

Full-scale experiments reveal the spatiotemporal controls on flood-induced erosion of road foundations

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Supplementary Material

This Supplementary File includes:

- Text S1
- Figures S1 to S5
- Tables S1 to S4
- Legend for Movie S1

Other Supplementary Material includes:

- Movie S1

S1 Additional experiments and setup optimization

Three initial trials were performed to assess the stability of the experimental setup, determine the optimal testing timeline, verify the measuring equipment, and evaluate the reproducibility of the results. First, a preliminary experiment (E0) was executed with discharges varying from 250 L s^{-1} to 500 L s^{-1} . Due to a startup surge, overtopping at higher discharges, and buoyancy-driven displacement of hollow bodies, this trial was used exclusively to verify flume performance, instrumentation, measurement procedures, and to optimize the setup.

Experiment E1 was designed to revisit the conditions of the preliminary experiment with improved instrumentation and targeted modifications to address the issues encountered. Pump parameters were adjusted to avoid a startup surge, and the reinforcement of the hollow bodies was improved. However, during execution, the water level approached the foundation shoulder when the discharge increased to 400 L s^{-1} , with occasional overtopping. Consequently, the upper limit for operation was established at a lower discharge. In addition, two acoustic Doppler velocimeters (ADV), which were installed at fixed stations located 1 m from the upstream and downstream edges of the testing track, 20 cm from the foundation face, and 20 cm above the bed, measured three-dimensional flow velocity fluctuations during the experiment. Differences between upstream and downstream measurements were discernible (Figure S1), but the increase in discharge did not result in a significantly steeper flow velocity gradient along the testing track.

Experiment E2 was performed to more precisely evaluate the impact of the automatic regulation of the movable downstream gate on the water surface profile along the testing track and to quantify morphological changes over shorter time intervals. During the experiment, it became clear that the maximum discharge not raising the water level above the control level was 350 L s^{-1} . In addition, morphological changes tended to be less quantifiable over

shorter time intervals, even when using the entire testing track to calculate redistribution volumes (Table S1).

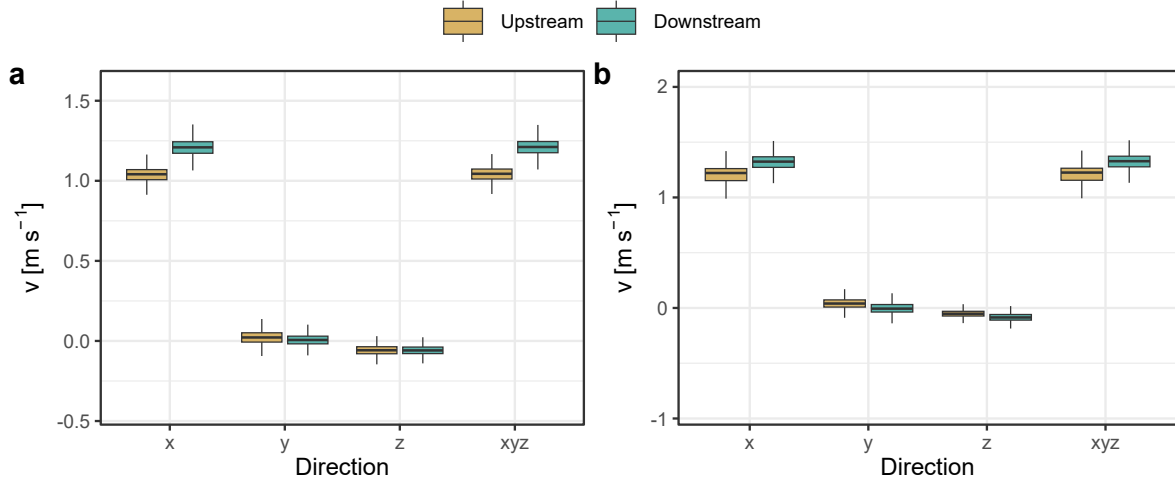


Figure S1: Flow velocity distributions in experiment E1. Flow velocities are shown in the streamwise (x), secondary (y and z), and all (x - y - z) directions at fixed stations located 1 m from the upstream and downstream edges of the testing track over the entire duration of the **a** first and **b** second loading intervals. Outliers are not shown.

