

Appendix. Modelling of landslides in a scree slope induced by groundwater and rainfall

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1. Field and instrumentation location

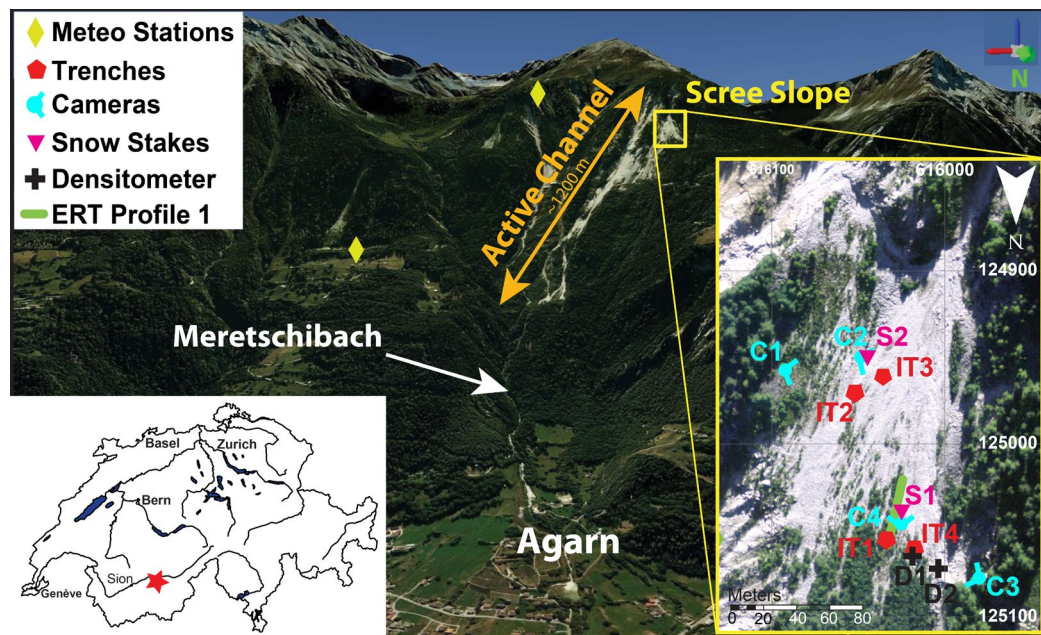


Figure S.1. Overview of the field area, located in canton Valais, Switzerland (star on small map). The image looking south shows a view of Agarn, situated on the Rhone valley floor and the Meretschibach catchment on the mountain slopes behind. The most active area within the catchment can be divided into an active channel and a scree slope. The weather stations (yellow diamonds) are located at 1370 m.a.s.l. (IGT) and 2220 m.a.s.l. (WSL). The right image shows an enlargement of the scree slope (yellow rectangle) with the locations of the instrumented trenches (IT1-IT4), the ERT profile on which the monitoring was performed, snow stakes (S1-S2), densitometer measurements (D1-D4) and cameras (C1-C4). Lucas et al. (2017) <https://doi.org/10.1016/j.enggeo.2016.11.018>

2. Physical model

a. Radial g level in model

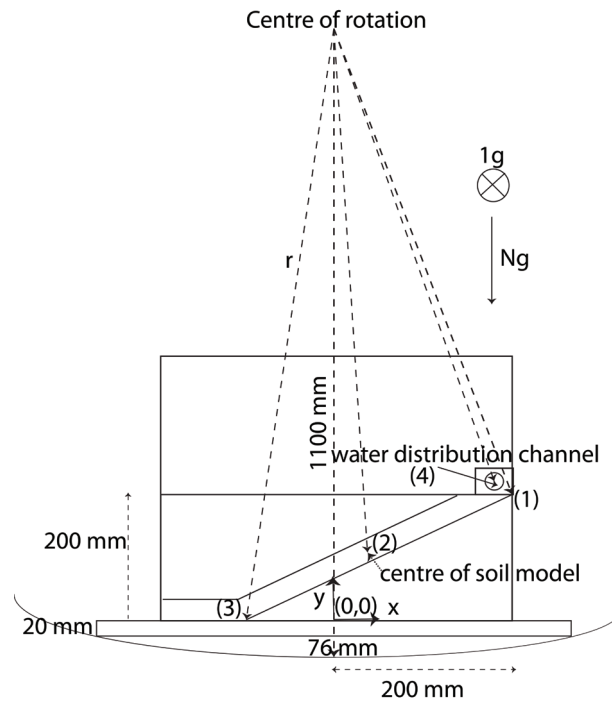


Figure S2. Sketch of model box in centrifuge, (1) top of slope, (2) centre of soil model, (3) bottom bedrock, (4) centre of water distribution system.

Tilting of bedrock to overcome 1g component for more uniform flow across the slope.

Table S1. Location of reference points.

	Radius (mm)	y _g (mm)	x _g axis (mm)	α (°)
1	828.50	804.00	200.00	13.97
2	919.23	918.74	30.00	1.87
3	1005.55	1004.00	-55.98	3.18
4	809.27	789.00	180.00	12.85

Conditions

- At the centre of the soil model $N=50$

Radius centre of the model $r=919.23$ mm

$$w = \sqrt{\frac{Ng}{r}} \text{ (rad/s)}$$

$$N = \frac{w^2 * r}{g} \text{ (-)}$$

$$w = 23.10 \Rightarrow rpm = w * \frac{60}{2\pi} = 220.58 \left(\frac{rad}{s}\right)$$

Calculation tilted in mm

$$\text{Tilted (mm)} = d * \cos \alpha$$

$$\text{with } d = \frac{400}{N}$$

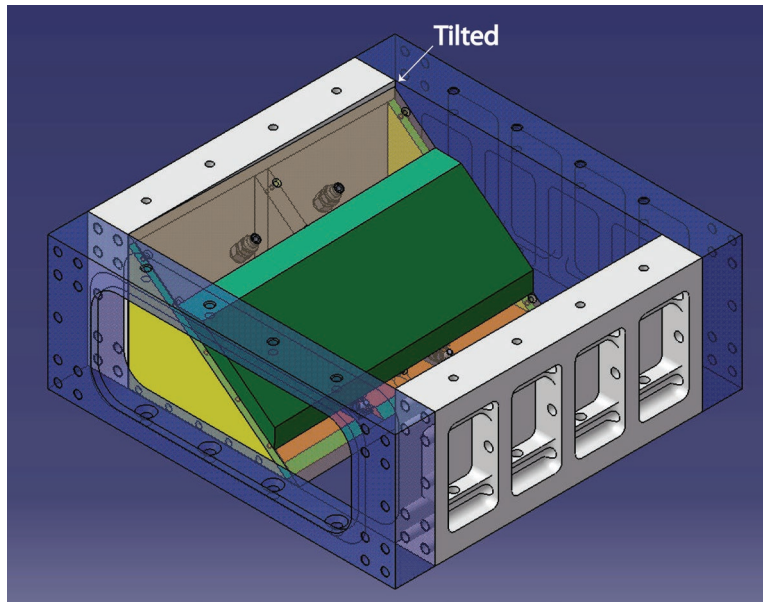


Figure S3. 3D sketch with bedrock step and tilting of bedrock plate (after H. Buschor 2018).

b. Bedrock steps and bedrock slope geometry

Bedrock step geometry

Tables S2, S3 and Figures S4-S5 show the 4 cases of bedrock step geometry (model scale). The tilted bedrock geometry is reflected in the wall side (opposite to the plexiglas). Therefore, the geometry is shown for both sides of the box (plexiglas and wall sides).

Table S2. Cases of bedrock step geometry side 1 (plexiglas)

cases	h (mm)	y (mm)	y/h (-)	X ₁ (mm)	X ₂ (mm)	X ₁ /X ₂ (-)
1	30.00	15.00	0.50	29.40	61.80	0.48
2				136.20	168.55	0.81
3	30.00	22.50	0.75	13.30	61.80	0.22
4				120.00	168.55	0.71

Where:

h: Soil thickness

y: Height of bedrock step

X₁: Length at the top of bedrock step

X₂: Length at the base of bedrock step

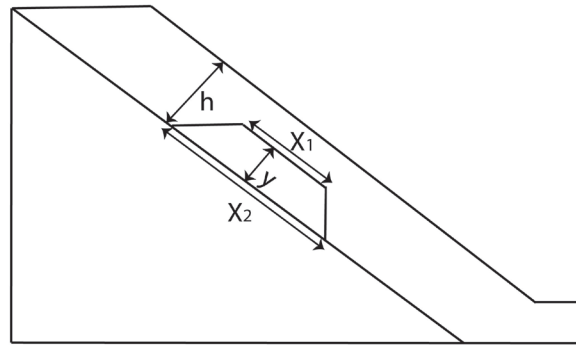


Figure S4. Sketch geometry model side 1 (plexiglas)

Table S3. Cases of bedrock step geometry side 2 (wall)

cases	h (mm)	y (mm)	y/h (-)	X ₁ (mm)	X ₂ (mm)	X ₁ /X ₂ (-)
1	30.00	15.00	0.50	29.40	61.80	0.48
2				136.20	168.55	0.81
3	30.00	22.50	0.75	13.30	61.80	0.22
4				120.00	168.55	0.71

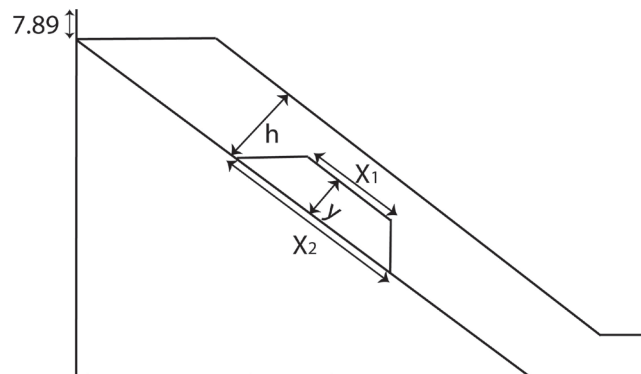


Figure S5. Sketch geometry model side 2 wall

Slope geometry

Tables S4, S5 and Figure S6 show the slope geometry (model scale).

