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

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Floods damage roads worldwide, undermining critical lifelines when communities need them most. Although field evidence shows flow velocity is a key damage driver, predictive models describe the hazard mainly through water depth. This overlooks a critical damage mechanism: erosion of the granular foundation supporting the pavement. Using full-scale flume experiments on a 5 m-long granular foundation exposed to sustained longitudinal flow, we show that flow velocity controls erosion severity, whereas water depth sets the elevation at which the flow attacks the foundation. During the experiments, erosion concentrated just below the water surface and deepened and localized as velocity increased from 0.8 m s^{-1} to 1.2 m s^{-1} , a range where existing damage functions are unconstrained. Although erosion decayed logarithmically over time, higher velocities amplified the rate of material loss, resulting in a local erosion depth of 9 cm within six hours. In contrast, deposition showed no systematic dependence on hydraulic forcing.

These results call for velocity-explicit fragility models and provide process-based evidence for protecting roads against intensifying hydrological extremes.

Introduction

Water-driven erosion of natural and engineered earth materials has received increasing attention due to its implications for landscape change and societal risk [1–5]. Road infrastructure is a particular concern, as road platforms frequently rest on granular foundations that are vulnerable to erosion [3–5]. Recent floods have exposed this susceptibility under hydraulic loading from different flood types [6, 7]. The July 2021 flood in western Europe resulted in over two billion euros of damage to roads and railways in Germany alone, with much of the destruction attributed to erosive processes [6]. Because hydroclimatic extremes of greater magnitude are becoming more frequent [8], the risk of damage to road infrastructure continues to grow [4, 9].

Transport networks are essential for connectivity and trade, so the consequences of such events extend beyond the directly damaged locations and carry significant economic costs [10–12]. Research has therefore focused on large-scale exposure and risk assessments of infrastructure assets [9, 13–15]. However, these assessments do not resolve the hydraulic forcing that governs erosion and structural instability. Although flow velocity strongly influences structural flood damage to roads [6, 16], damage assessments for transport infrastructure have traditionally relied on inundation depth as the sole hazard metric [14, 17, 18] or represented flow velocity in a coarse manner, such as through binary variables [15]. When studies explore material-specific behavior, they commonly focus on the long-term consequences of inundation exposure [19–21] and on internal erosion of granular materials [22, 23], overlooking short-term external erosion that causes rapid, extensive damage.

Current understanding of the processes underlying these rapid responses remains limited, as it is primarily based on theoretical and numerical analyses of specific cases [24, 25] and analogies with riverbank behavior [3]. However, riverbanks differ fundamentally from road foundations in their boundary conditions. While riverbanks are also subject to erosion [1, 2], particularly in anthropogenically modified systems [26, 27], natural channel banks are self-formed landforms shaped by the coupled processes of erosion, sediment transport, and accretion. In contrast, road foundations are engineered systems characterized by prescribed geometry, mechanically compacted materials, and well-defined material properties. Hydraulic erosion of a road foundation alters its designed profile and directly threatens structural integrity [28], rather than representing an intrinsic adjustment. To date, no field-scale experimental observations have documented how a road foundation erodes under varying hydrodynamic forcing, leaving damage models without a process-based foundation.

Among the flood configurations that cause erosion, longitudinal flow is particularly important because many roads have historically been constructed adjacent to river courses [29]. In longitudinal flow, water moves approximately parallel to the road foundation, typically following local topographic gradients and exerting sustained hydrodynamic forces along the slope. Such conditions also arise during pluvial and flash floods, which allow little warning time [30] and are becoming increasingly damaging as short-duration rainfall extremes intensify [31]. A comprehensive understanding of the morphological response of road foundations to such flows is crucial for the effective protection of road infrastructure.

Here we report full-scale experiments on a 5 m-long granular road foundation subjected to long-duration, variable longitudinal hydrodynamic forcing. They covered quasi-steady, fully turbulent, subcritical flows with velocities around $1.0 \pm 0.2 \text{ m s}^{-1}$, a range in which existing damage assessments for roads are largely unconstrained and typically indi-

cate no damage risk [15]. In a high-performance flume, the foundation profile was exposed to controlled hydrodynamic loading and monitored from its intact state through progressive sediment redistribution. The experiments maintained full-scale grain geometry and size distribution, supporting process fidelity. Therefore, morphological change was quantified at field-relevant dimensions, thereby eliminating the need for corrections required in reduced-scale morphodynamic studies [32].

Because identical material and geometry were subjected to varying flow conditions, observed changes in erosion patterns can be attributed directly to hydrodynamic forcing rather than to differences in foundation composition or structure. The resulting observations established a direct link between hydrodynamic forcing and the location, magnitude, and temporal evolution of erosion. Erosion decreased logarithmically over time, but higher flow velocities caused greater volumetric erosion rates. Substantial erosion, locally up to 9 cm within six hours, developed even at the tested moderate velocities. Deposition, by contrast, exhibited no systematic dependence on the hydrodynamic drivers.

A fundamental distinction between flood exposure and erosive forcing was ultimately identified. Water depth determines the elevation at which the foundation is exposed to erosion attack, whereas flow velocity governs the intensity of erosion once exposure occurs. This challenges the common representation of road flood hazard centered on water depth, where increased flood depth is often treated as a proxy for greater damage [14, 17, 18]. While this remains reasonable for structural damage to residential buildings, flood damage to road infrastructure cannot be inferred from water depth alone [6, 16]. Our results provide a mechanistic basis for improved failure analysis and advancing large-scale models of flood-induced road damage.

Results

Moving beyond damage evidence constrained by variability in materials, geometries, and boundary conditions, we isolated, through full-scale experiments, how longitudinal hydrodynamic forcing governs material redistribution in a typical granular road foundation. The experimental procedure subjected the 5 m-long model to a range of local combinations of streamwise mean velocity, mean water depth, and near-foundation turbulent kinetic energy along the flume (Figure 1a). For readability, we refer to these variables hereafter as flow velocity, water depth, and turbulent kinetic energy.