As a second iteration of optimizing the hollow PVC foam structures, the egress track was extended to prevent any effect of backwater on flow hydrodynamics in the testing track. This led to the final configuration of the experimental track (Figure S2a). In addition, experiments E1 and E2 established the basis for developing the instrumental setup (Figure S2b) and timeline (Figure S2c) for the long-duration experiments (E3 and E4). Because of the observed flow velocity differences, one ADV probe was mounted on the flume's movable traversing bridge, enabling precise positioning along the testing track for a subsequent segmented evaluation of morphological changes. In retrospect, E1 and E2 (Table S1) confirmed the reproducibility of the results reported in the main text. The cumulative eroded volume after 30 min in E2 was only approximately 4 % lower than in the first run of E3.

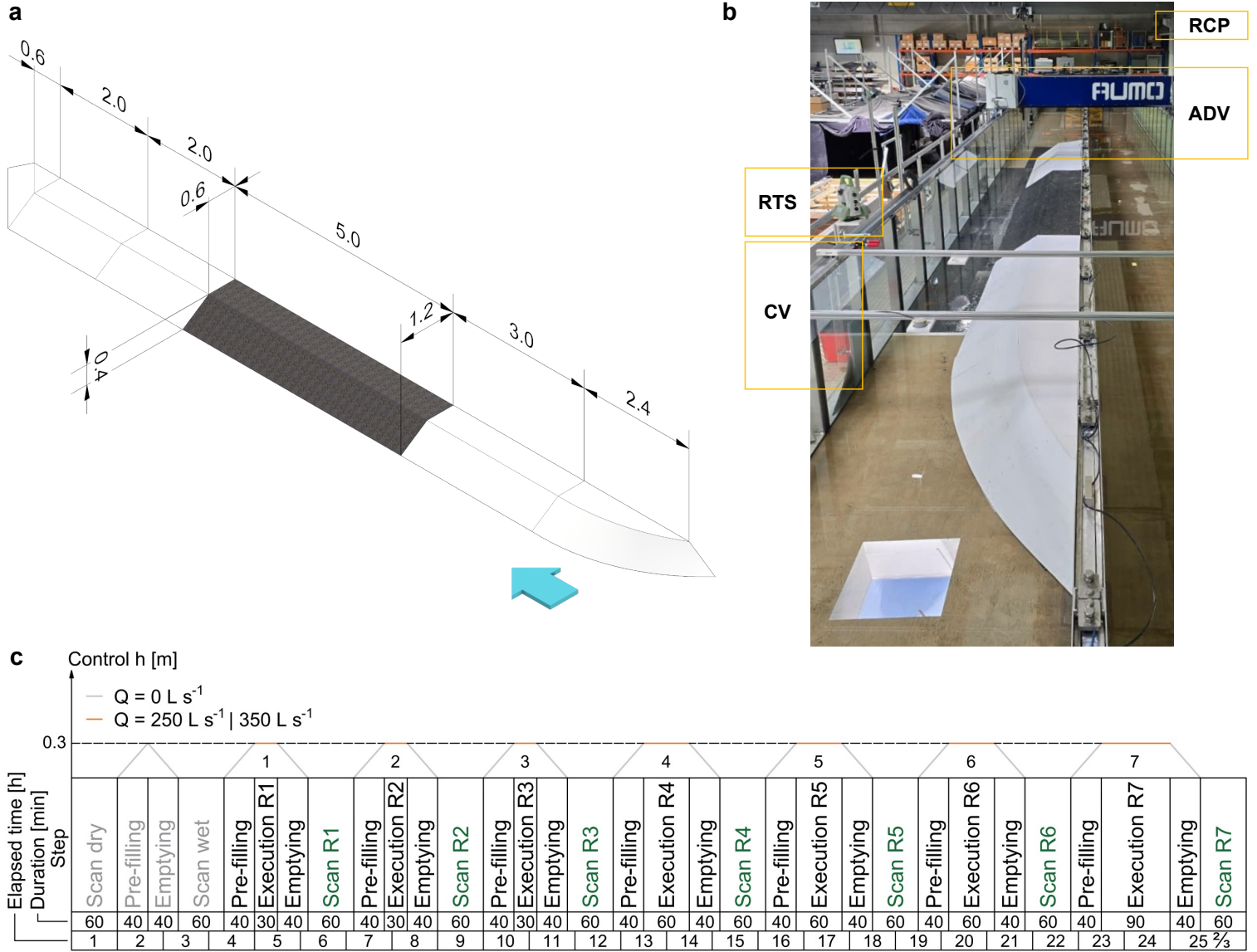


Figure S2: Experimental setup and timeline. **a** Dimensions of the ingress and egress tracks (white) and the testing track (black). The arrow indicates main flow direction. **b** Flume setup with apparatus [a georeferenced control point (RCP), acoustic Doppler velocimeter (ADV) mounted on the traversing bridge, robotic total station (RTS), and a communicating vessel (CV)] indicated. **c** Phases and their durations in the long-duration experiments. Control h denotes the control water level at the start of each loading interval. Elapsed time excludes preparation, cleaning, construction, and instrument installation.