Table S4. Geometry bedrock side 1 (plexiglas) with 4 cases of bedrock step.

geometry	h (mm)	y (mm)	y/h (-)	X ₁ (mm)	X ₂ (mm)	a (mm)	b (mm)	L ₁ (mm)	L ₂ (mm)	L ₃ (mm)	L ₄ (mm)	L ₅ (mm)	length slope bedrock (mm)
1	30.00	15.00	0.50	29.40	61.80	149.80	113.20	25.50	19.00	20.60	11.70	185.20	324.82
2				136.20	168.55	91.74	64.50					180.50	
3	30.00	22.50	0.75	13.30	61.80	148.00	115.00	38.20	28.50	30.90	17.50	185.60	324.82
4				120.00	168.55	91.74	64.50					182.60	

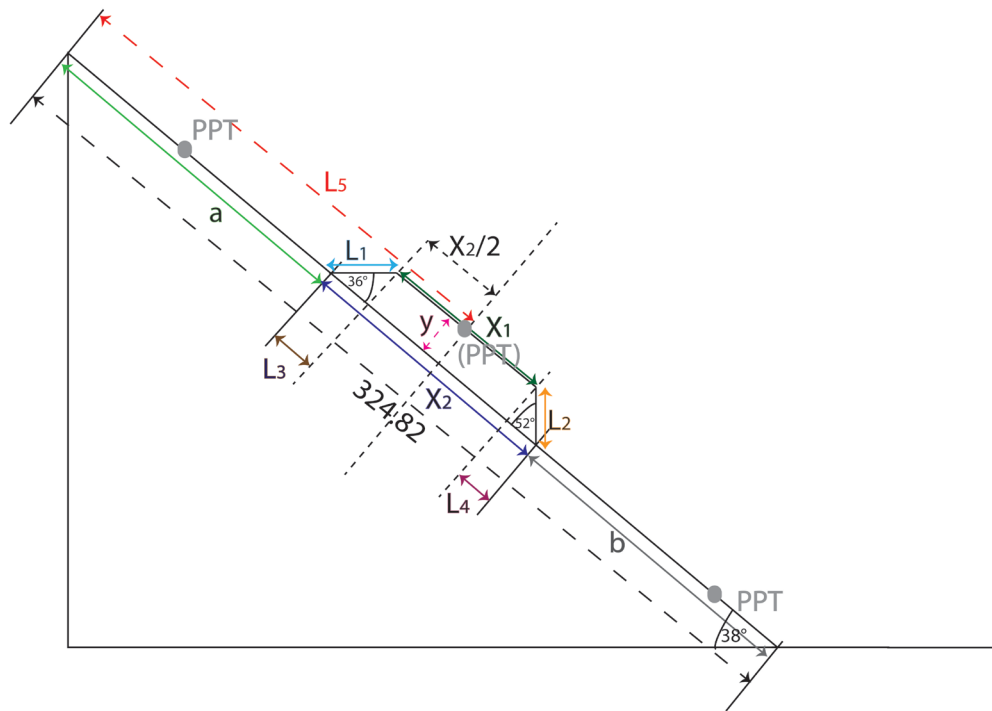


Figure S6. Sketch with geometry of slope and bedrock step

Table S5. Geometry bedrock step side 2. (Wall) with 4 cases of bedrock step

geometry	h (mm)	y (mm)	y/h (-)	X ₁ (mm)	X ₂ (mm)	a (mm)	b (mm)	L ₁ (mm)	L ₂ (mm)	L ₃ (mm)	L ₄ (mm)	L ₅ (mm)	length slope bedrock (mm)
1	30.00	15.00	0.50	29.40	61.80	149.80	100.30	25.50	19.00	20.60	11.70	185.20	311.98
2				136.20	168.55	91.50	51.90					180.20	
3	30.00	22.50	0.75	13.30	61.80	148.00	102.20	38.20	28.50	30.90	17.50	185.60	311.98
4				120.00	168.55	91.50	51.90					182.50	

c. PPT locations x 3

Figures S7-S8 show the PPTs location observed from the plexiglas and wall sides. Figure S9 show the PPTs location from a frontal view of the bedrock plate. All dimensions in model scale.

Sampling rates were 10 Hz for PPTs model a: 11325 (PPT1), 6437k (PPT2), 11322 (PPT2), 11321 (PPT4), model b: 11189 (PPT1), 11391(PPT2, 4), 6430k (PPT2), 11401 (PPT4), 9448(PPT6) and 1 Hz for the remaining six model a: 9373(PPT3), 9355 (PPT5), 9356 (PPT6), and model b: 9357(PPT2), 11193 (PPT3), 9359 (PPT5).

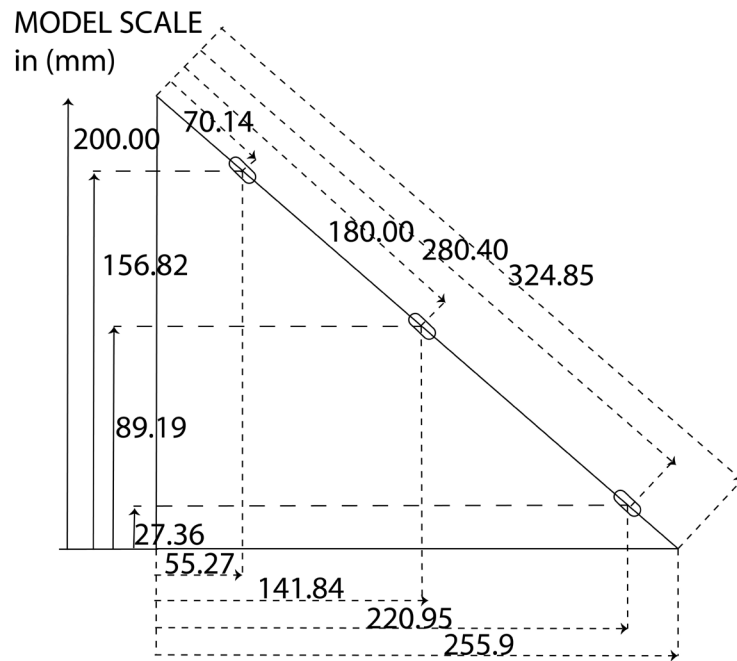


Figure S7. Sketch with geometry of PPT location in bedrock view side 1 (Plexiglas)

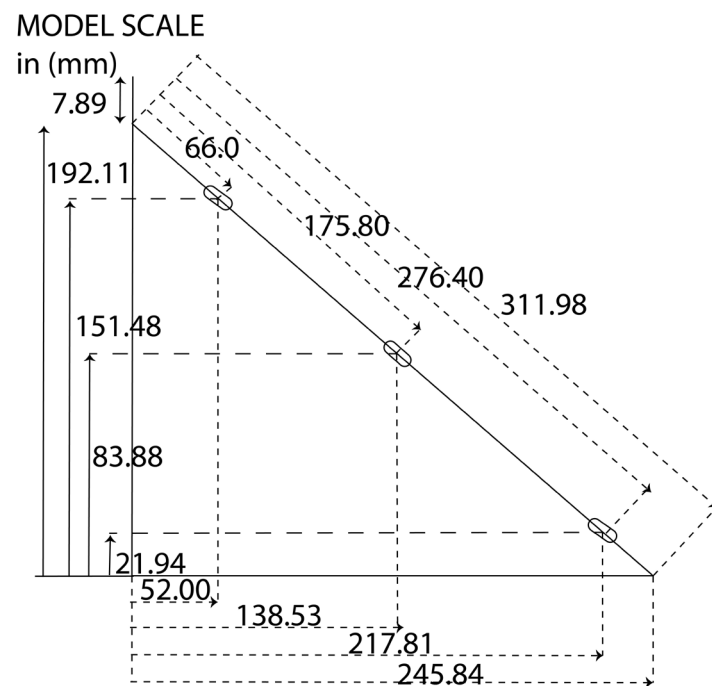


Figure S8. Sketch with geometry of PPT location in bedrock view side 2 (wall)