Section-by-section analysis of the flow field (Figure 1b) and evolving foundation morphology (Figure 1c) resolved the spatiotemporal progression of morphological change. Due to the longitudinal slope of the flume and the imposed discharges, flow velocity and water depth varied inversely along the model in each hydrodynamic scenario, yielding two velocity classes (0.82 m s^{-1} to 0.90 m s^{-1} and 1.02 m s^{-1} to 1.17 m s^{-1}) and depth classes (0.28 m to 0.30 m and 0.29 m to 0.33 m). As a proxy for the energy of fluctuations in near-foundation flow velocity, turbulent kinetic energy varied from $28.28 \text{ cm}^2 \text{ s}^{-2}$ to $63.33 \text{ cm}^2 \text{ s}^{-2}$. Summary statistics for the measured and derived hydrodynamic variables are provided in Table S2. Movie S1 shows the execution of the first experimental run (30 min) under 250 L s^{-1} .

Spatiotemporal morphological patterns Morphological change was organized into a persistent banded pattern comprising erosion predominantly along the upper to middle exposed foundation face and deposition at the toe (Figure 2). This spatial structure was already evident after 30 min of loading and subsequently intensified primarily in magnitude rather than shifting markedly in position. The deepest erosion occurred with the progressive undercutting of the upper foundation face near the waterline, where the vertical structure of flow velocity reaches the highest values. Limited material removal above the mean water level

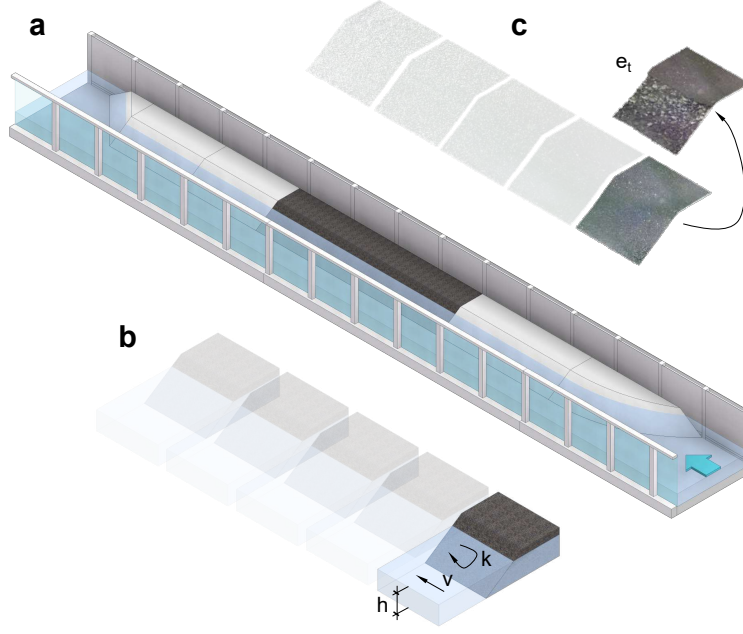


Figure 1: Experimental setup and domain segmentation. **a** Isometric view of the flume configuration showing the ingress and egress tracks and the intervening testing track. The arrow indicates main flow direction. Dimensions of each element are provided in Figure S1a. **b** Segmentation of the fluid domain. The hydrodynamic variables used in the sectional analysis are streamwise mean velocity (v), mean water depth (h) and near-foundation turbulent kinetic energy (k). **c** Segmentation of the granular domain. The comparison between segmented true-color point clouds illustrates the progression of surface morphology over time. Morphological change (e_t) is quantified as the elevation difference between the post-loading and initial surfaces.

was observed, resulting from localized loss of support leading to sliding or by fluctuations in water level. Positive elevation changes remained concentrated near the model foot.

In the lower flow velocity class, erosion was distributed over a relatively broad band along the foundation face and increased gradually through time, reaching 4.8 cm after 30 min and 5.5 cm after 6 h (Figure 2a). Deposition remained confined to a narrow toe band and changed more modestly than erosion. By contrast, the higher flow velocity class exhibited a more intense morphological response. Erosion became concentrated within a narrower band, and its magnitude increased more intensively with loading time, reaching 7.7 cm after 30 min and 9.1 cm after 6 h (Figure 2b). Deposition at the toe was also more extensive than