Table S1: Material redistribution in experiments E1 and E2. Each row corresponds to a loading interval characterized by its loading time (t , cumulative per experiment), control water depth (h), discharge (Q), and volumetric redistribution balance ($V_t - V_{t-1}$).

Experiment	t [min]	h [m]	Q [L s^{-1}]	$V_t - V_{t-1} (\pm)$ [L]
E1	40	0.25	250	$+8.29 - 53.92 = -45.63$
E1	100	0.40	400	$+31.00 - 121.42 = -90.42$
E2	15	0.30	250	$+6.14 - 38.36 = -32.22$
E2	30	0.30	250	$+7.22 - 7.71 = -0.49$
E2	45	0.30	250	$+4.70 - 8.81 = -4.11$
E2	65	0.30	250	$+8.66 - 4.26 = +4.40$
E2	85	0.30	250	$+5.64 - 7.37 = -1.73$
E2	100	0.30	350	$+9.98 - 26.11 = -16.13$
E2	115	0.30	350	$+7.17 - 14.20 = -7.03$
E2	130	0.30	350	$+7.34 - 11.31 = -3.97$
E2	150	0.30	350	$+8.46 - 10.64 = -2.18$
E2	170	0.30	350	$+7.89 - 8.55 = -0.66$

Additional figures

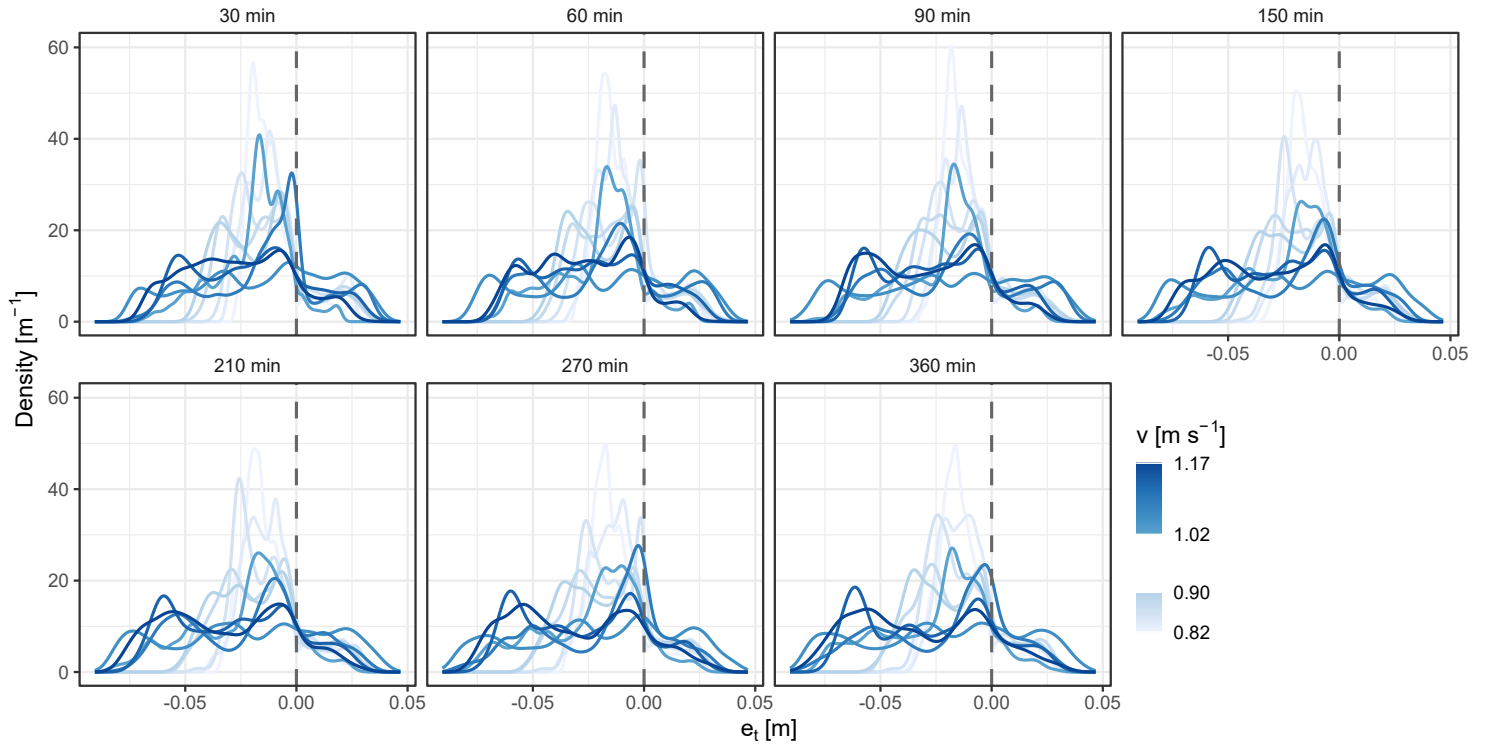


Figure S3: Density curves of elevation change over time. Elevation change (e_t) curves are colored by streamwise mean velocity (v).