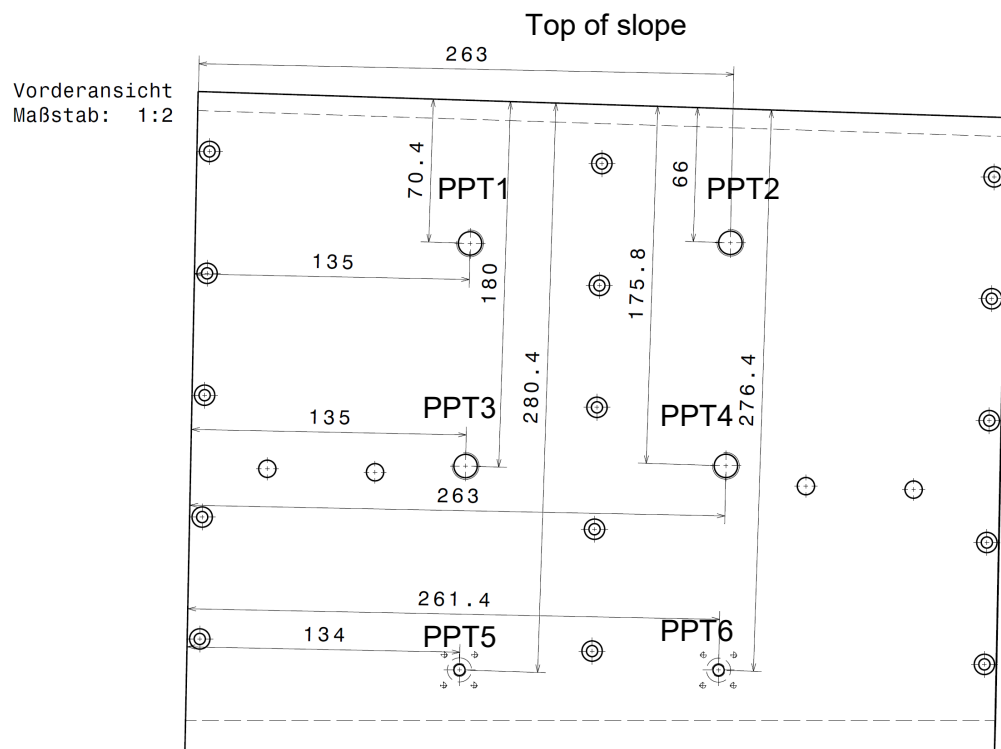
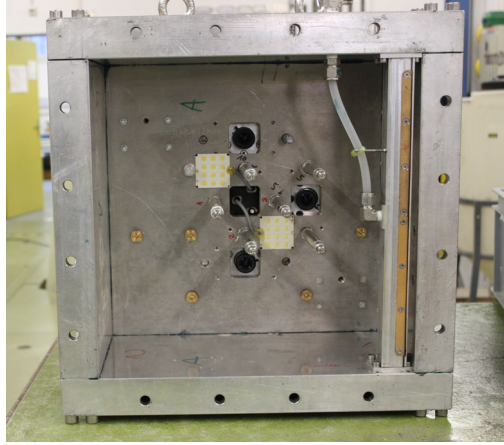
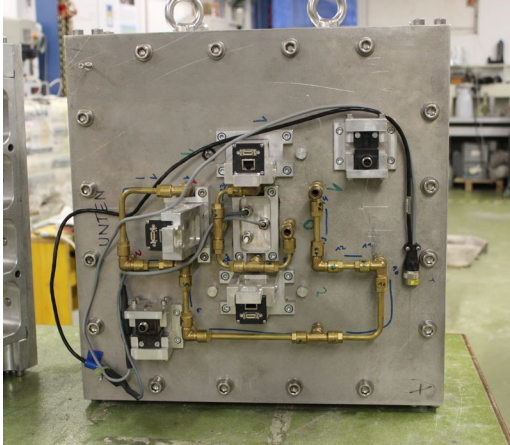


Figure S9. Sketch with geometry of PPT location in bedrock top view

d. Climate chamber

The climate chamber (Figure S10) is the top box container placed on top of model container, which contain the rain nozzles, Groundwater distribution system and the photography cameras. Figure S10, show for models a, b the interior of the climate chamber: nozzles and cameras, and the exterior: cameras and inner and outer rain pipe channels. Figure S11 show the position of model container and climate chamber in the centrifuge.

	Nozzles	Cameras
Box a		

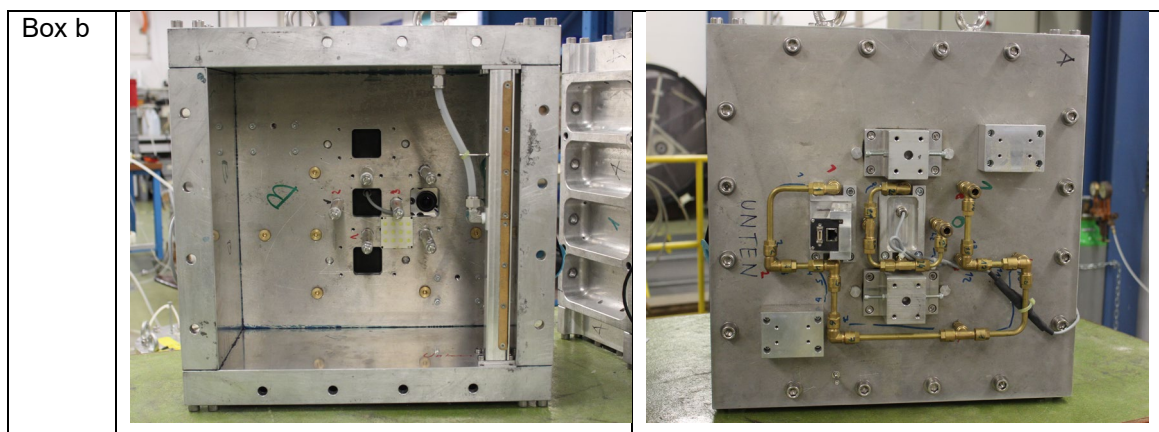


Figure S10. Climate chamber of models a and b. Frontal view of nozzles, cameras, inner and outer channels for rainfall.

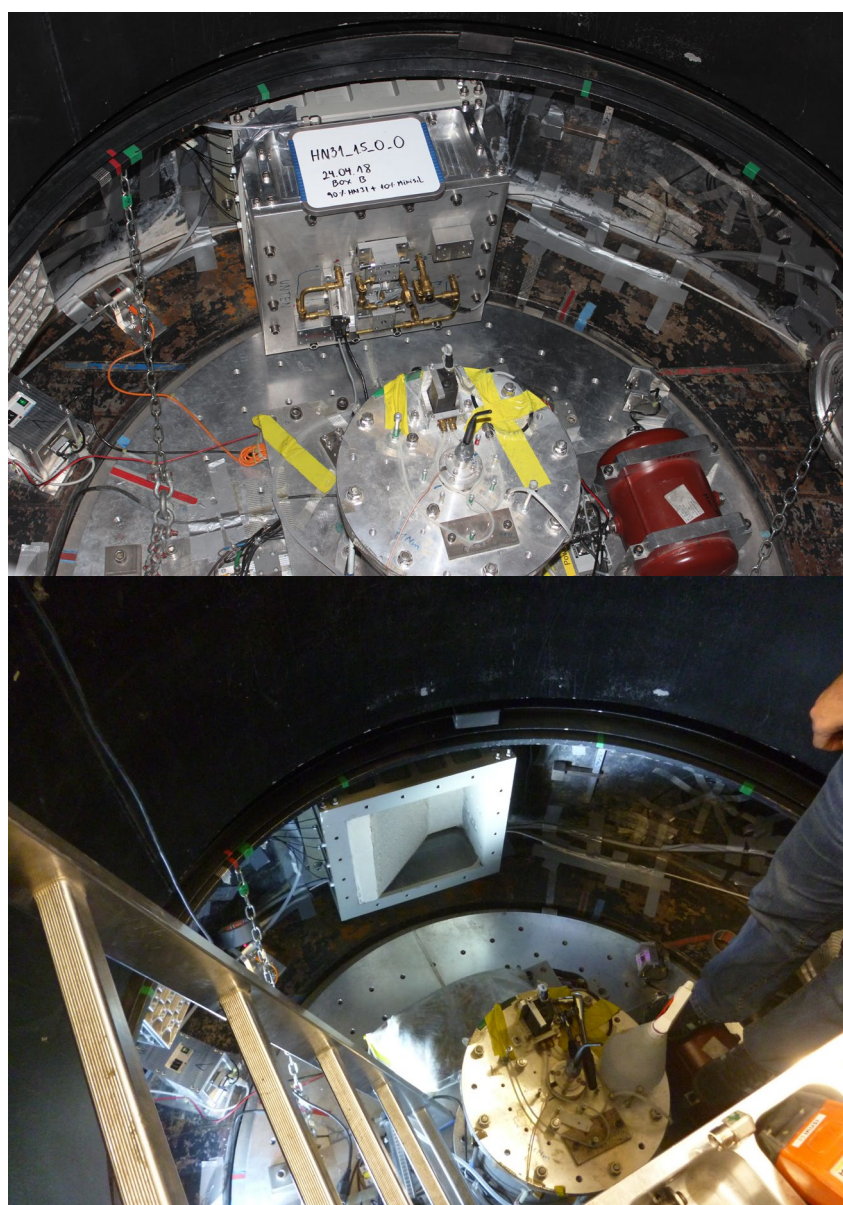


Figure S11. Climate chamber and model box in the drum centrifuge in testing position.

e. Rainfall nozzles

The rainfall is applied over the slope by means of non-uniformly distributed nozzles (Figure S12), which have been extended below the strong box roof to a certain height above the slope surface to reduce the Coriolis effect. The fine fraction of the soil can be washed out if the nozzles are too close to the soil surface. Therefore, the rainfall was sprayed into the chamber through aluminium extension tubes of 5 to 10 cm in length, so that the rainwater emerged as a spray within a range of 18.9-26.7 cm and 13.9-21.7 cm respectively, above the ground surface.