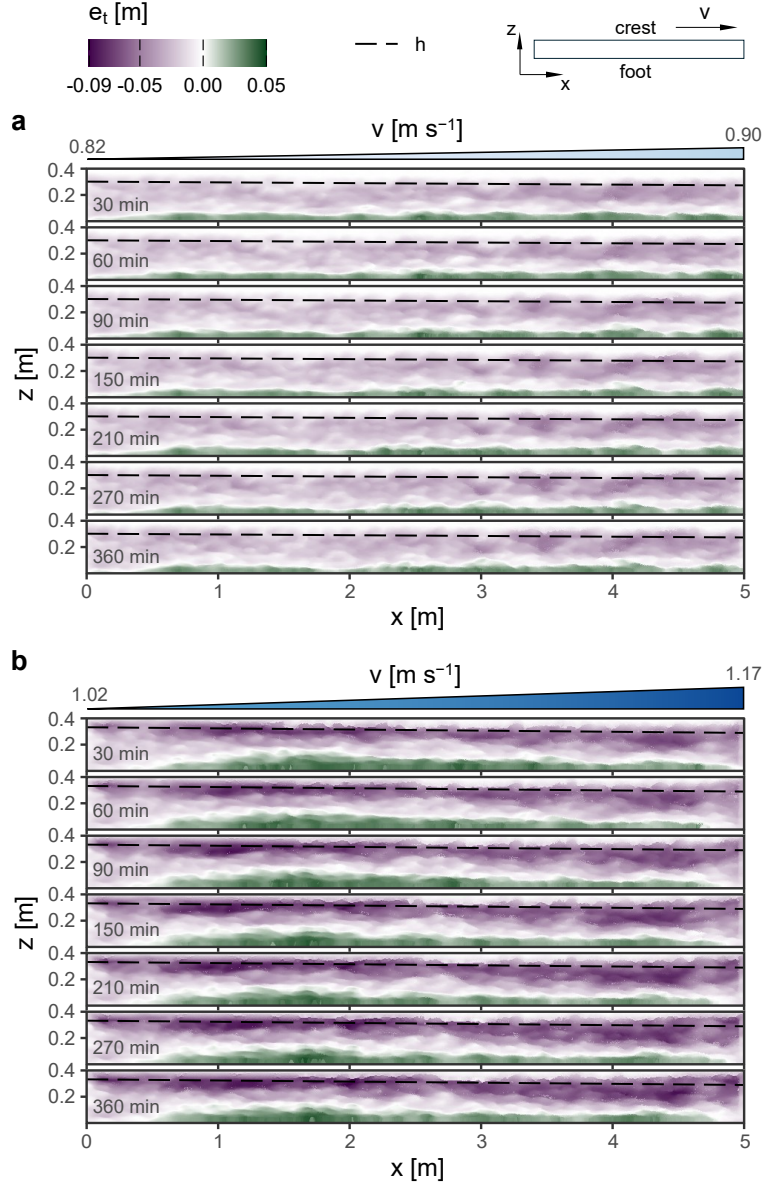


Figure 2: Spatial and temporal patterns of morphological change. Elevation differences (e_t) on the exposed foundation face are shown after each loading interval for **a** the lower ($v = 0.82 \text{ m s}^{-1}$ to 0.90 m s^{-1}) and **b** the higher ($v = 1.02 \text{ m s}^{-1}$ to 1.17 m s^{-1}) streamwise mean velocity classes. The color gradient indicates the strength and direction of e_t . The dashed black line shows the water depth (h). The inset schematic shows the plan view of the foundation face in the x - z plane, indicating the coordinate system, streamwise flow direction, and the relative positions of the foot and crest.

129 in the lower flow velocity class, producing a sharper transition between the erosional and
 130 depositional zones and thus a steeper overall cross-slope morphological gradient. The density

distributions of elevation change confirm these patterns (Figure S3).

At the longitudinal edges, morphological change differed from that in the central part of the foundation. Erosion was more heterogeneous and deposition was less pronounced, particularly in the higher flow velocity class. There, localized scour zones developed near the boundaries and intensified with loading time, while depositional accumulation was minimal (Figure 2b). Despite this local intensification, the overall magnitude of erosion remained comparable to that in the central part. As also shown in Figure S4, the shoulder remained best preserved in the central part under higher flow velocity. The downstream edge exhibited pronounced shoulder erosion despite lower local water depth. In contrast, the upstream edge experienced concentrated shoulder erosion due to the water level remaining close to the shoulder. Together, these patterns suggest that instability depended on both the spatial arrangement of water depth and the magnitude of flow velocity.

Hydrodynamic associations with morphological change Comparison of the unsaturated and saturated states before loading revealed no bulk displacement or subsidence, indicating that measurable morphological change developed only after the onset of flow. Among the hydrodynamic variables measured during the first loading intervals, only flow velocity showed a monotonic association with erosion (Figure 3). Both erosion volume and maximum erosion depth increased with flow velocity, with the model for erosion volume showing near linearity, and the LOESS-smoothed curves showed high local precision across the observed range. Sections exposed to higher velocities thus generally exhibited larger eroded volumes and greater maximum erosion depths. However, scatter increased toward the upper end of the velocity range, revealing that erosional responses become more heterogeneous under faster flow conditions. In contrast, deposition showed no comparably clear structure. Relationships for both deposition volume and maximum deposition depth remained diffuse.

Although flow velocity and water depth varied together in each experiment, no definitive monotonic relationship was observed between water depth and quantitative morphological response. Across both erosion and deposition metrics, the LOESS fits were non-monotonic and sensitive to local fluctuations in the data, without a stable trend supporting a physically compelling interpretation. Accordingly, water depth did not emerge as a reliable descriptor of the observed morphological variability. Likewise, turbulent kinetic energy showed weak and inconsistent associations with morphological change. Across all response metrics, the smoothed trends were weakly undulating, with substantial dispersion around them.

