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Sand-fraction transport and mixing in a sand-and-gravel beach face: insights from wave flume experiments

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Abstract Predicting the morphodynamics of coarse-grained beaches remains challenging due to complex interactions between sediment heterogeneity, hydrodynamic forcing, and subsurface processes. This study explores hydro-sedimentary dynamics in composite and mixed sand-gravel beaches using reduced-scale physical modelling in a glass wave flume. Bimodal low-density analogues, PET granules (gravel) and polymer abrasive (sand), enabled real-time observation of sediment transport and morphological evolution under controlled wave scenarios with and without water level oscillations. Experiments reproduced key features of natural gravel beaches, including steep foreshore slopes, crest formation, and beach step development. Fine particle infiltration into the coarse matrix generated an internal sediment bar that migrated landward and aggraded, modifying subsurface permeability and driving morphological changes such as shoreline retreat and slope reduction. These adjustments influenced swash zone dynamics and sediment mobility. Despite scaling constraints, the results provide first-order insights into subsurface processes that are difficult to observe in situ. Findings suggest that fine-coarse sediment interactions may enhance wave energy dissipation, with potential implications for coastal flood mitigation. Further investigation using advanced instrumentation is needed to resolve subsurface hydro-sedimentary processes with greater precision.

Non-technical summary Beaches made of a mix of sand and pebbles change their profile shape in complex and difficult-to-predict ways. Their behaviour is influenced not only by waves and tides, but also by how water circulates within the beach. The interactions and arrangements between the two particle sizes affect beach permeability, and consequently how the beach absorbs wave energy and reshapes over time. To explore these processes, this study used a small-scale beach model in a laboratory wave tank. Lightweight plastic particles were used to simulate sand and gravel, making it possible to closely observe how the beach changed during wave action and water level shifts. The experiments successfully recreated features commonly seen on natural coarse sediment beaches, including steep upper slopes, the formation of a raised crest near the high-water mark, and a submerged step at the base of the beach. One key finding was the formation of hidden sandy layers that gradually moved inland, reshaping the beach and influencing how water flowed through it. These results suggest that the mix of sand and pebbles may help absorb wave energy, potentially reducing coastal flood risk.

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1 Introduction

The morphodynamics of beaches composed of sand and gravel is considered more difficult to predict in comparison with beaches with a single dominant type of sediment (Kirk, 1980; Buscombe and Masselink, 2006; López-Ruiz et al., 2020). According to the classification of Jennings and Shulmeister (2002), there are two main types of sand and gravel beaches: (1) mixed sand-and-gravel beaches (MSGB) where sediment is fully mixed across the beach profile, and (2) composite beaches (CB) in which gravels are located on the steeper upper beach and the sand is located in the gently sloping lower beach. A third type has also been described, in which the upper part of a composite beach—typically composed of pure gravel—is instead made up of a sand-gravel mixture similar to that found on MSGB (Horn and Walton, 2007). The percentage of sand in coarse-grained beaches represents one of the major uncertainties as it can be different from one site to another according to the geological framework and the hydrodynamic forcings (Mason and Coates, 2001; Holland and Elmore, 2008), and because of its high degree of spatial and temporal variability (Horn and Walton, 2007; Bayle et al., 2021; Matsumoto et al., 2025).

The wide range of grain sizes in the beach profile has a significant influence on the in-/exfiltration processes. These processes are key hydrodynamic parameters in the swash zone, influencing wave run-up and overtopping, and thereby playing a crucial role in beach morphodynamics (Holmes et al., 1997; Mason and Coates, 2001; Kulkarni et al., 2004; Austin and Mas-