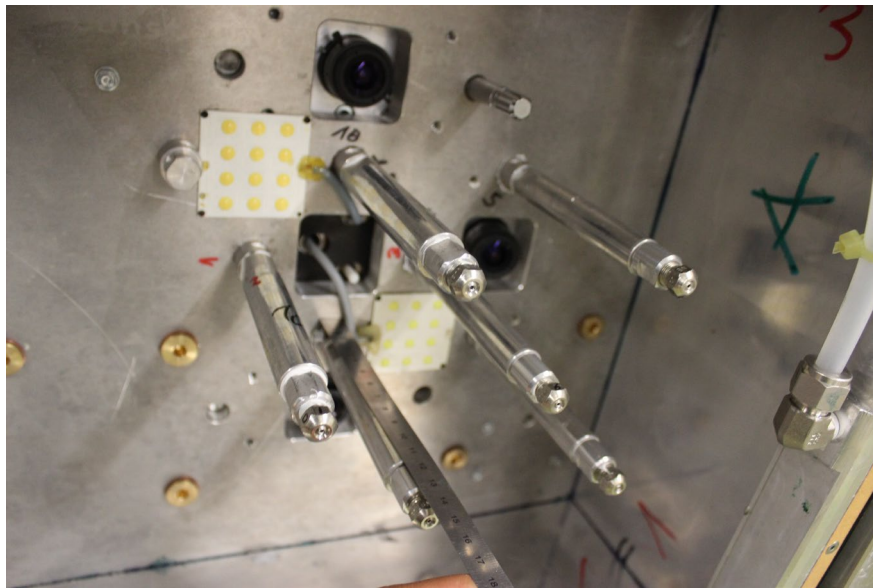


Figure S12. Rain nozzles six MW7 with 10 cm extension.

The rain intensity per nozzle was calculated measuring their respective flow (mL/min) Figure S13 and area (Table S6), depending on length extension. Assuming that each nozzle rain spray overlapped the soil surface, the total rainfall intensity in model scale (mm/h) (Table S7) is estimated as the addition all intensities. Applying scaling laws the rain intensity at prototype is estimated as N times smaller than the model scale (Askarinejad, 2013) (Table S8).

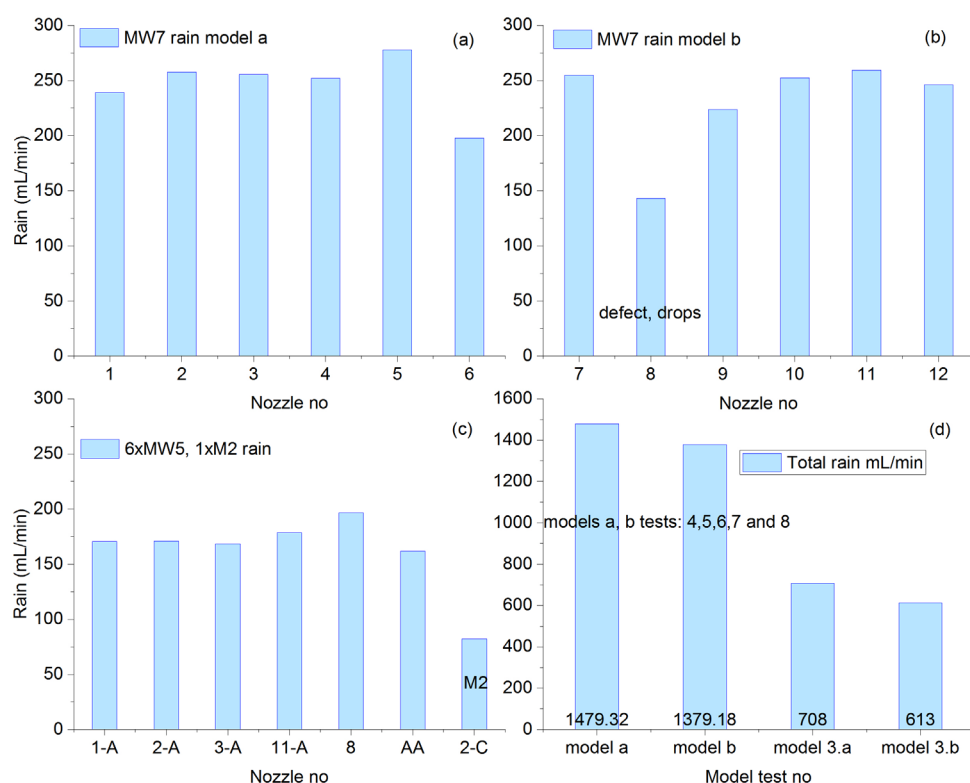


Figure S13. Rain: a) nozzle model a (tests:4-8), b) nozzle model b (tests 4-8), c) nozzle tests 3a,3b, d) total rain per model and test.

Table S6. Calculation rainfall area.

nozzle	distance nozzle to soil average (cm)	length nozzle extension (cm)	time (min)	average radius (cm)	area (cm ²)	average (cm ²)
M2	17.80	10.00	1.00	16.00	804.25	780.00
M2				15.50	754.77	
M2	22.80	5.00	1.00	18.00	1017.88	911.00
M2				16.00	804.25	
MW5	17.80	10.00	1.00	33.00	3421.19	3526.00
MW5				34.00	3631.68	
MW5	22.80	5.00	1.00	35.00	3848.45	3848.00
MW5				35.00	3848.45	
MW7	17.80	10.00	1.00	35.00	3848.45	3848.00
MW7				35.00	3848.45	

Table S7. Calculation of rainfall intensity per nozzle.

Nozzles	Average flow (mL/min)	Average flow (cm ³ /hr)	Tube extension (cm)	Average area infiltration (cm ²)	Rain intensity model scale (cm/h)	Rain intensity model scale (mm/h)	Rain intensity prototype scale (mm/h)
MW5	176.99	10619.51	5.00	3848.00	2.76	27.60	0.55
MW5	176.99	10619.51	10.00	3526.00	3.01	30.12	0.60
M2	82.28	4936.60	5.00	911.00	5.42	54.19	1.08
M2	82.28	4936.60	10.00	780.00	6.33	63.29	1.27
MW7 model a	246.55	14793.20	10.00	3848.00	3.84	38.44	0.77
MW7 model b	229.86	13791.80	10.00	3848.00	3.58	35.84	0.72

Table S8. Calculation of rainfall intensity per test.

Test	Nozzle	Tube extension (cm)	Rain intensity total model scale (mm/h)	Rain intensity total prototype scale (mm/h)
test 3a	2xMW5	5.00	55.19	1.10
	2xMW5	10.00	60.24	1.20
		total	115.43	2.31
test 3.b	1xM2	5.00	54.19	1.08
	1xMW5	5.00	27.60	0.55
	2xMW5	10.00	60.24	1.20
		total	142.02	2.84
Model a tests 4-8	6xMW7	10.00	230.66	4.61
Model b test 4-8	6xMW7	10.00	215.05	4.30

f. PPT zero offset measurements

Zero offset was measured for every PPTs at different dates (Figure S14) in the laboratory.

The differences in zero offset between dates for a same PPT, could be due to a variation in the atmospheric pressure changes, this is shown in Figure S15. Were atmospheric pressure QFE (hPa indicating the atmospheric pressure (Q) adjusted to mean sea level and certain field elevation (FE). Data obtained from automatic weather station in Mythenquai (Zürich, Switzerland) located at 406 m.a.s.l. website <https://www.tecson-data.ch/zurich/mythenquai/>

Zero offset measurements were not measured between consecutive tests which were performed in a row in a limited period of time. During this time PPTs were kept carefully moist and the measurement from zero offset from a closer test for this PPT was adopted (Table S9).