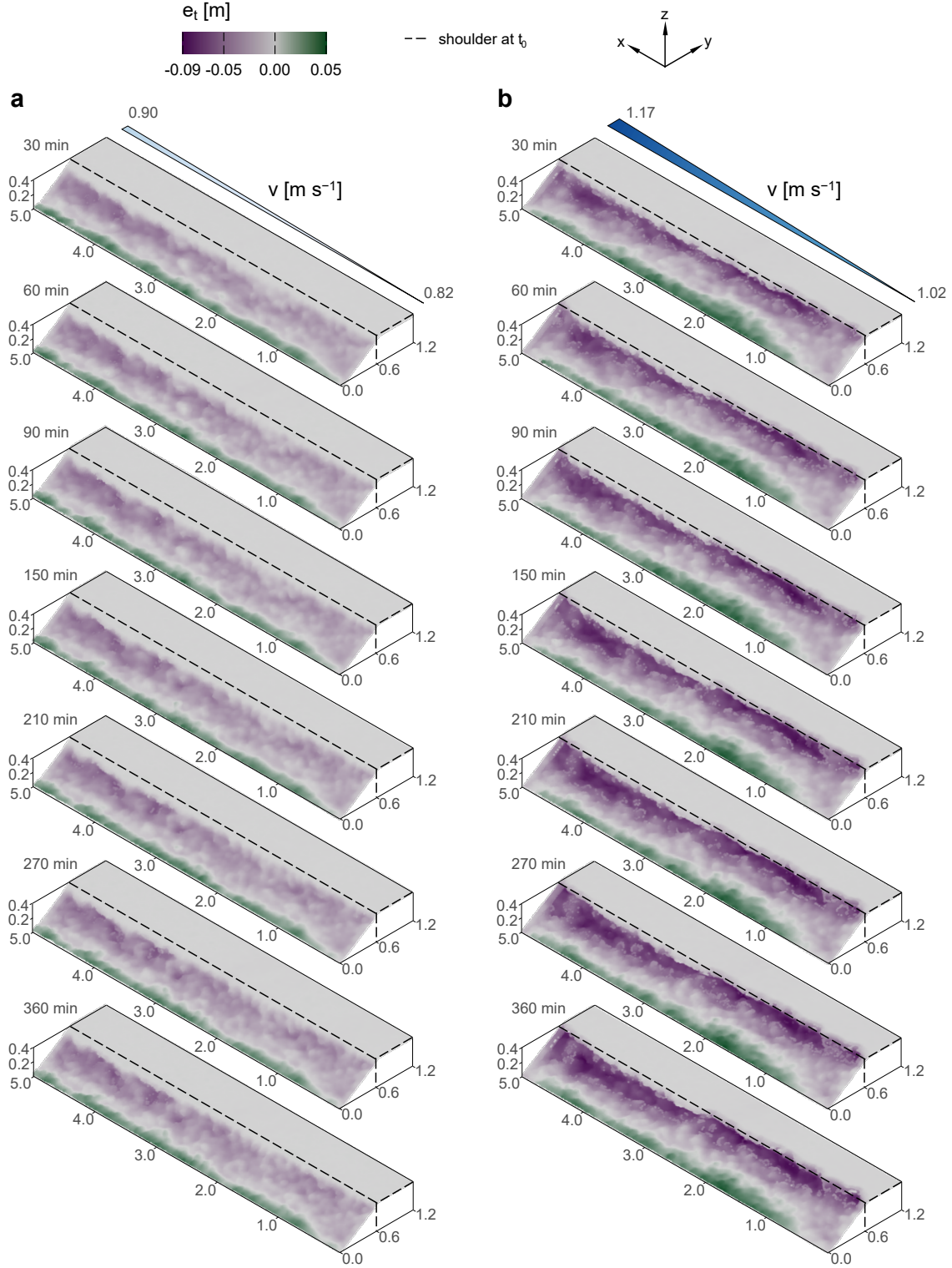


Figure S4: Spatiotemporal patterns of elevation change. Elevation changes (e_t) are shown after each loading interval for **a** the lower velocity class and **b** the higher velocity class, colored by strength and direction. The streamwise flow direction is along the x -axis.