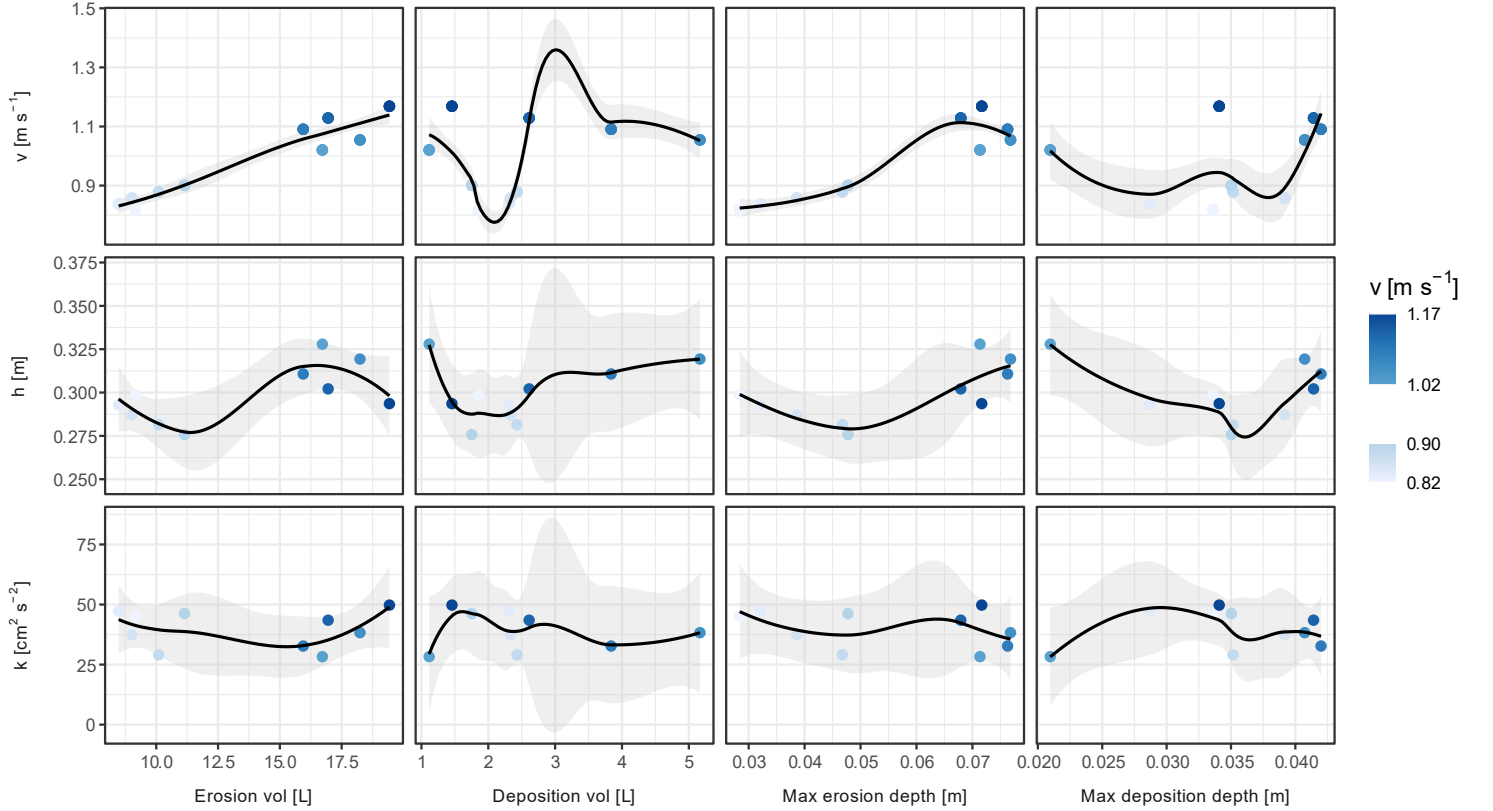


Figure 3: Pairwise relationships between hydrodynamic variables and morphological response. Rows show streamwise mean velocity (v), mean water depth (h), and near-foundation turbulent kinetic energy (k). Columns show erosion volume, deposition volume, maximum erosion depth, and maximum deposition depth. Points represent individual sections and are colored by v . Curves show LOESS-smoothed trends (span = 0.75), and shading indicates 95 % confidence intervals.

163 **Morphological evolution over time**

164 Temporal trajectories differed between erosion and
165 deposition and between depth and volume observations (Figure 4). Based on the corrected
166 Akaike information criterion (AIC_c), logarithmic regressions were identified as the best-fit
167 formulation for all erosion volume time series and for 60 % of erosion depth time series
168 (Table S3), indicating rapid initial adjustment followed by progressive attenuation. This
169 was reflected in higher coefficients of determination for erosion volume models than for
170 erosion depth models. By contrast, deposition exhibited a less systematic temporal response.
171 The best-fit formulations varied among sections for both deposited volume and maximum
172 deposition depth, and no single functional form was consistently favored across all sections.
173 Linear models were therefore retained for parsimony. Although deposited volumes were
174 well described for most flow velocities, maximum deposition depths showed typically little
temporal structure and no significant dependence on loading time.

175 Maximum erosion depth (Figure 4a) increased with loading time, with the greatest
176 changes occurring early in the experiments and gradually attenuating thereafter. Higher flow
177 velocities generally produced deeper erosion, and flow velocity affected the depth magnitude
178 more strongly than its temporal rate of change. In contrast, maximum deposition depth
179 remained confined to a relatively narrow range at the end of the experiments. Nevertheless,
180 cumulative volume series were more strongly structured than maximum depth (Figure 4b).
181 Deposited volume increased through time, but with weaker separation among different flow
182 velocities. This divergence between deposited volume and deposition depth suggests that
183 depositional adjustment occurred mainly through spatial spreading of sediment rather than
184 pronounced vertical thickening. The erosion volume models were more clearly structured by
185 flow velocity, with higher velocities producing steeper slopes and larger cumulative losses.
186 This dependence to flow velocity was stronger than that for maximum depth and indicates
187 that flow velocity exerted a more pronounced control on the rate and magnitude of erosion

188 volume than on maximum depth.

189 Combined fits across datasets reinforce these patterns. Maximum depth was well de-
 190 scribed by a logarithmic model, whereas cumulative volume was captured even more strongly
 191 by including a $v \cdot \ln(t)$ interaction (Table S4). Model residuals are shown in Figure S5 and
 192 increase with higher flow velocity. The additive structure of the depth model (Figure 4a)
 193 indicates a common decelerating temporal trajectory across velocity classes, with flow ve-
 194 locity primarily shifting the overall magnitude of the response. By contrast, the interaction
 195 term in the volume model (Figure 4b) shows that the temporal slope of cumulative erosion
 196 depended on flow velocity. Although erosion volume rate decreased with time, cumulative
 197 erosion volume increased by about 90 % from $t = 0.5$ h to $t = 6$ h for the highest flow velocity,
 198 while the increase was about 80 % for the lowest.