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selink, 2006b). The study of in situ swash processes is in itself challenging, but it is all the more so in coarse-grained beaches where the measurement instruments can easily be damaged (Masselink et al., 2010). Recent developments in non-intrusive techniques, such as laser scanners, have improved our ability to quantify surface hydro-sedimentary processes (e.g., Almeida et al., 2015; Bayle et al., 2023). In parallel, the use of large-scale flume facilities has proved in the last decades to be one of the most appropriate solutions for studying swash processes in coarse-grained beaches (e.g., López de San Román-Blanco et al., 2006; Williams et al., 2009; Polidoro et al., 2018; Blenkinsopp et al., 2022; Foss et al., 2023). Yet despite these advances, subsurface hydro-sedimentary processes remain difficult to investigate on a 1:1 scale. Several studies managed to track some subsurface beach parameters, such as water table elevation, pore water pressure, hydraulic conductivity or moisture content (e.g., Kulkarni et al., 2004; Isla and Bujalesky, 2005; Austin and Masselink, 2006b; Masselink and Turner, 2012; Austin et al., 2013; Turner et al., 2016), but do not provide a dynamic vision of all the processes occurring below the sediment surface.

Reduced-scale physical models in glass-sided flumes seem to be more suitable for studying underground instantaneous process as they allow the observation of the beach profile cross-section in real time. Most of the studies that have implemented this kind of physical model used natural material and focused on beach morphology (e.g., Powell, 1990; Quick and Dyksterhuis, 1994; Holmes et al., 1997; Loveless et al., 1997; Kobayashi et al., 2011, 2015), while a few others focused on sediment sorting (Petrov, 1989) and nearshore hydrodynamics (Powell, 1989). Even though the challenging scaling of mixed sediment impedes the proper modeling of the whole beach dynamics, reduced-scale models can nevertheless bring valuable information on specific mechanisms (Loveless et al., 1997; Mason and Coates, 2001). An existing solution that has been tested to reduce scaling errors in physical models is to use analogue materials, such as plastic, with lower densities than natural materials (e.g., Grasso et al., 2009; Berni et al., 2013; Petruzzelli et al., 2013; Rocha, 2016). A further advantage of using plastic materials is the possibility of selecting more rounded particles, rather than the typically angular siliciclastic gravels or crushed anthracite, thereby better representing the geometrical characteristics of natural beach sediments. However, these studies have primarily focused on sandy beaches, and investigations into the use of plastic for reduced-scale physical models of coarse-grained beaches remain scarce (e.g., Hashimoto et al., 2017).

This study investigates subsurface hydro-sedimentary processes that occur within composite and mixed sand-and-gravel beaches, focusing on a scenario where sand is available in the lower foreshore. This sand may be accumulated in swash bars, typically created during accretive conditions, or deposited following the exfiltration of sand after high-energy events. Using a reduced-scale beach model in a wave flume, wave-driven sediment dynamics are simulated with low-density bimodal sediment analogues. The primary goals are: (1) to compare the morphological evolution of coarse-grained beach profiles under different wave energy conditions and mean water level fluctuations in a physical model, (2) to observe the behaviour of fine particles within a porous coarse massif, and (3) to assess the influence of fine sediment when incorporated into the coarse massif on beach morphodynamics.

2 Material and methods

2.1 Scaling approach and sedimentary material

The physical model has been scaled to replicate the particle-size ratio of sand and gravel beaches, estimated to range from 2 to 128 between the finest and coarsest sedimentary particles. As the reduction of particle size results in an increase in cohesion effects that have no place in these types of beaches, it has been decided to work with analogue low-density particles that are easier to transport. Two analogue particles have been selected: 0.20 ± 0.05 mm polymer abrasive representative of the sand fraction, and 2.5 mm polyethylene (PET) granules representative of the gravel fraction (Table 1, Fig 1). The PET granules are sub-spherical, thus representing beaches with rounded gravel; the polymer abrasive is more angular. The abrasive was selected primarily because its density is similar to that of the PET granules, and because its size range produces a reasonable coarse-fine ratio for the mixture. Practical considerations such as price and availability also guided the choice. Its angularity further reduces settling velocity and increases the threshold for motion, providing a conservative analogue for sand transport under scaled conditions. The size ratio between the coarsest and finest particles (c. 1:10) corresponds to the approximate scale reduction of the experiment. Thus, the scaling of the experiment is less than 1:14, the threshold estimated by Ranieri (2002) beyond which the scaling effects with lightweight sediment can increase significantly. With this scale, the abrasive polymer corresponds in real size to particles of 2 ± 0.5 mm (from coarse sand to granules), while PET granules correspond to particles of 2.5 cm (pebbles) (Wentworth, 1922). The wave conditions are scaled according to a Froude similitude (main gravity waves forcing), as recommended by several authors (e.g., Dean and Dalrymple, 2001; Grasso et al., 2009; Henry and Aberle, 2018).