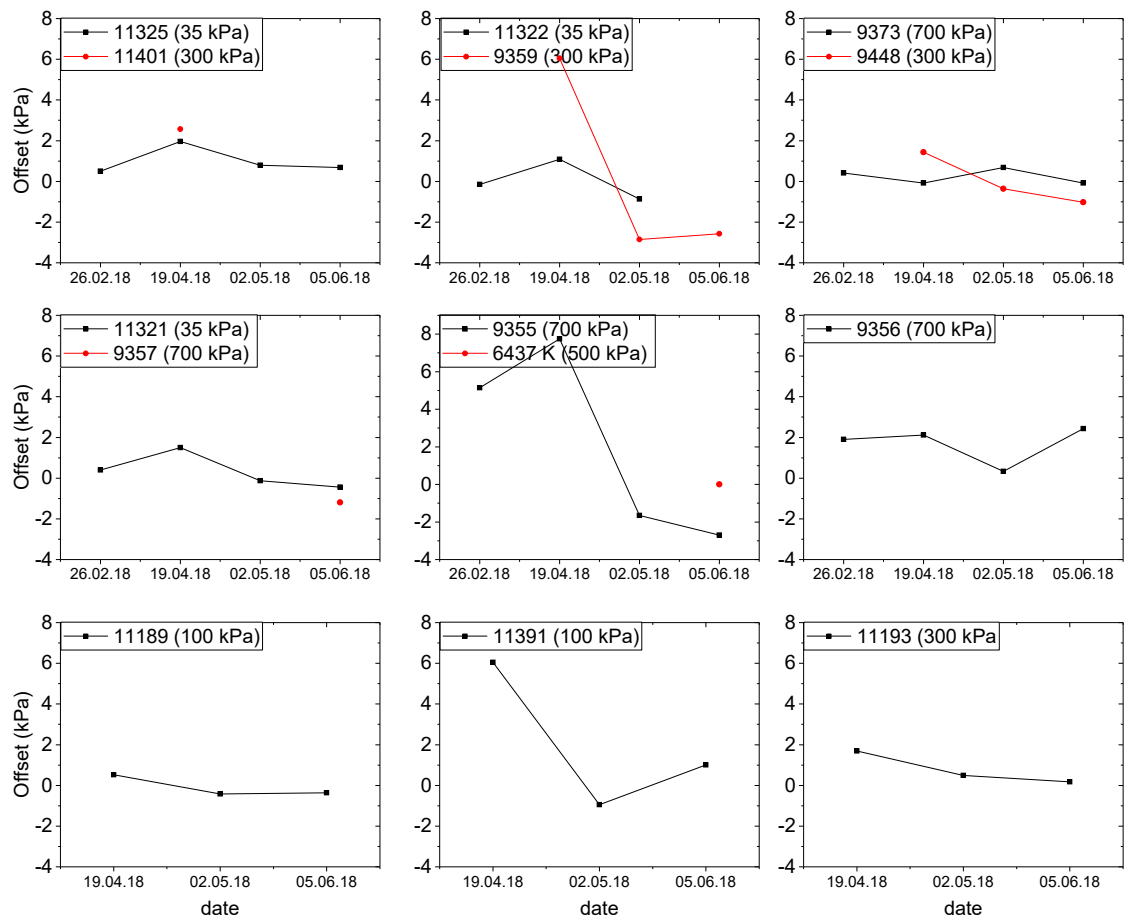
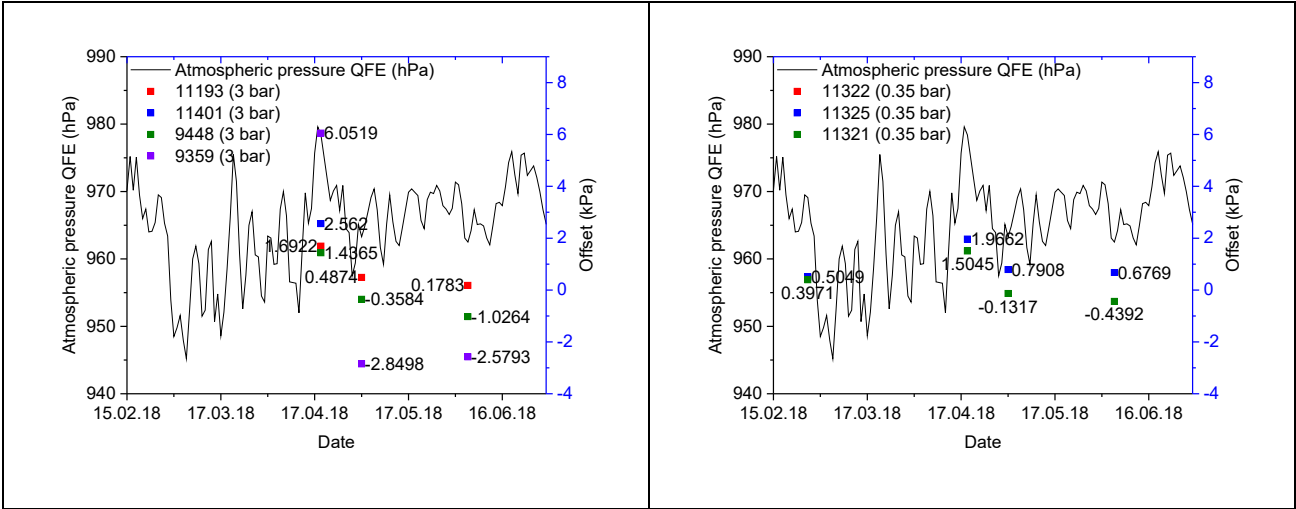


Figure S14. PPT's zero offset measurements by date in parenthesis the range of measurement in kPa.



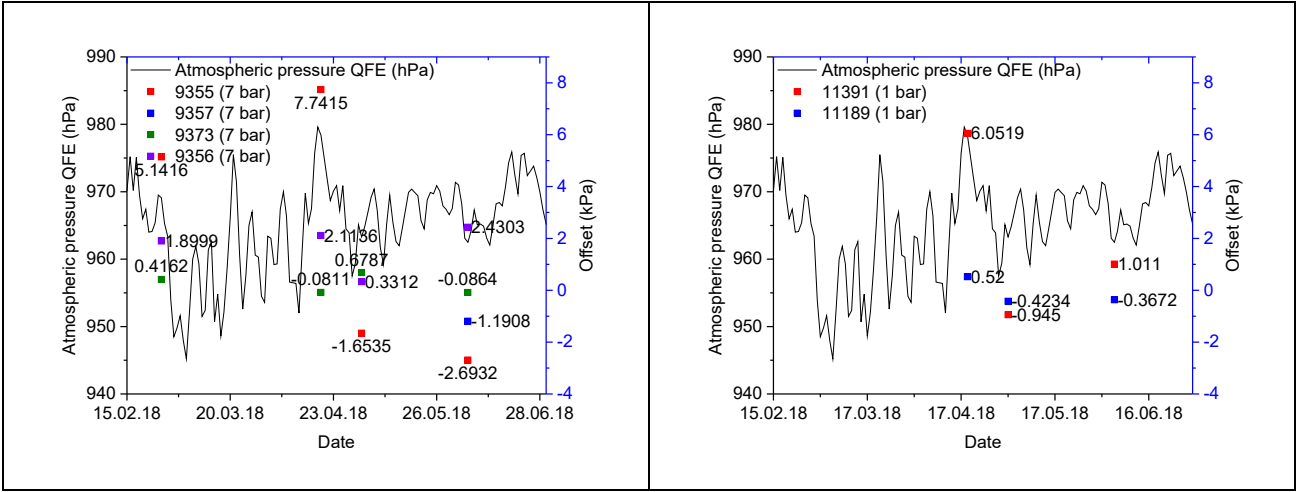


Figure S15. PPTs zero offset measurements by date in parenthesis the range of measurement in kPa and variation of atmospheric air pressure.

Table S9 zero offset applied to PPTs in test.

test	upslope PPT (#)	zero offset (kPa)	midslope PPT (#)	zero offset (kPa)	downslope PPT (#)	zero offset (kPa)	date offset test	zero offset adopted
proof	11325	0.5049	9373	0.4162	9355	5.1416	26.02.2018	26.02.2018
	11322	-0.1502	11321	0.3971	9356	1.8999		
1a	11325	1.9662	9373	-0.0811	9355	7.7415	19.04.2018	19.04.2018
	11322	1.0805	11321	1.5045	9356	2.1136		
1 b	11189	0.52	11193	1.6922	9359	6.0519		
	11391	6.0519	11401	2.562	9448	1.4365		
2a	11325	0.7908	9373	0.6787	9355	-1.6535	02.05.2018	02.05.2018
	11322	-0.8628	11321	-0.1317	9356	0.3312		
2b	11189	-0.4234	11193	0.4874	9359	-2.8498		
	6430K		11391	-0.945	9448	-0.3584		
3a	11325	0.7908	9373	0.6787	9355	-1.6535	(-)	02.05.2018
	11322	-0.8628	11321	-0.1317	9356	0.3312		
3b	11189	-0.4234	11193	0.4874	9359	-2.8498		9357 (05.06.2018)
	9357	-1.1908	11391	-0.945	9448	-0.3584		
4a	11325	0.7908	9373	0.6787	9355	-1.6535	(-)	02.05.2018
	11322	-0.8628	11321	-0.1317	9356	0.3312		
4b	11189	-0.4234	11193	0.4874	9359	-2.8498		9357 (05.06.2018)
	9357	-1.1908	11391	-0.945	9448	-0.3584		
5a	11325	0.6769	9373	-0.0864	9355	-2.6932	(-)	05.06.2018
	11322	-0.8628	11321	-0.4392	9356	2.4303		11322 (02.05.2018)
5b	11189	-0.3672	11193	0.1783	9359	-2.5793		
	9357	-1.1908	11391	1.011	9448	-1.0264		
6a	11325	0.6769	9373	-0.0864	9355	-2.6932	(-)	05.06.2018
	6437K	0.0041	11321	-0.4392	9356	2.4303		
6b	11189	-0.3672	11193	0.1783	9359	-2.5793		
	9357	-1.1908	11391	1.011	9448	-1.0264		
7a	11325	0.6769	9373	-0.0864	9355	-2.6932	05.06.2018	05.06.2018
	6437K	0.0041	11321	-0.4392	9356	2.4303		
7b	11189	-0.3672	11193	0.1783	9359	-2.5793		
	9357	-1.1908	11391	1.011	9448	-1.0264		
8a	11325	0.6769	9373	-0.0864	9355	-2.6932	(-)	05.06.2018
	6437K	0.0041	11321	-0.4392	9356	2.4303		
8b	11189	-0.3672	11193	0.1783	9359	-2.5793		
	9357	-1.1908	11391	1.011	9448	-1.0264		

g. Water distribution system for GW flow

Figure S16 shows the water distribution system located in the climate chamber and used in the centrifuge tests to apply the groundwater flow.

