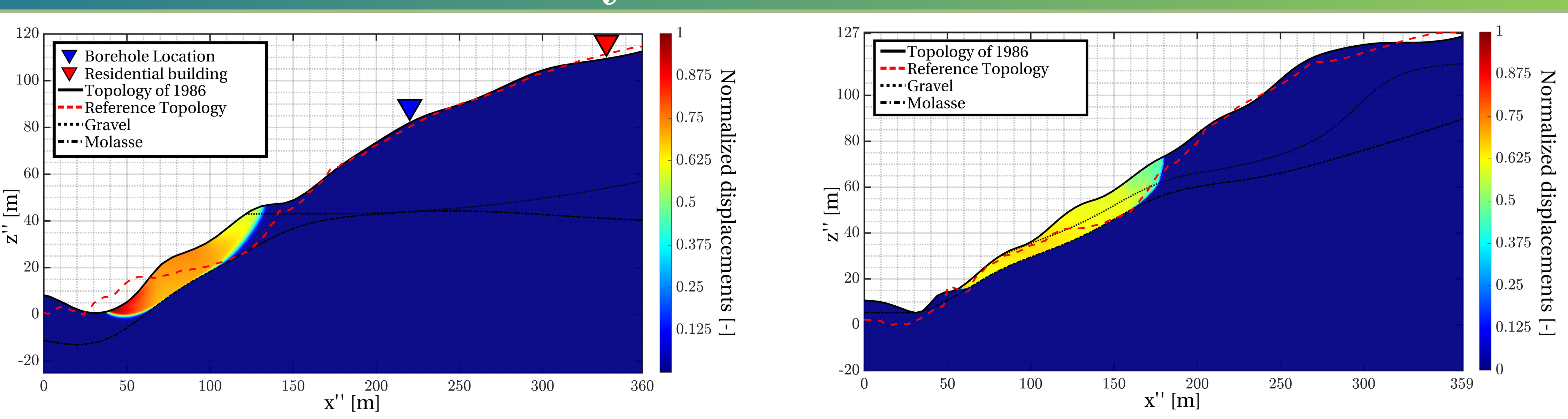
Section A - A': three formations considered (lacustrian deposits, gravel and molasse) based on borehole data, *Felsreliefkarte* [Kanton Bern] and outcrops; water table from springs, borehole logs and observations; topology recreated from ancient national map 1188 Eggiwil [Swisstopo]; Topology 2014 based on LiDAR data [Kanton Bern] acquired in 2012.

4. Inverse analysis

$$\begin{pmatrix} \mathcal{G}_m(\text{fixed}) \\ \mathcal{G}_l(\text{fixed}) \\ \mathcal{H}(\text{fixed}) \\ \mathcal{M}(\text{var.}) \\ \mathcal{B}_E(\text{fixed}) \\ \mathcal{B}_H(\text{fixed}) \end{pmatrix} \xrightarrow[\text{Section A - A'}]{\substack{SSR \\ \text{finite element} \\ \text{limit analysis} \\ \mathbf{C}}} \begin{pmatrix} \mathbf{u} \\ \sigma \\ \mathbf{p} \\ \mathbf{q} \\ \mathcal{E} \end{pmatrix} \xrightarrow{f} \begin{pmatrix} \mathbf{z_r} \\ \mathbf{V} \end{pmatrix} \rightarrow \Delta$$

with $\mathcal{G}_m$ topology, $\mathcal{G}_l$ geology, $\mathcal{H}$ hydrology and $\mathcal{M}$ material parameters, $\mathcal{B}_E$ elastic and $\mathcal{B}_H$ hydraulic boundary conditions, SSR shear strength reduction method, C constraints, $\mathbf{u}$ displacement, σ stress, $\mathbf{p}$ pore pressure, $\mathbf{q}$ flow and $\mathcal{E}$ energy dissipation fields, f an evaluation function, $\mathbf{z_r}$ the surface after rupture, $\mathbf{V}$ the volume of displaced mass and Δ the error.
Hypothesis: rigid-plasticity / Mohr-Coulomb constitutive model for all materials / SSR on all materials → ONE global security factor / hydrostatic conditions on lateral boundaries / normal displacements constrained on lateral boundaries / all displacements fixed on lower boundary / only the material parameters are varied.

