The driving force of all nature. Modelling water pressure and its stability consequences on alpine bedrock slopes.

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Abstract. Hydrostatic pressure is one of the most important but still not fully understood destabilising factors of bedrock slopes. Water presence has often been recorded in major rock failures like at Piz Cengalo in 2017 but still its quantification and its effective destabilizing role remain unsolved issues in rockfall forecasting. Intensification of rainstorms due to climate change will enhance hydrostatic pressures in fractured bedrock, which will likely lead to increase in rockfall activity and connected risks for humans and infrastructures. Here we present a hydro-mechanical stability analysis of the Hochvogel summit (2,592 m AA) in the Northern Calcareous Alps. At this site, an imminent high-magnitude rockfall could destabilise up to 260,000 m³ and is therefore acutely monitored. Displacement measurements on the summit showed daily acceleration following intense precipitation. With the help of direct investigations and laboratory tests from previous studies, we implemented the Hochvogel SE slope and its mechanical parameters in the 2D Universal Distinct Element Code (UDEC). Our model shows that the presence of water columns of 10 m decreases the factor of safety (FoS) on average by 11 % and can increase the max displacement by up to 70 %. When including the effects of cleft weathering in the model, FoS < 1 can be reached. The friction angle of clefts has a key role in this destabilization process. This study provides key elements for interpreting the mechanical behaviour of this imminent rockfall in connection with hydrostatic pressures, helping to improve hazard forecasting at the Hochvogel and at similar sites.

1. Introduction
Already in the 15th century Leonardo Da Vinci knew that water is the driving force of all nature. This definitely applies also to rockfalls, where the presence of water is crucial at multiple stages. It accelerates the weathering processes and rock fatigue, it reduces shear strength, it is a triggering factor, it enhances the fluidization of material during runof, or it obstructs the path producing dangerous tsunami. Consequently, water presence often enhances the magnitude of damages [1].

Since the catastrophic failure of Vajont in 1963, the destabilizing role of groundwater on slopes has been investigated with increasing interest [2,3]. On the contrary, hydrostatic pressure in fractured bedrock and its triggering potential are rarely investigated in the field. This despite evidence from events like Piz Cengalo failure, where water columns of more decameters above the basal failure plane were registered after the disastrous event [4]. Impermeable layers, sludge or ice can seal fractured rock and promote the accumulation of water within affected rock faces during precipitation, snow- and ice melt [5,6]. Excessive water accumulation is likely to increase due to climate change related...
intensification of rainstorms [7]. Improving the understanding of hydrostatic pressure as triggering process of mass movements is essential to reduce fatalities and damages to structures in the future.

We used the 2D distinct-element model UDEC (Itasca) is here used to set up a hydromechanical model for analyzing the influence of water pressure on slope stability. Two scenarios are analyzed: in the first we gradually increase the hydrostatic pressure until a realistic value is overcome, in the second we reduce friction angles of the main clefts, to simulate the effects of joints weathering in combination with water pressure. This case study aims at answering two questions. (i) Can realistic hydrostatic pressure alone destabilize the rock slopes at our site? (ii) At which level does material weathering influence the stability in the presence of hydrostatic pressure?

1.1. Hydrostatic pressure in rock slopes
In the Mohr-Coulomb failure criterion water within a rock slope reduces the shear strength by counteracting the normal stress. The hydrostatic pressure in tension cracks equals zero at the water surface and rises vertically with increasing water depth. The uplift force of water along a sliding plane decreases linearly, vanishing at the surface of the slope face [9]. Unfortunately, the friction-reducing effect of water within joints as well as the reduction in joint cohesion is often neglected.

Water accumulation in rock discontinuities requires (i) an interconnected fracture network, (ii) punctual sealing of the former and (iii) infiltration of water. Only the simultaneous presence of these elements allows the creation of enhanced water pressure in bedrock [3,6,9]. (i) Discontinuities are the preferential flow paths of water. The general transmissivity of the whole slope and thus the possibility for water to flow depends on the spacing and aperture of its fractures. (ii) Fracture sealing can happen e.g. due to sediment sludge sealing, due to ice sealing in freezing conditions or - like at the Hochvogel - due to interstitial low-permeability layers (here marl) between fractured bedrock (dolomite). (iii) Extreme precipitation and/or accentuated melting periods produce exceptional quantities of water within few hours/days, allowing water recharge to exceed the outflow.

1.2. Rock weathering
Weathering and erosion of superficial rock causes a relief of lower layers and therefore a loosening of their structure. The newly created water paths increase the rock surface exposed to chemical and physical weathering processes. Physical weathering disintegrates rock by temperature fluctuations, changes in stress conditions and water content without altering its composition. During chemical weathering water and carbon-dioxide cause dissolution of the carbonates [9].

Mechanism and intensity of landslides are directly linked to the durability and weathering of the involved rocks. Nickmann and Kurosch [10] show that the friction angle of carbonate rocks strongly varies with the degree of weathering. In fact, intact marlstone can reach $\Phi > 40^\circ$, while the same material presents $\Phi$ between 10° and 20° in advanced weathering stages. In the field, different levels of weathering usually appear right next to each other and complicate an accurate assignment in the model.