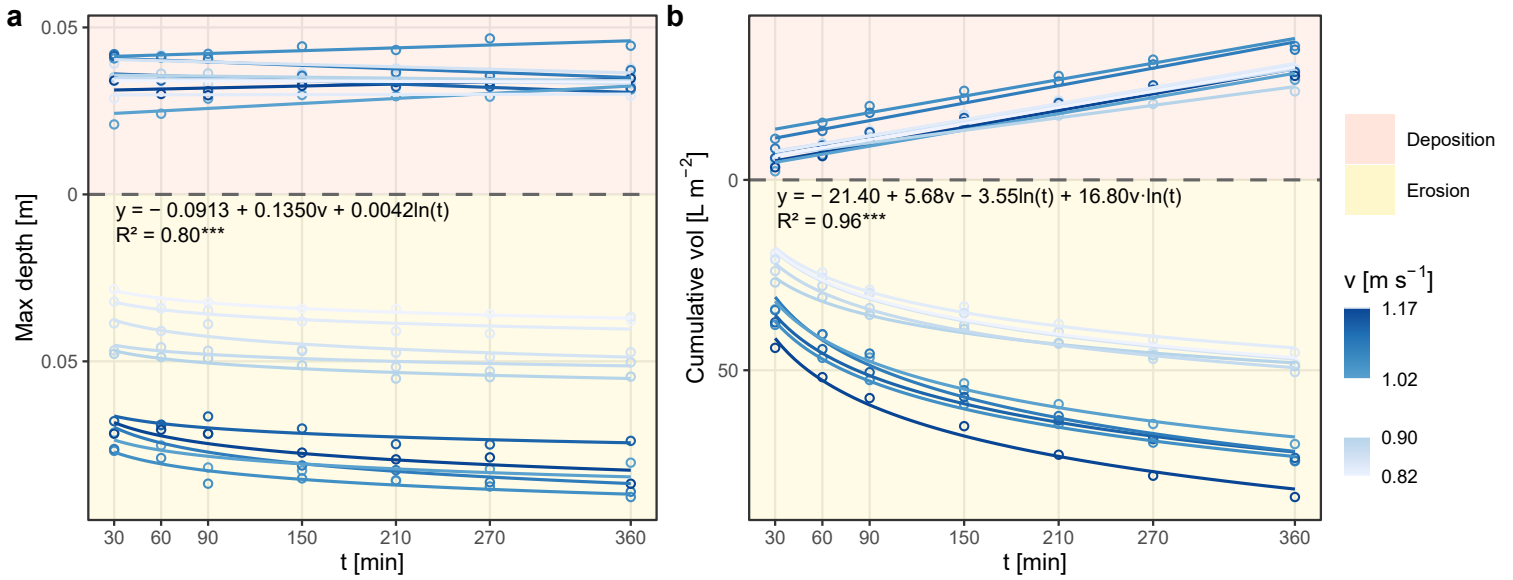


Figure 4: Temporal evolution of morphological change with loading time. **a** Maximum depth and **b** cumulative volume for deposition and erosion as functions of loading time (t). Points show observations of individual streamwise mean velocities (v), and solid lines show the corresponding fitted temporal models, colored by v . Equations give the best-fit models to the combined erosion datasets using v and t as predictors, with the corresponding R^2 values reported. Asterisks denote model significance ($*** p < 0.001$).

Morphological depth–volume relationships

Robust linear regression revealed that the relationship between depth and volume is more coherent for erosion than for deposition (Figure 5). The clearer and more consistent scaling in the erosion domain shows that erosional adjustment was more spatially organized than depositional adjustment. Additionally, error in elevation change estimates for erosion depth was consistently below 1 mm, while the maximum error for deposition measurements reached 6 mm. In the erosion domain, cumulative volume increased with maximum depth in both velocity classes, yielding positive slopes and moderate fits. The higher flow velocity class showed stronger depth–volume scaling than the lower class, indicating that higher flow velocity strengthened the coupling between maximum erosion depth and volumetric material removal. Moreover, the steeper depth–volume model at higher flow velocity indicates greater material removal per unit maximum depth. By contrast, deposition exhibited much weaker structure. For the lower flow velocity class, maximum deposition depth was only marginally related to cumulative deposited volume. For the higher flow velocity class, the relationship was statistically significant but still weak, showing that deeper depositional pockets were associated with somewhat larger deposited volumes, but with substantial scatter.

Discussion

By combining a controlled experimental environment with high-precision instrumentation, we provide, to our knowledge, the first assessment of individual hydrodynamic drivers acting on a full-scale granular road foundation, keeping the findings free of scaling effects. Because hydrodynamic conditions varied systematically along the test section, a single experiment yielded multiple velocity–depth combinations, representing a distinct advance in sediment dynamics research. The results also reduce the current reliance on riverbank morphology as a proxy for understanding external erosion of granular road foundations. The result-

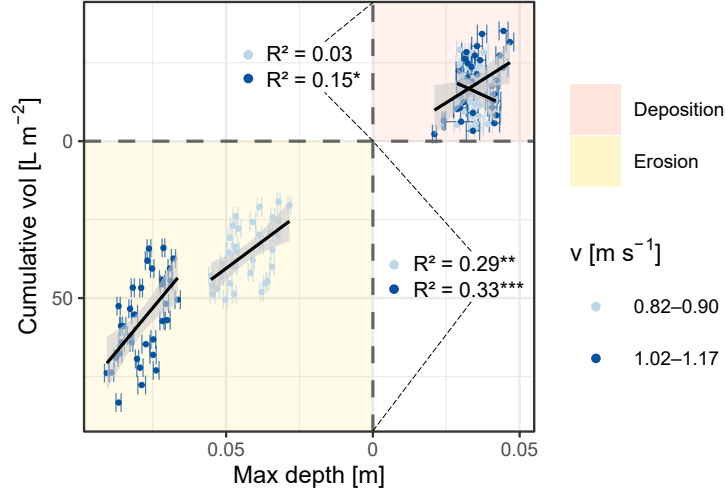


Figure 5: Depth–volume relationships for erosion and deposition. Points represent maximum depth and cumulative volume pairs for both erosion and deposition, and error bars represent uncertainty in elevation change estimates, both colored by streamwise mean velocity (v) class (0.82 m s^{-1} to 0.90 m s^{-1} and 1.02 m s^{-1} to 1.17 m s^{-1}). Solid lines show robust linear fits, and shading indicates 95 % confidence intervals. Pseudo- R^2 values are given for each regression, with asterisks indicating the significance of the regression slopes (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

ing spatiotemporal erosion data also provides benchmark conditions for the validation of
morphodynamic models describing the transport of compacted unbound materials.