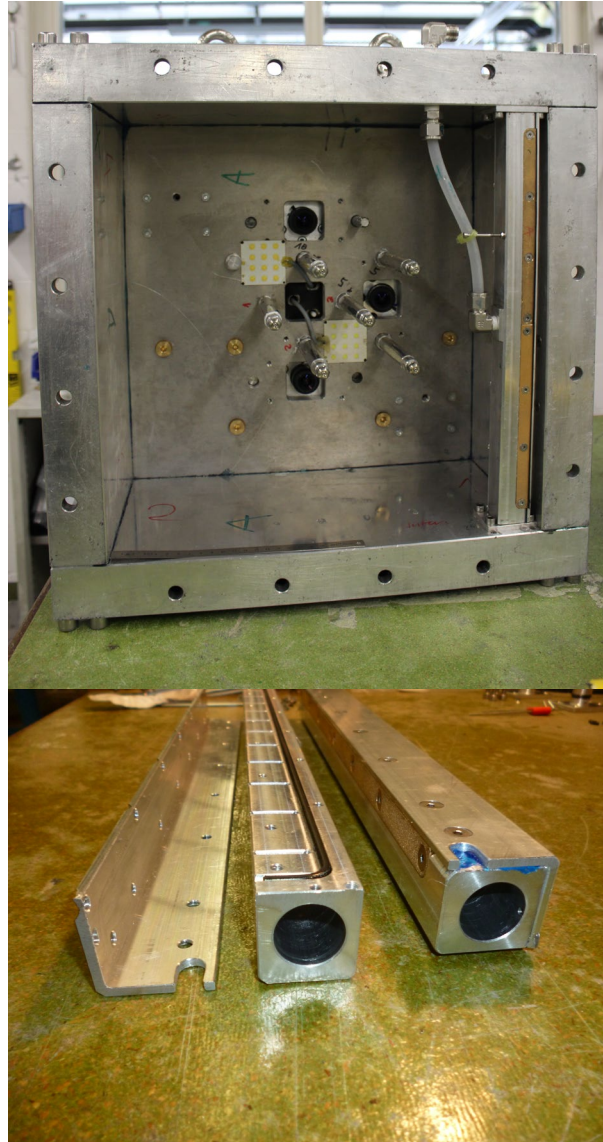


Figure S16. Top: water distribution system placed in climate chamber; bottom: channel, cover and porous stone.

Adjustments water distribution system to 1g and Ng component for more uniform flow across the slope.

Figure S16 show the top view geometry model in drum centrifuge all dimensions in mm.

The diagram shows a beam balance with a 1g weight and a 42.237g weight. The beam is horizontal, and the weights are suspended from it. The 1g weight is on the left, and the 42.237g weight is on the right. The beam is deflected by 14° from the horizontal. The displacement of the 42.237g weight is 9.47 mm. A circular arrow indicates the direction of rotation.

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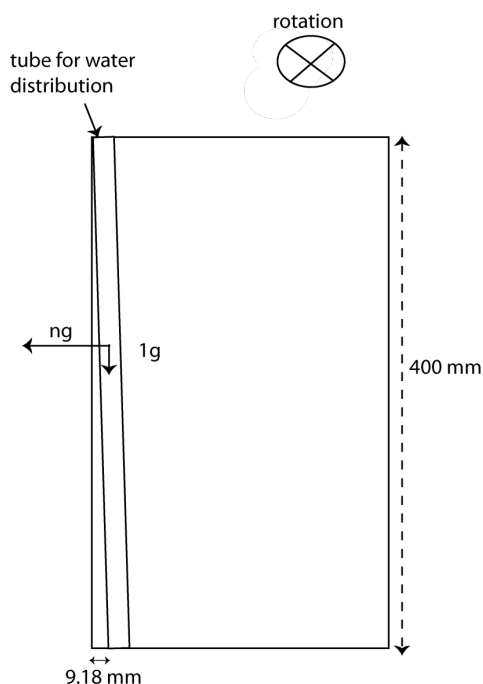


Figure S19. Displacement correction for water distribution system.

h. Pump calibration at 50g

The calibration of the pump (Reglo-Z, Analog Z-140, Ismatec) was performed at the laboratories of ETH Zürich.

Table S10, Figure S20 show the flow measured at 50g level during centrifuge tests, the flow measured at 1g level, and the nominal flow by the manufacturer for different pump speeds.

Table S10. Water flows measured in pump

pump speed selector (-)	pump speed (rpm)	time (min)	measured Flow Lab 50g level (mL/min)	Measured Flow lab 1g level (mL/min)	Flow manufacturer (mL/min)	centrifuge @ 50g (rpm)	Ng level	radius (m)
80	4040	1.00		2890	2659.90			
69	3485	1.00	2500	2500	2294.20	211	50	1
60	3030	1.00	2125	2180	1994.90	211	50	1
45	2273	1.00	1500	1620	1496.20	211	50	1
30	1515	1.00	930	1050	997.47	211	50	1
10	505	1.00	180	400	332.49	211	50	1

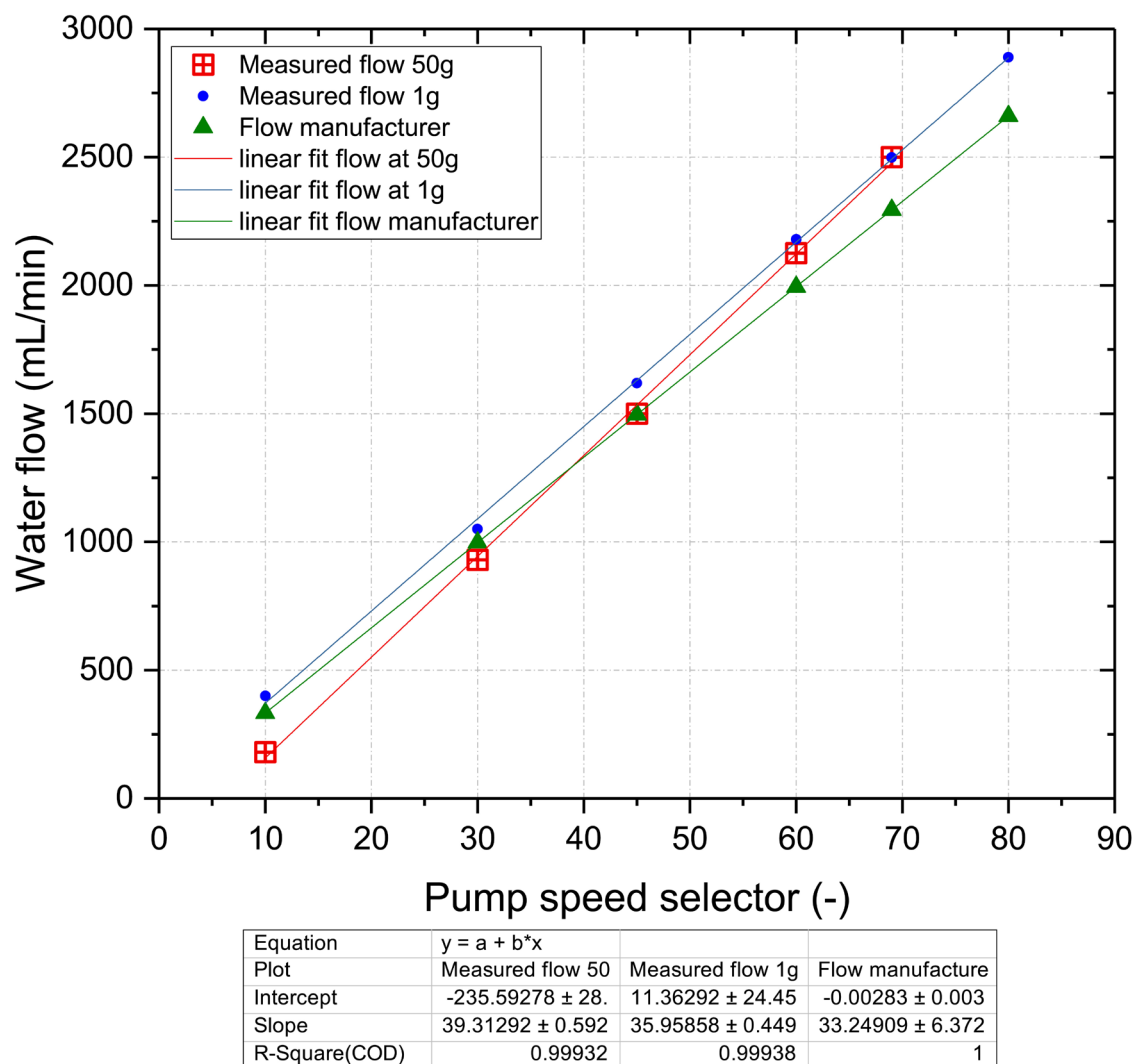


Figure S20. Comparison of flow at different pump velocity at 1g (green), 50g and (red) and reference manufacturer (blue).

i. Programme physical modelling

The detailed programme of the centrifuge testing is given in Table S11.