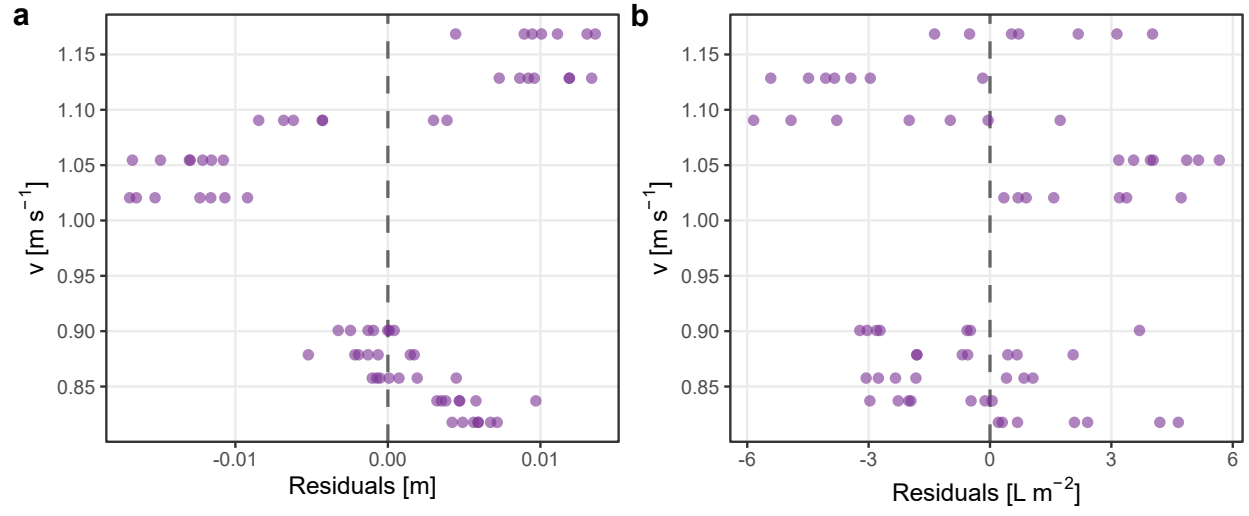


Figure S5: Model residuals of erosion evolution over time. Residuals are shown for the fitted erosion **a** maximum depths and **b** cumulative volumes, grouped by streamwise mean velocity (v).