Across experiments, flow velocity is highlighted as the primary driver of the morphological response of granular road foundations exposed to longitudinal flow within the tested range of 0.8 m s^{-1} to 1.2 m s^{-1} . Nevertheless, flood-induced erosion depends on two interrelated hydrodynamic attributes: the magnitude of flow velocity, which controls erosion intensity, and the elevation of the water surface, which dictates the location of erosion attack on the exposed foundation face. In open-channel flow, velocity typically peaks just below the water surface. The results show that this near-surface zone is where erosion concentrates, meaning the position of the water surface governs where support is progressively removed and instability is most likely to initiate. The shoulder erosion observed in the higher flow velocity class illustrates how the two attributes interact. Even in the absence of overtop-

ping, erosion of the granular layer close to the road surface can compromise the shoulder and, especially under repeated traffic loading, evolve into severe surface damage.

The foundation models constructed and compacted to standard specifications and exposed to moderate flow velocities still experienced consistent erosion, while deposition remained limited and variable. This challenges the common practice of associating transportation infrastructure fragility to inundation depth alone [14, 17, 18], or of generalizing water surface position and assuming that moderate velocities are unlikely to cause severe damage [15]. This is also consistent with post-event evidence from the 2002 Dresden flood, where substantial road damage was observed at flow velocities below 1 m s^{-1} [16]. Similarly, post-event analysis of the July 2021 European floods concluded that structural instabilities were better explained by flow velocity than by water depth [6], directly supporting our experimental findings. However, damage may still correlate strongly with water depth when depth and velocity co-vary, a pattern typical of riverine flooding but less so of pluvial floods.

We argue that the mismatch between current flood risk modeling practice and the physically driven failure of roads can be reduced by representing hydrodynamic forcing more explicitly. Hazard representation should resolve flow velocity in finer classes and relate water depth to the elevation of the shoulder. Such discretization would enable fragility models that distinguish failure conditions by hydrodynamic and geometric class. These hydrodynamics carry three operational consequences. First, erosion begins rapidly and intensifies sharply as flow velocity increases, leaving little time for effective reactive intervention during high-magnitude events. Proactive measures are therefore essential, particularly in the context of projected global urban expansion [33, 34]. Second, damage can accumulate across successive smaller events if initial erosion remains unrepaired, which makes monitoring erosion through field-based surveys and remote observations valuable [7, 35]. Because erosion depth

and cumulative eroded volume were positively related in the experiments, local depth measurements can serve as a first-order indicator of sediment loss and transfer, and volumetric estimates help constrain the likely intensity of local erosion. Third, the enhanced erosion at the longitudinal edges, where the foundation abuts rigid structures, confirms that transitions between granular layers and rigid elements are particularly vulnerable to localized scour and deserve specific attention in design, inspection, and maintenance [6, 36, 37].

In the controlled, full-scale laboratory setting used here, the hydrodynamic range was narrow but representative of field conditions. However, although no direct correlation was identified between turbulent kinetic energy and erosion development, turbulence-related quantities are commonly associated with erosion under adverse flow conditions in the field [37–39]. The mechanisms identified here therefore apply to an unprotected granular foundation of fixed slope under predominantly longitudinal flow. In the field, slope, surface protection such as vegetation, and more severe and complex hydraulic forcing may further modulate the erosion response. Stronger fluctuations in flow velocity and changes in flow direction in particular warrant future investigations. This work provides a basis for further mechanistic assessment of where and how flood-induced instability begins under different hydrodynamic and physical conditions. Improved damage models will also require the collection and systematic analysis of additional damage data, which remain scarce [3, 13, 16], to inform the large scale implementation of structural and non-structural measures aimed at preventing direct failure and minimizing disruption to road networks [4, 5, 25, 35, 40].

Exposure assessments and engineering strategies that incorporate the identified erosion mechanisms can better protect road infrastructure against future hydrometeorological hazards. These assessments and strategies can be sharpened with vulnerability data, including material properties and historical performance. In resource-constrained contexts that

require prioritization of inspection and protection efforts, these considerations become even more critical. Based on the present findings, the central question for road infrastructure shifts from whether flooding will occur to whether flow will be fast enough and the water surface positioned to trigger progressive erosion at locations vital to structural stability. Our experimental results show that this threshold can be crossed at velocities of about 1 m s^{-1} , a condition that existing damage models leave unresolved. This implies that the fragility of flooded roads may be systematically underestimated by current flood risk approaches.

Methods

Experimental configuration Full-scale experiments were conducted in the high-performance morphological flume at the Hubert-Engels Laboratory, TUD Dresden University of Technology [41], with the aim of reproducing floodwater flowing longitudinally along a representative granular road foundation under varying hydrodynamic conditions, thereby inducing material redistribution on the foundation profile. The flume is 35 m long and 4 m wide, and a removable wall divides it into two parallel 2 m-wide channels. Two movable gates are used at the downstream end to regulate the water level. The channels are elevated 1.65 m above ground level to accommodate an underlying recirculation reservoir and have a slope of 0.1%. The system is fully automated and equipped with two pumps, each with a capacity of 500 L s^{-1} . To achieve the target flow velocities, all experiments were performed in a single channel.