Table S11. Programme centrifuge testing.

Test name number	Test name	GW of failure (mL/min)	rpm	g level	GW flow range mL/min	Nozzle rain	length nozzle (cm)	rain (mL/min)
1.0Proof (same as 1a)	HN31_1.5_0.75_8.5	Failure at 1500	221	50	500-2000	(-)	(-)	(-)
1a	HN31_1.5_0.75_8.5	Failure at 1500	221	50	500-2000	(-)	(-)	(-)
1b	HN31_1.5_0_0	No failure after max flow	225	52	500-2500	(-)	(-)	(-)
2a	HN31_1.5_0.5_8.5	No failure after max flow	225	52	500-2500	(-)	(-)	(-)
2b	HN31_1.5_0.75_3	Failure at 2500	225	52	500-2500	(-)	(-)	(-)
3a	HN31_1.5_0.5_8.5_R	No failure after max flow	225	52	500-2500	4xMW5	5 top, 10 bottom	708
3b	HN31_1.5_0.75_3_R	No failure after max flow	225	52	500-2500	3xMW5+1 M2	5 top (M2), 10 bottom	613
4a	HN31_1.0_0.75_8.5_R	erosion near plexiglas at 500	225	52	500-1000	6XMW7	10	1479.32
4b	HN31_1.5_0.75_3_R	remobilisation at 1500+rain	225	52	500-2500	6XMW7	10	1379.18
5a	HN31_1.5_0.75_8.5_R	Failure at 1000 +rain	225	52	500-1000	6XMW7	10	1479.32
5b	HN31_1.5_0.5_3_R	No failure after max flow and rain	225 & 230	52	500-2500	6XMW7	10	1379.18
6a	HN31_3.0_0.375_8.5_R	No failure after max flow and rain	225	52	500-2500	6XMW7	10	1479.32
6b	HN31_1.5_0_0_R	No failure after max flow and rain	225	52	500-2500	6XMW7	10	1379.18
7a	HN31_1.25_0.6_8.5	Failure near plexiglas at 2000	225	52	500-2000	(-)	(-)	(-)
7b	HN31_1.25_0.6_3_R	Failure with max flow and rain	225	52	500-2500	6XMW7	10	1379.18
8a	HN31_1.25_0.6_8.5_R	Failure at 1500 +rain	230	54	500-1000	6XMW7	10	1479.32
8b	HN31_1.25_0_0_R	No failure after max flow and rain	230	54	500-2500	6XMW7	10	1379.18

3. Results

j. Centrifuge test results

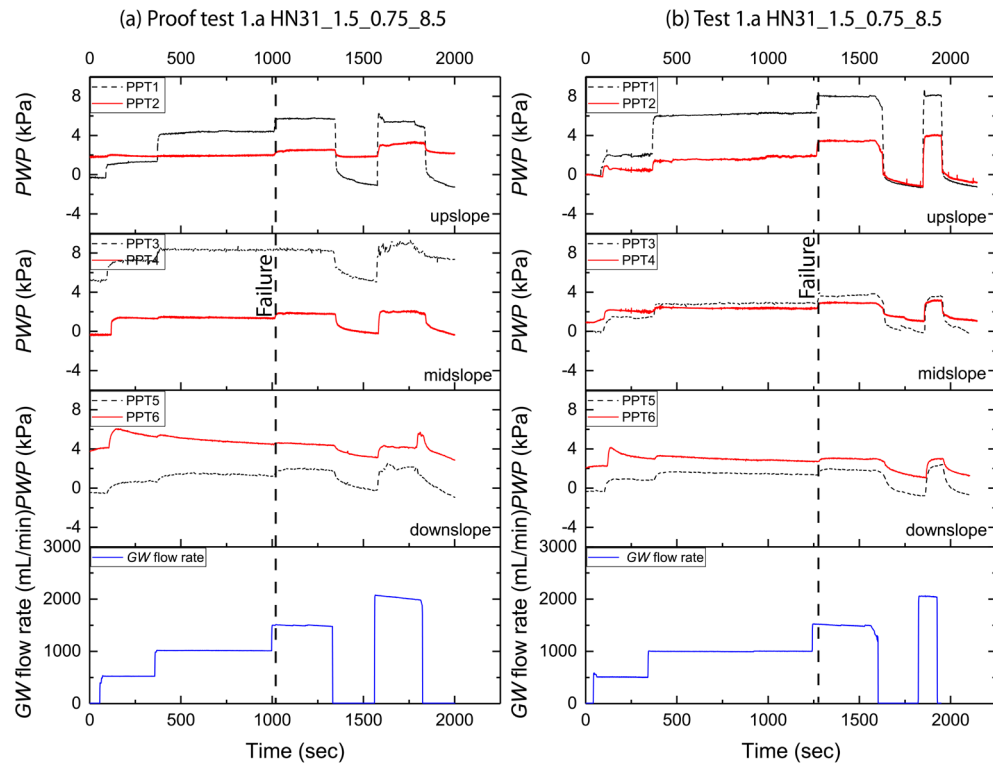


Figure S21. *PWP* and *GW* flow rate versus time for identical models with $h=1.5$ m, and bedrock step $y/h=0.75$ with bedrock step length $X_2= 8.5$ m (prototype). A black dashed line shows the time of failure. (a) Proof test 1.a and (b) test 1.a.

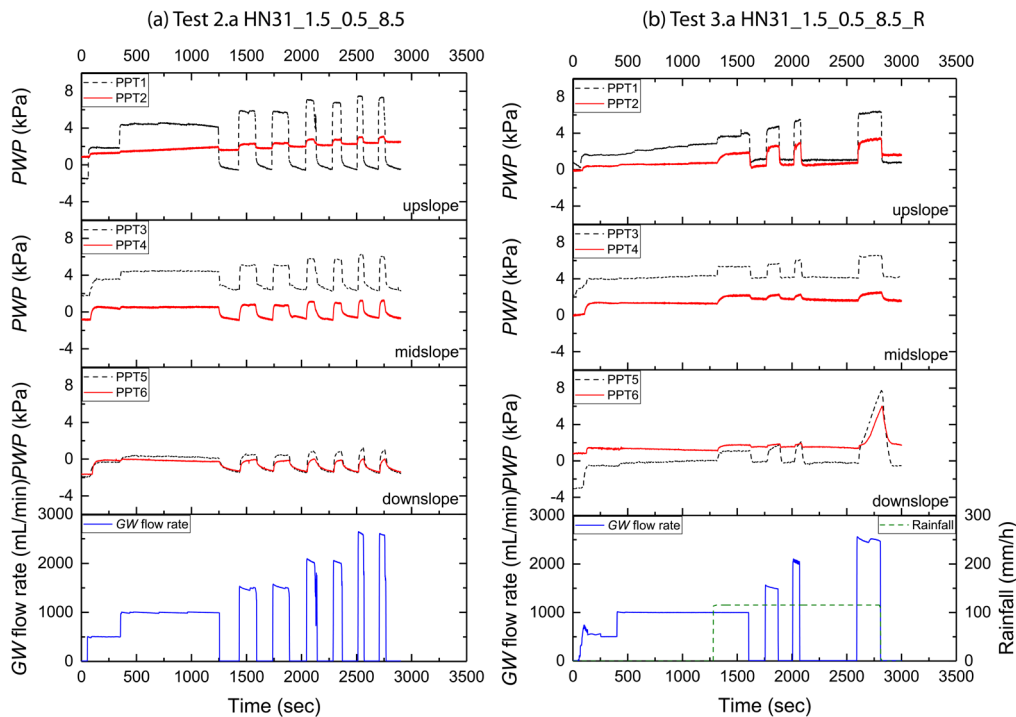


Figure S22. *PWP* and *GW* flow rate versus time for identical models with $h=1.5$ m, and bedrock step $y/h=0.5$ with bedrock step length $X_2= 8.5$ m (prototype). (a) test 2.a and (b) test 3.a.