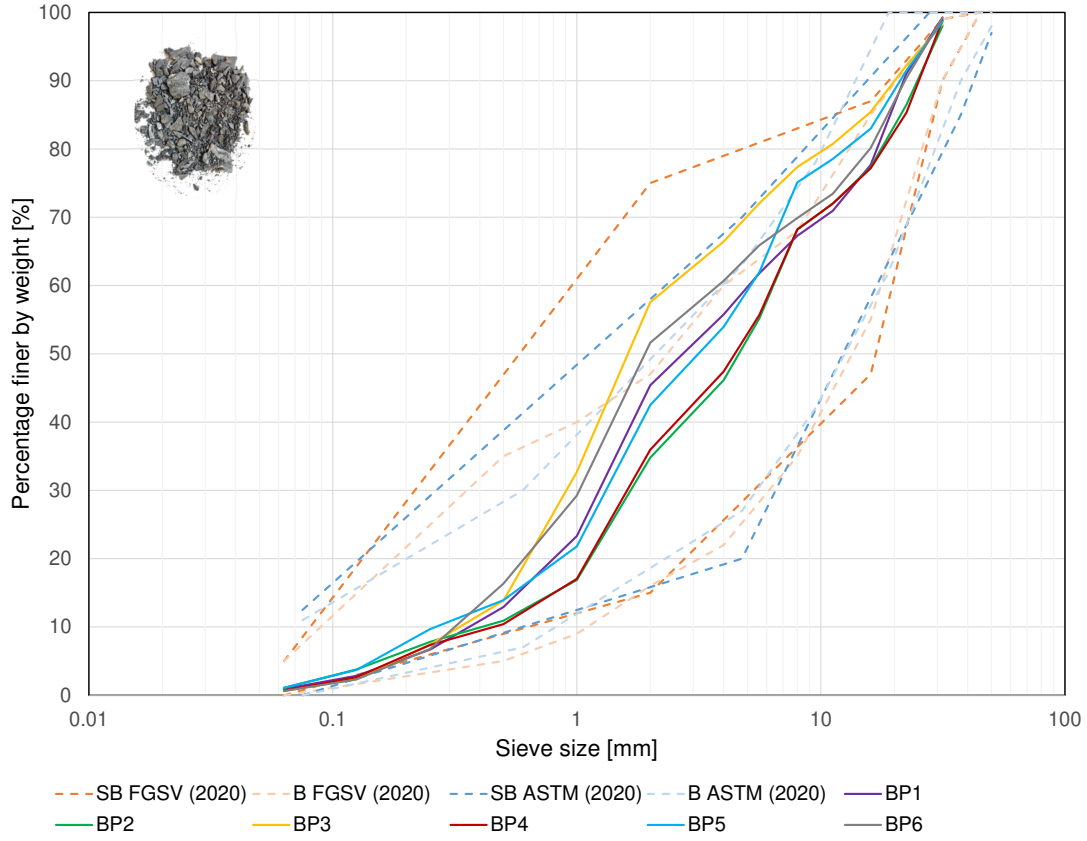


Figure S6: Material and limit particle size distributions. Solid lines depict the individual distributions for each big pack. Dashed lines show the limits for the subbase (SB) and base (B) course layers as defined in [1] and [2]. The inset shows a photograph of the material.

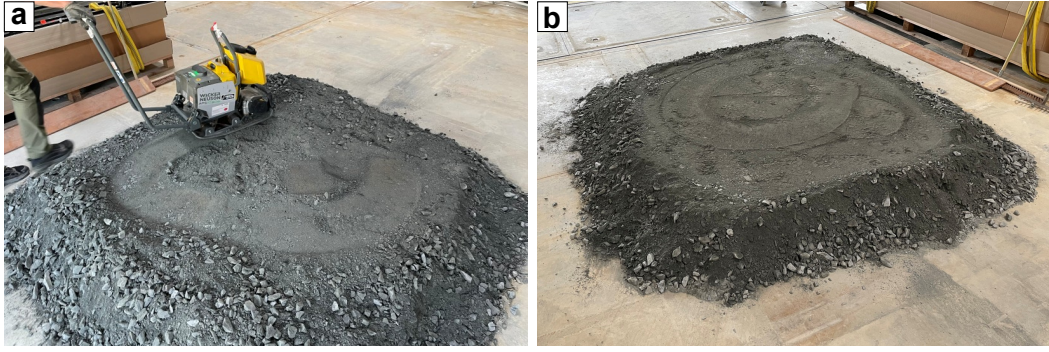


Figure S7: Execution of the compaction trial. **a** Compaction of the trial layer using a vibratory plate compactor. **b** Compacted trial layer used for the evaluation of the dynamic deformation modulus.



Figure S8: Experiment preparation in the high-performance morphological flume. **a** Compaction of the foundation body in layers. **b** Profiling of the foundation slope. **c, d** Placement of the hollow bodies.

Additional tables

Table S2: Summary statistics of key hydrodynamic variables during the long-duration experiments. The mean, standard deviation (*sd*), minimum (*min*), and maximum (*max*) values are reported for the mean water depth (*h*), streamwise mean velocity (*v*), near-foundation turbulent kinetic energy (*k*), Reynolds number (*Re*), and Froude number (*Fr*) for each hydrodynamic scenario. Values correspond to the midpoint of each longitudinal section.

discharge	variable	mean	sd	min	max
250 L s ⁻¹	h [m]	0.29	0.01	0.28	0.30
250 L s ⁻¹	v [m s ⁻¹]	0.86	0.03	0.82	0.90
250 L s ⁻¹	k [cm ² s ⁻²]	42.76	8.37	29.07	61.72
250 L s ⁻¹	Re	$1.82 \cdot 10^5$	$9.02 \cdot 10^3$	$1.64 \cdot 10^5$	$1.98 \cdot 10^5$
250 L s ⁻¹	Fr	0.56	0.03	0.53	0.60
350 L s ⁻¹	h [m]	0.31	0.01	0.29	0.33
350 L s ⁻¹	v [m s ⁻¹]	1.09	0.05	1.02	1.17
350 L s ⁻¹	k [cm ² s ⁻²]	40.00	7.74	28.28	63.34
350 L s ⁻¹	Re	$2.35 \cdot 10^5$	$9.80 \cdot 10^3$	$2.18 \cdot 10^5$	$2.47 \cdot 10^5$
350 L s ⁻¹	Fr	0.69	0.05	0.63	0.76