2. Study site
Here we present a detailed hydromechanical analysis of the Hochvogel preparing high-magnitude rockfall, in the Northern Calcareous Alps at the German-Austrian border. Its summit reaches 2592 m a.s.l. and is entirely composed by main dolomite with a well pronounced banking structure from few decimeters to some meters, as shown in figure 1. The upper layers present marl interlayers that may promote accumulation of water levels in the clefts above the present shear plane. Due to lithology, the region is subject to high erosion rates and repeated rockfalls have been historically recorded. Texts from the 19th century already report a cleft on the summit, while areal images in the last decades show how this cleft is continuously expanding, announcing a possible failure soon [8].
Nowadays, the main cleft (C0) has a horizontal opening of up to 6 m, depths up to 10 m and movement rates of 1–2 mm/month. Acceleration of movement rates has been recorded during intense rainfall events in summer. 3D models generated from more than 1,500 UAV photos detected different unstable blocks that could detach independently at different times, for a total unstable mass of about 260,000 m³ [8].

![Summit of the Hochvogel with well visible the main fracture, C0 in the model. Photo taken in 2017 by A. Dietrich from N-NE.](image)

**Figure 1.** Summit of the Hochvogel with well visible the main fracture, C0 in the model. Photo taken in 2017 by A. Dietrich from N-NE.

3. Model

3.1. UDEC

The numerical model of the Hochvogel was set up using the 2D distinct-element program UDEC (Universal Distinct Element Code), a popular tool for slope stability analysis [11]. The program performs slope stability analysis of discontinuous media based on the explicit finite difference method: values of the next time step are exclusively calculated from known variables of the previous time step. When implementing water pressure within the slope, a fully coupled mechanical-hydraulic analysis is included into the rock-mechanical model.

With the help of the 3D photogrammetric model, the 2D cross-section presented in figure 2 was extracted [8]. The profile cuts perpendicular to the main cleft C0 and thus points in the expected direction of failure. Mechanically relevant clefts (C0 to C4) and the water-confining marl layer (C5) were identified. A highly simplified geometry with few coordinates was produced for the UDEC model.

It was assumed that all clefts (i) maintain the same orientation as on the surface, (ii) are intersecting and that (iii) the marl layer pervades about two thirds of the mountain. A bedding plane with dip angle
of 12° in NW direction and a joint set with a dip angle of 55° with direction S-E were identified as dominant among others in the field [12] and are implemented in the model. To reduce computation time, spacing and tracing of the joint set was increased.

**Figure 2.** On the left: picture of the Hochvogel summit with highlighted the visible clefts. Photo: A. Dietrich from S-SE. On the right: 2D geometry implemented in UDEC with clefts, obtained from a 3D model and its pole stereograph [8].

**Table 1.** Joints and rock properties chosen for the UDEC modelling.

| Properties | State     | Main dolomite | Marl and C5 | Clefts C0-C4 |
|------------|-----------|---------------|-------------|--------------|
| Joints     | Friction angle [°] | unweathered 58 | 31 | 23.4 |
|            |          | weathered 15 - 10 | 15 - 10 | 15 - 10 |
|            | Cohesion [MPa] | saturated 0.921 | 0.021 | 0 |
| Rocks      | Density [kg/m³] | 2600 | 2200 |
|            | Cohesion [MPa] | 9 | 0.03 |
|            | Angle of internal friction [°] | 41 | 25 |
|            | Bulk modulus [MPa] | 23 000 | 13 420 |
|            | Shear modulus [MPa] | 20 250 | 8 240 |
|            | Tensile strength [MPa] | 11.5 | 7.3 |

**3.2. Parameters and scenarios**

Main rock and joint properties have been obtained from literature and with measurements both in the field and in the laboratory including JCR/JCS measurements, uniaxial compressive strength tests and shearing tests [13,14]. The values used for the modelling can be seen in table 1.

Two scenarios are here presented: in the first analysis we focused only on consequences of hydrostatic pressure on stability. This has been accomplished by introducing a column of water of 10 m, considered realistic in this environment, and then increasing the value to 20 m and 30 m, which are supposed to be possible only during extreme events. The pore pressure distribution inside the slope for the 30m scenario is shown in figure 3.
On the contrary, in the secondary scenario we investigated the influence of the angle of friction of the joints on the slope stability. Despite the intensive investigation of rock and joint properties, heterogeneity and weathering do not always allow the choice of a single value. Therefore, we stepwise reduced the friction angle of the marl layer and the cleft C5 ($\Phi_M$) and of the clefts C0–C4 ($\Phi_C$), modelling the slope stability first without water and then with 10 m of water column. For $\Phi_M$, laboratory tests deliver a value of 31°, which was used as starting value. Considering weathering, this angle has been reduced to 15° and then to 10°, values reported for highly weathered zones [10]. Three different values have been selected for $\Phi_C$: 23.4° from [15], 15° as an intermediate value and 10° as the lowest value found in literature for limestone with interbedded marl [16].