The experimental setup comprised an upstream ingress track, a central testing track, and a downstream egress track (Figure 1a). The ingress and egress tracks were designed to progressively concentrate and disperse the flow along the foundation, thus promoting predominantly longitudinal flow conditions within the test section. Both tracks were con-

structed as hollow PVC foam structures filled with limestone. The flume bed was covered with rough carpet to promote the development of a more realistic near-bed boundary layer, prevent slippage of the installed inserts, and protect the flume floor during compaction. A rubber mat was placed at the interface between the foundation material and the PVC structures to increase roughness and simulate contact with rigid structural surfaces.

Within the testing track, a 5 m-long granular foundation was compacted along the right-hand wall for each experiment. The model had a trapezoidal cross-section with a base width of 1.2 m and a height of 0.4 m (Figure S1a). The wall-side face was vertical, while the exposed face had a slope of 1:1.5 (vertical:horizontal), which is consistent with the geometry of a typical road foundation. The 0.6 m-wide crest represents the roadway platform. The crest was not overtopped, so it was left unpaved to allow for inspection.

Aggregate & construction procedure A 0 mm to 32 mm aggregate commonly used in Germany for unbound base and frost protection layers was ordered from a local quarry and received in 6 bulk bags (total mass ≈ 7 t). Material management was performed by the Claus-Köpcke Laboratory at TUD Dresden University of Technology [42]. The material was characterized as Paleozoic diabase, with rough, angular particles. Particle size distributions were determined for samples from each bulk bag by sieve analysis in accordance with DIN 66165-1 [43] and DIN 66165-2 [44]. According to TL SoB-StB 20 [45], the particle size distributions of all bulk bags fell within the gradation envelope for a subbase course (Figure S6). However, three of the bulk bags slightly exceeded the upper limit specified for a base course for fractions from 2 mm to 8 mm. Since the remaining bulk bags accounted for approximately 97 % of the necessary volume for compaction, the coarsest of the finer bulk bags was used to reach and complete, during reconstruction, the required volume. The recovered eroded material was also used in subsequent experiments. The resulting mixture was intermediate

between a subbase and a fine base material, leading to a more conservative assessment since finer grains are more likely to be transported by water. Considering the permitted tolerances for field applications, the mixture also aligned with global limits for subbase and base layers (Figure S6) [46]. In addition, internal stability was tested using eight empirical criteria (Table S5). The material was deemed internally stable because it generally satisfied the evaluated criteria, with one marginal exception, where $d_{90}/d_{60} \approx 106 \%[1.86\log(d_{90}/d_{15}) + 1]$ [47]. Therefore, structural destabilization was assumed to be exclusively associated with external erosion.

Before foundation construction in the flume, a compaction trial was performed in a test area of approximately 2×2 m, using a lift thickness of 20 cm, to determine the dynamic deformation modulus (Figure S7). Compaction was performed using a vibratory plate compactor. The material was conditioned to a target moisture content of 6.6 %, corresponding to the optimal content obtained from a Proctor Compaction Test performed according to DIN EN 13286-2 [48]. This target was implemented under expert laboratory supervision to reproduce near-optimum compaction conditions. Compaction quality was assessed with a Light Weight Deflectometer (LWD) in accordance with TP BF-StB [49], yielding an average dynamic deformation modulus of $E_{vd} = 69.75 \text{ MN m}^{-2}$. Because the trial was performed on a concrete floor, the measured E_{vd} was attributed primarily to the compacted granular layer. According to ZTV E-StB 17 [50], $E_{vd} > 50 \text{ MN m}^{-2}$ is considered satisfactory. The construction in the flume used the same procedure (Figure S8). To properly execute the slope, the exposed face was initially compacted manually and then with the vibratory plate compactor.

Hydrodynamic scenarios & instrumentation Two hydrodynamic scenarios were defined for the long-duration experiments (6 h) conducted under quasi-steady, fully turbulent

($Re \sim 10^5$), subcritical flow ($Fr < 1$) reported here. Before these long-duration experiments (E3 and E4), three preliminary trials (E0, E1, and E2) were conducted to validate and optimize the instrumentation and experimental design and to ensure the reproducibility of the results. A full description of these trials is available in Text S1. They led to improved fixation of the hollow structures, extension of the egress track to prevent backwater effects, adjustment of discharge to remain within the flume’s operating limits while preventing over-flow, and optimization of measurement intervals. It was also verified that the final design (Figure 1a) produced a predominant longitudinal flow. Given the performance limits of the flume and the measured flow velocities, the discharges for the long-term experiments were set to 250 L s^{-1} and 350 L s^{-1} .

The selected discharges spanned characteristic longitudinal flow velocities around 1 m s^{-1} . Velocities beyond this range were not tested due to technical and conceptual reasons. Technically, it is difficult to achieve velocities above this limit in large-scale laboratory experiments, and increasing the flow rate does not automatically increase the velocity, as energy dissipates before it reaches the test section. Second, this range is of particular interest because widely used flood damage functions for roads either relate damage solely to water depth [14, 17, 18] or assume that velocities of this magnitude do not cause important damage [15].

During the experiments, a high-resolution acoustic Doppler velocimeter (ADV; Vectorino) [51] was used to measure the three-component flow velocities in the streamwise (x), lateral (y), and vertical (z) directions at an approximate depth of 10 cm and a lateral distance of 20 cm from the foundation face, with a signal-to-noise ratio > 11 . The ADV probe was mounted on the movable traversing bridge integrated into the flume, enabling controlled positioning along the testing track (Figure S1b). The use of a single ADV prevented inter-

instrument variability, including probe misalignment and bias. Measurements were collected at longitudinal positions corresponding to the midpoints of five consecutive 1 m sections. At each position, flow velocity time series were recorded for at least 60 s at a sampling interval of 0.04 s.