Table S3: Regression models applied to the temporal evolution of deposition and erosion. Pseudo- R^2 , corrected Akaike information criterion ($AICc$), slope coefficient, and significance value (p_value) are reported for each streamwise mean velocity (v), morphological response (deposition and erosion volumes and depths), and formulation. Models were built as linear and logarithmic formulations of the load time (t).

v (m s^{-1})	response	model	R^2	$AICc$	slope	p_value
0.82	dep_volume	linear	0.97	37.25	0.07	0.0000
0.82	dep_volume	log	0.97	38.34	9.57	0.0001
0.82	ero_volume	linear	0.96	42.80	0.08	0.0001
0.82	ero_volume	log	0.98	38.64	11.35	0.0000
0.82	dep_depth	linear	0.13	-77.41	0.00	0.4336
0.82	dep_depth	log	0.03	-76.68	0.00	0.7088
0.82	ero_depth	linear	0.89	-63.74	0.00	0.0015
0.82	ero_depth	log	0.95	-69.85	0.00	0.0002
0.84	dep_volume	linear	0.98	36.71	0.07	0.0000
0.84	dep_volume	log	0.97	38.34	9.48	0.0001
0.84	ero_volume	linear	0.95	42.87	0.08	0.0002
0.84	ero_volume	log	0.98	35.22	10.60	0.0000
0.84	dep_depth	linear	0.01	-64.21	0.00	0.8501
0.84	dep_depth	log	0.07	-64.64	0.00	0.5763
0.84	ero_depth	linear	0.46	-50.51	0.00	0.0954
0.84	ero_depth	log	0.66	-53.84	0.00	0.0259
0.86	dep_volume	linear	0.97	38.10	0.07	0.0001
0.86	dep_volume	log	0.97	36.80	9.21	0.0000
0.86	ero_volume	linear	0.97	41.54	0.08	0.0001
0.86	ero_volume	log	0.97	40.55	11.39	0.0000
0.86	dep_depth	linear	0.41	-56.29	0.00	0.1189
0.86	dep_depth	log	0.40	-56.12	0.00	0.1276
0.86	ero_depth	linear	0.72	-52.14	0.00	0.0156
0.86	ero_depth	log	0.81	-54.68	0.00	0.0060
0.88	dep_volume	linear	0.98	33.26	0.07	0.0000
0.88	dep_volume	log	0.96	39.35	8.74	0.0001
0.88	ero_volume	linear	0.95	43.90	0.08	0.0002
0.88	ero_volume	log	0.98	37.36	11.02	0.0000
0.88	dep_depth	linear	0.21	-63.45	0.00	0.3067
0.88	dep_depth	log	0.18	-63.21	0.00	0.3457
0.88	ero_depth	linear	0.63	-56.20	0.00	0.0327
0.88	ero_depth	log	0.60	-55.60	0.00	0.0413
0.90	dep_volume	linear	0.96	36.62	0.05	0.0001
0.90	dep_volume	log	0.98	32.21	7.47	0.0000
0.90	ero_volume	linear	0.94	41.89	0.06	0.0003

0.90	ero_volume	log	0.99	31.64	9.00	0.0000
0.90	dep_depth	linear	0.21	-61.55	0.00	0.3054
0.90	dep_depth	log	0.19	-61.42	0.00	0.3257
0.90	ero_depth	linear	0.83	-60.10	0.00	0.0044
0.90	ero_depth	log	0.87	-62.03	0.00	0.0022
1.02	dep_volume	linear	0.97	38.26	0.07	0.0001
1.02	dep_volume	log	0.97	37.69	9.61	0.0000
1.02	ero_volume	linear	0.95	46.94	0.10	0.0002
1.02	ero_volume	log	0.99	38.78	14.34	0.0000
1.02	dep_depth	linear	0.65	-52.89	0.00	0.0292
1.02	dep_depth	log	0.87	-59.63	0.00	0.0024
1.02	ero_depth	linear	0.34	-44.38	0.00	0.1727
1.02	ero_depth	log	0.63	-48.49	0.00	0.0328
1.05	dep_volume	linear	0.96	40.27	0.07	0.0001
1.05	dep_volume	log	0.98	36.77	9.85	0.0000
1.05	ero_volume	linear	0.93	49.49	0.10	0.0004
1.05	ero_volume	log	0.99	31.31	14.29	0.0000
1.05	dep_depth	linear	0.67	-61.34	0.00	0.0252
1.05	dep_depth	log	0.75	-63.38	0.00	0.0117
1.05	ero_depth	linear	0.74	-51.16	0.00	0.0131
1.05	ero_depth	log	0.85	-54.87	0.01	0.0033
1.09	dep_volume	linear	0.96	41.04	0.08	0.0001
1.09	dep_volume	log	0.98	37.99	10.43	0.0000
1.09	ero_volume	linear	0.97	46.84	0.12	0.0001
1.09	ero_volume	log	0.97	44.95	16.32	0.0000
1.09	dep_depth	linear	0.57	-55.55	0.00	0.0502
1.09	dep_depth	log	0.75	-59.42	0.00	0.0115
1.09	ero_depth	linear	0.81	-47.72	0.00	0.0054
1.09	ero_depth	log	0.66	-43.59	0.01	0.0255
1.13	dep_volume	linear	0.98	34.86	0.07	0.0000
1.13	dep_volume	log	0.96	40.48	9.15	0.0001
1.13	ero_volume	linear	0.95	47.81	0.10	0.0002
1.13	ero_volume	log	0.99	37.64	14.48	0.0000
1.13	dep_depth	linear	0.32	-49.00	0.00	0.1824
1.13	dep_depth	log	0.57	-52.21	0.00	0.0489
1.13	ero_depth	linear	0.72	-55.32	0.00	0.0164
1.13	ero_depth	log	0.68	-54.42	0.00	0.0229
1.17	dep_volume	linear	0.97	38.08	0.07	0.0000
1.17	dep_volume	log	0.96	40.31	9.87	0.0001
1.17	ero_volume	linear	0.96	47.57	0.12	0.0001
1.17	ero_volume	log	0.98	42.09	15.93	0.0000
1.17	dep_depth	linear	0.36	-57.36	0.00	0.1563