5. Results of inverse analysis and validation

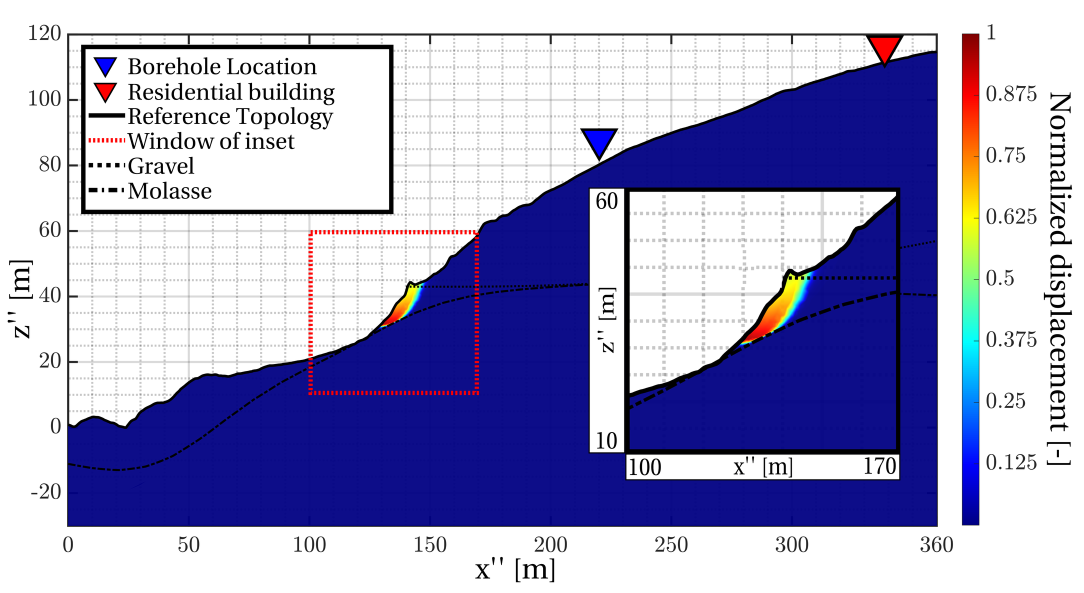


The best fit parameter combination underwent a crude sensibility analysis guiding to the adapted and retained solution with following strength parameters: $\phi'_{lac} = 35°, c'_{lac} = 7.5\,\text{kPa}, \phi'_{grav} = 10°, c'_{grav} = 10\,\text{kPa}, \phi'_{mol} = 27.5°, c'_{mol} = 500\,\text{kPa}$. Left figure shows the adapted solution on back analysis section A - A', right figure the accepted validation simulation on section C - C'.

7. Discussion

Based on a literature review and observations, a geological model was established. Using finite element, limit analysis SSR method, a back-analysis (in 2D) was performed. The results were validated on two different sections and a stability analysis (in 2D and 3D) on the current system adopted. The back-analysis highlights a unrealistically low value of gravel internal friction angle (the most sensitive parameter). The 2D stability analysis highlights, despite the insufficient values of the security factor, no alarming signs for the local population (downstream side). The 3D analysis highlights some risk for the upstream buildings upon worst case conditions. Despite the large uncertainties the model seems to be appropriate in the first order and can serve as indication for further observation.

6. Stability analysis



All simulations used the adapted parameter set. The 2D stability analysis reveals strongly insufficient security factors (around $SF \approx 0.3$). Simulations were performed with intermediate and low water tables and the adapted parameter set described previously. A worst case scenario incorporating reduced strength parameters for the lacustrian deposites ($\phi'_{lac} = 25°, c' = 7.5\,\text{kPa}$, see left figure) was performed as well. Locations of the rupture surfaces indicate no risk for the downstream population. The 3D analysis used limit equilibrium method of Janbu (right figure) with a extremely high water level (worst case). Displayed are all rupture contours with $SF < 1$. Verifying 2D observations downstream but indicating some risk on the upstream side.