Two communicating vessels, located 0.25 m and 3.75 m downstream from the start of the testing track and integrated into the flume automation system, recorded the water depth (h) at intervals of 1 minute (Figure S1b). Clamp-on ultrasonic sensors, also integrated into the flume automation system, recorded the discharge in the suction line. After the pump was turned on, there was a transient period until the target discharge was reached, which then marginally fluctuated over time. However, the fluctuations observed in the flume differed from those in the suction line due to the intermediary components between the pump and the testing track. Discharge fluctuations along the testing track were captured by the measured flow velocities. After the pump was turned off, a transient period also occurred before it fully stopped.

Because most erosion occurred during the early stage of loading, the long-duration experiments were divided into seven consecutive hydraulic loading intervals: three intervals of 30 min, followed by three intervals of 60 min, and a final interval of 90 min (Figure S1c). At the start of each experiment, the flume was pre-filled to a depth of 0.30 m without imposed discharge, such that flow velocities were negligible. This level was used as the control water depth to regulate the height of the movable gate. After each loading interval, the flume was drained to allow surveying of the granular surface.

Temporal morphology To quantify the temporal evolution of material redistribution, foundation profile topography was surveyed using a scanning robotic total station (Nova MultiStation MS60) [52]. Surveys were conducted (i) before water was introduced into

the flume, representing the initial dry surface, (ii) after filling and subsequently draining the flume, to assess whether wetting alone induced morphological change, and (iii) after each loading interval in the drained flume. Underwater measurements were not performed because the length of the test section, combined with turbidity caused by suspended fines from erosion, prevented the acquisition of reliable data.

All scans were acquired from a fixed site on the left-hand flume glass wall, located approximately 3 m upstream of the start of the test section (Figure S1b). Instrument positioning was referenced to the laboratory coordinate system, which comprises 19 permanently installed georeferenced control points on the hall pillars and the west wall. For each survey, the instrument was oriented by resection using at least three control points, including at least one located in a different azimuthal direction, resulting in a positioning accuracy of at least 1 mm in both plan and elevation. This procedure yielded scaled, georeferenced point clouds. In addition to the scans, the instrument acquired series of photographs during each survey and enabled high-precision point measurements.

Statistical analysis The water depth measurements from the most stable phase of the flow were used to derive the water line along the flume via linear interpolation using ordinary least squares (OLS). For each longitudinal section, the streamwise mean velocity (v , in m s^{-1}) was computed at its midpoint following the volumetric flow rate standard formula

$$v = \frac{Q}{A} \quad (1)$$

where Q is the discharge and A is the flow cross-sectional area.

To characterize the energetic content of turbulent velocity fluctuations near the foundation, the turbulent kinetic energy per unit mass (k , in $\text{m}^2 \text{s}^{-2}$) was calculated from the

three velocity components measured by the ADV as

$$k = \frac{1}{2} (\sigma_x^2 + \sigma_y^2 + \sigma_z^2) \quad (2)$$

where σ_i denotes the standard deviation of the fluctuating velocity components in the x , y , and z directions.

To relate foundation morphological evolution to hydrodynamic variables, the point clouds were cropped to include only the initial surface of the compacted aggregate and then segmented into five 1 m longitudinal sections. Morphological change within each section was quantified for each run relative to the initial, non-eroded surface using (i) maximum erosion and deposition depths and (ii) erosion and deposition volumes. Depths and associated distance uncertainty were derived using the Multiscale Model-to-Model Cloud Comparison (M3C2) [53]. Volumes were computed by rasterizing the elevation change field into a 1×1 mm grid and the **2.5D Volume** tool [54] in CloudCompare v2.14.alpha [55], with z as the projection direction. Empty cells were interpolated. Cumulative erosion and deposition volumes were normalized by the wetted area (m^2) and reported as volumetric change per unit inundated area (L m^{-2}). As a local extreme metric, maximum depth was not normalized.

Using the processed datasets, relationships between hydrodynamic drivers and morphological response metrics (erosion and deposition volumes and maximum depths) were examined for the first run of each experiment, whereas the relationship between the two response metrics (depth–volume) was assessed across all runs. Relationships between hydrodynamic drivers and morphological metrics were visualized using LOESS smoothing (span = 0.75) [56]. For the depth–volume relationship, robust linear models were fitted by M-estimation using the **MASS** package in R [57], and slope significance was assessed with the robust F-test implemented in the **sfsmisc** package [58].

Temporal trends in the response metrics were analyzed by OLS using both linear ($y \sim x$) and log-linear [$y \sim \log(x)$] formulations. In addition, OLS models were fitted to predict erosion responses (maximum depth and cumulative volume) as a function of v and loading time (t), testing both additive [$y = \beta_0 + \beta_1 v + \beta_2 \ln(t)$] and interaction [$y = \beta_0 + \beta_1 v + \beta_2 \ln(t) + \beta_3 v \cdot \ln(t)$] formulations, where β_i denotes the estimated regression coefficients. The best models were selected using the corrected Akaike information criterion (AICc) [59], which is suitable for smaller datasets.

The two-dimensional visualization of depths was done by projecting them in the x - z plane and creating a raster with a 1×1 mm grid size. Remaining gaps in the gridded surface were filled by assigning each empty cell the value of its nearest non-empty neighbor, identified via a k-d tree nearest neighbor search using the RANN package in R [60]. Density curves were generated using the same grid strategy and a bandwidth factor 20 % larger than the default bandwidth for smoothing. The depths in the range from -0.001 m to 0.001 m were excluded because they fall within the precision of the measurements. In the three-dimensional visualization, depths are shown as individual points. All statistical analyses and visualizations were conducted in R 4.3.3 [61].

Data availability

The data generated in this study are available at <https://data.goettingen-research-online.de/privateurl.xhtml?token=a4b4efcb-046a-4f13-b661-6a903f36826d>.

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