1.17	dep_depth	log	0.16	-55.51	0.00	0.3684
1.17	ero_depth	linear	0.92	-56.97	0.00	0.0007
1.17	ero_depth	log	0.78	-49.85	0.01	0.0088

Table S4: Regression models summarizing the temporal evolution of erosion. Adjusted R^2 , corrected Akaike information criterion ($AICc$), F-statistic (F_stat) and significance value (p_fmt) are reported for each formulation and erosion volume and depth. Models were built as additive and interaction formulations of the streamwise mean velocity (v) and load time (t).

response	model	R^2	$AICc$	F_stat	p_fmt
ero_volume	$v + t$	0.94	393.2	530.12	0.0000
ero_volume	$v + \log(t)$	0.95	374.9	698.40	0.0000
ero_volume	$v \cdot t$	0.95	380.1	439.37	0.0000
ero_volume	$v \cdot \log(t)$	0.96	355.3	635.32	0.0000
ero_depth	$v + t$	0.80	-463.1	141.77	0.0000
ero_depth	$v + \log(t)$	0.80	-463.8	143.38	0.0000
ero_depth	$v \cdot t$	0.80	-461.5	94.20	0.0000
ero_depth	$v \cdot \log(t)$	0.80	-461.9	94.89	0.0000

Table S5: Criteria used to assess the internal stability of the granular mixture.

Reference	Parameters	Stability criteria	Type
[3]	D_{15}^c, D_{85}^f	$(D_{15}^c/D_{85}^f)_{max} \leq 4$	all
[4]	D_{15}^c, D_{85}^f	$(D_{15}^c/D_{85}^f)_{max} \leq 5$	all
[5]	F, H	$F \leq 20 \%$ and $(H/F)_{min} > 1$	granular
[6]	d_{90}, d_{60}, d_{15}	$0.76 \log(d_{90}/d_{15}) + 1 < d_{90}/d_{60} < 1.86 \log(d_{90}/d_{15}) + 1$	cohesionless
[7]	F, H	$F \leq 15 \%$ and $(H/F)_{min} > 1$	granular
[8]	$d_{90}, d_{60}, d_{20}, d_5$	$15/\log(d_{20}/d_5) \geq 22$ and $30/\log(d_{90}/d_{60}) \leq 80$	broadly graded
[9]	P, H, F	$P < 5 \%$ and $(H/F)_{min} > 1$	well-graded
[10]	P_c, D_{15}^c, D_{85}^f	$P_c < 60 \%$ and $(D_{15}^c/D_{85}^f)_{max} < 9.5$	gravelly

Criteria selected for the type of aggregate used. d_x is the sieve size through which $x \%$ passes by weight. D_x^f refers to the fine component, and D_x^c refers to the coarse component. F is the weight fraction finer than grain size D, and H is the weight fraction between D and 4D. P is the mass percentage of particles smaller than 0.063 mm. P_c is the content of coarse particles, calculated as the percentage ratio of the mass of the coarse component to the total mass.

Movie legend

Movie S1: First run of experiment conducted with a discharge of 250 L s^{-1} , recorded at 1 frame per second.

References

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