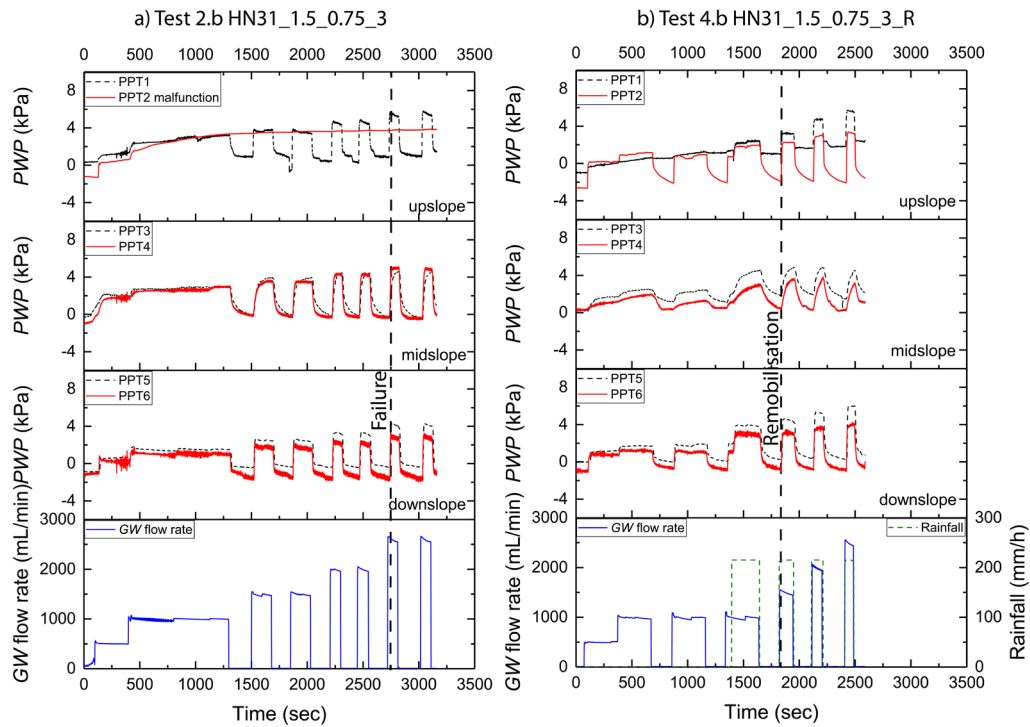


Figure S23. *PWP* and *GW* flow rate versus time for identical models with $h=1.5$ m, and bedrock step $y/h=0.75$ with bedrock step length $X_2=3$ m (prototype). (a) test 2.b and (b) test 4.b.

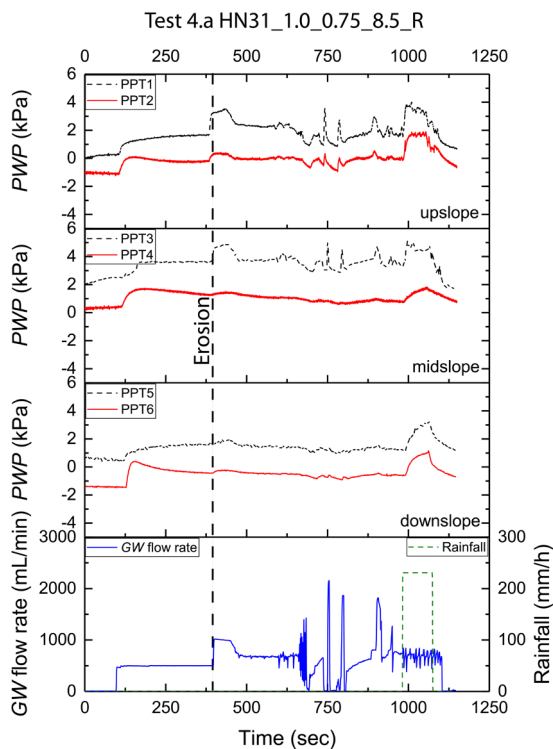


Figure S24. *PWP* and *GW* flow rate versus time model with $h=1.0$ m, and bedrock step $y/h=0.75$ with bedrock step length $X_2=8.5$ m.

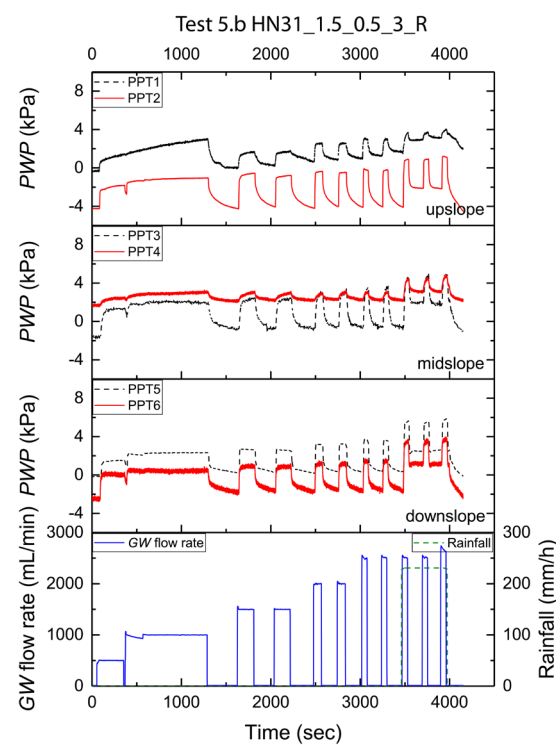


Figure S25. *PWP* and *GW* flow rate versus time model with $h=1.5$ m, and bedrock step $y/h=0.5$ with bedrock step length $X_2=3$ m.

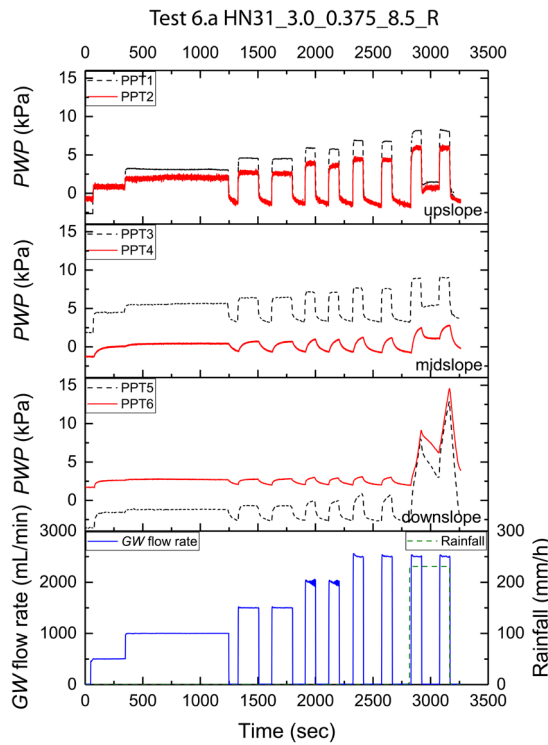


Figure S26. *PWP* and *GW* flow rate versus time model with $h=3.0$ m, and bedrock step $y/h=0.375$ with bedrock step length $X_2=8.5$ m.

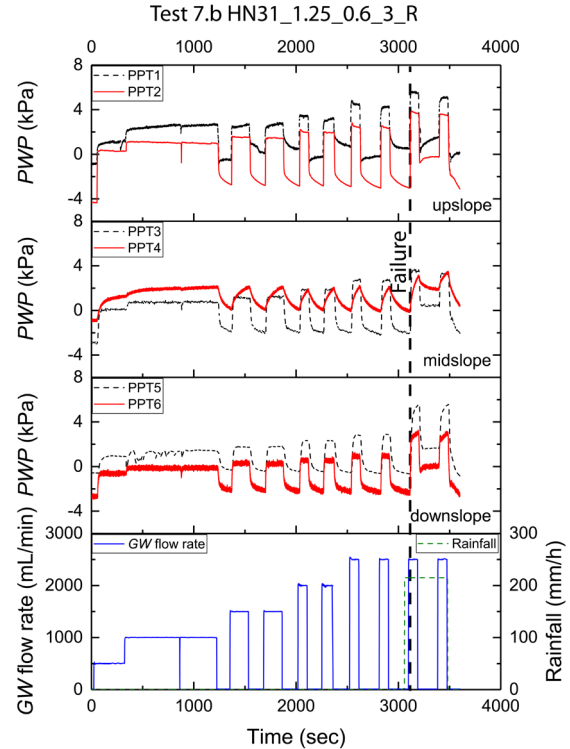


Figure S27. *PWP* and *GW* flow rate versus time model with $h=1.25$ m, and bedrock step $y/h=0.6$ with bedrock step length $X_2=3$ m.

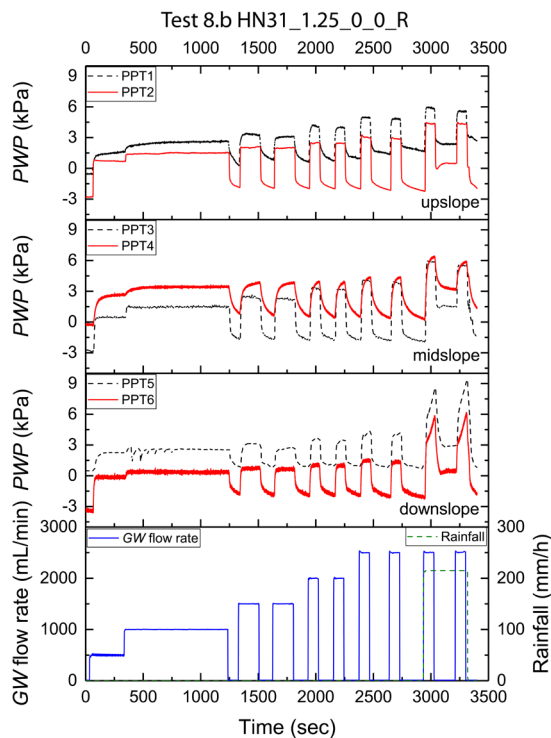


Figure S28. *PWP* and *GW* flow rate versus time model with $h=1.25$ m, and bedrock step $y/h=0$ with bedrock step length $X_2=0$ m.