4. Results & Discussion

The results are evaluated using the factor of safety (FoS) and the maximum displacement. Analyzed models are classified with three numbers, X-Y-Z, where X represents the column of water in meters, Y is $\Phi_M$ and Z corresponds to $\Phi_C$.

4.1. Destabilization due to water pressures

As it can be seen from table 2, in the primary scenario the presence of water pressures in the Hochvogel model has limited effects. In fact, when considering the initial parameters $\Phi_M = 31°$ and $\Phi_C = 23.4°$, the FoS reduces by 24 % but the slope is still stable with a final FoS of 1.33 even with an extreme water column. In agreement to this, the maximum displacement is increasing only by 0.5 mm, a neglectable effect considering the amount of water included. Knowing from measurements on site that the instable masses at the Hochvogel are reacting to high-intensity precipitation with temporary strong acceleration, we hypothesize that the chosen initial parameters for marl and clefts are not appropriate to reproduce the real condition.

Table 2. Results from UDEC for the first scenario, where water column is gradually increased from 0 m to 30 m, maintaining the friction angle values of the unweathered state.
4.2. Destabilization due to water pressure and reduction of the friction angle

The results of the second scenario (figure 4) show how a reduction of $\Phi_M$ and $\Phi_C$ leads to important changes in the stability: a FoS < 1 can be reached even without the presence of water (model 0-15-10 and 0-10-10). Over all nine models that have been tested in this study, the application of a hydrostatic pressure comparable to a water column of 10 m produces an average reduction of the FoS by 11 %, which can be crucial if the sliding masses are already at the border of instability. An example is the model 0-10-15 with a FoS > 1 compared to the model 10-10-15 with a FoS < 1. Different combinations of parameters can deliver similar FoS, for example x-31-10 and x-15-15, which makes it hard to identify which parameters are best fitting to reality.

A general growth in maximum displacement is obtained even without water when the angles of friction reduce. By adding 10 m water columns into the models, displacement increase up to 70 % with $\Phi_C = 10^\circ$. Increases between 8 % and 25 % are recorded for $\Phi_C = 15^\circ$ and smaller than 6 % for the models with the biggest $\Phi_C = 23.4^\circ$. Probably due to the steeper inclination of C0-C4 compared to the Marl Layer, $\Phi_C$ has a stronger destabilizing effect compared to $\Phi_M$, as it can be seen also from the FoS. E.g., models x-10-23 show FoS bigger than 1.4, with water 1.2, while in models x-31-10 the FoS reaches values smaller than 1.2, with water 1.1.

![Figure 4](image.png)

**Figure 4.** On the left: factor of safety of the model. On the right: maximum displacement. In green the models without water, in blue those with 10 m water. The percentage is given for the change from the model without water to the one with water.

4.3. Limitations

We performed a 2D analysis of a 3D slope: the choice of the profile has significant effects on modelling results. In a 2D state the fundamental assumption is that there are no deformations or displacements in the direction orthogonal to the model, whereas in the reality we cannot exclude them. This bi-dimensional model helps deciphering the destabilizing power of water; a 3D model would, in addition, allow better understanding the dynamic of different potentially sliding blocks. Still, great
uncertainty in the model geometry lies in the extension of the clefts and of the marl layer inside the mountain, that can only be estimated. This would be amplified in a 3D modelling.

A sensitivity analysis of the parameters obtained in the field and laboratory (not shown here) indicate that $\phi_M$ and $\phi_C$, together with the joint cohesion of marl can strongly influence the modelling results. For all other parameters, changes were not significant. Although friction angles of $10^\circ$ for weathered marlstone and saturated marly limestone can be found in literature, these values might be hard to measure at this location. Therefore, they must be interpreted as extreme conditions that provides information on the behavior of Hochvogel at its very stability limit.

Lastly, trying to express the state of a model with only a number (e.g. FoS, displacement) is always a strong simplification but it is necessary for comparison.

5. Conclusions

Instruments at the summit of the Hochvogel record acceleration in displacement rates connected with intense precipitations. We collected the available information and implemented a 2D distinct-element model that allows testing the influence of hydrostatic pressures in this situation.

The presence of hydrostatic pressure alone is not destabilizing the slope with the chosen initial rock/joint properties, even when water reaches extreme levels. Since displacement measurements at the Hochvogel are sensitive to precipitation events, we postulate that the joints’ and marl’s angle of friction are additionally reduced by weathering, as shown by literature [10]. Including the variation of these parameters, we obtain strong reductions of the FoS up to failure. The angle of friction of clefts has a stronger destabilizing effect compared to the angle of friction of marls and therefore it can be expected that its decrease controls the equilibrium at the Hochvogel. The presence of 10 m water column in the models reduces FoS on average of $10\%$, almost independent of the other parameters. This water pressure is considered realistic and together with even just a moderate reduction of the friction angle, it can lead the Hochvogel very close to failure.

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