The particle settling velocities and the fluid shear velocities at the threshold of motion are measured for both particle sizes. The experimental setup for measuring settling velocities consists of a 2 m high plexiglas sedimentation column, a Nikon D700 camera, and a strobe flash. Particles are manually released from the top, and as they pass through the camera field of view, a 2-second exposure captures multiple positions using synchronised stroboscopic flashes. Analysis of over 20 images per particle yielded average settling velocities of 0.14 m/s for PET granules and 0.02 m/s for the polymer abrasive (Table 1). According to the formulations of Soulsby (1997), settling velocities of 2.5 cm pebbles (0.8 m/s) are 5 to 6 times higher than that of PET granules, while settling velocities of 2 mm sand (0.22 m/s) are 11 times higher than that of the polymer abrasive. The threshold velocity of water for particle motion was determined in a 2 m long open-channel flume using a recirculating water system and an acoustic Doppler velocity profiler (ADVP – Nortek Vectrino Profiler) to measure flow velocities. Velocity profiles were recorded near the sediment bed, and the critical shear velocity was extracted via logarithmic regression of flow speed against heights, revealing distinct boundary layer characteristics for PET granules and the polymer abrasive. PET granules exhibited a thicker boundary layer (4 cm) and higher shear velocity (0.02 m/s) compared to the polymer abrasive (1.5 cm, 0.01 m/s).

These values are then used to calculate the Shield, Rouse and Reynolds numbers (Table 1). The Shields numbers show that PET granules and the polymer abrasive are set in motion at lower velocities than those of quartz gravel and sand particles, which have Shields numbers of 0.04 and 0.05, respectively. The lower values of the Reynolds number of the PET granules and the polymer abrasive indicate a greater influence of viscous forces on the analogue particles. The difference between natural and analogues particles is higher for pebbles and PET granules as pebbles in nature are fully dominated by inertial forces.

Table 1 Characteristics of the sedimentary material used during the experiment and their natural equivalent made of quartz. The settling velocities and the shear velocity of the quartz particles are calculated from the formulations of Soulsby (1997) and Paphitis et al. (2001), respectively.

		Physical description					Hydrodynamic features		Dimensionless parameters		
Material		Composition	Shape	Size (mm)	Density ($g{\cdot}cm^{-3}$)	Bulk density ($g{\cdot}cm^{-3}$)	Settling velocity (w_s - $m{\cdot}s^{-1}$)	Shear velocity (u^* - $m{\cdot}s^{-1}$)	Shields (θ_{cr})	Rouse (P)	Shear Reynolds (Re*)
Natural	Gravel	Various	Various	25.0	2.65	1.80 ± 0.20	0.80	0.13	0.05 ± 0.02	15.47	2370.45
	Coarse sand	Quartz	Rounded	2.0	2.65	1.60 ± 0.20	0.22	0.03	0.04 ± 0.02	17.86	45.06
Analogue	PET granules (AMP Polymix)	Polyethilene Terephthalate	Spheric	2.5	1.40 ± 0.01	0.88	0.14	0.02	0.01	15.70	41.30
	Polymer abrasive (Dieblast)	Urea	Angular	0.20 ± 0.05	1.49 ± 0.04	0.75 ± 0.05	0.02	0.01	0.02	5.60	1.10
Ratio											
Natural / Analogue	Gravel / PET granules	-	-	10.0	1.89 ± 0.01	2.05 ± 0.23	5.65	5.73	4.70 ± 2.00	0.99	57.40
	Coarse sand / Polymer abrasive	-	-	10.0 ± 2.5	1.78 ± 0.05	2.13 ± 0.30	12.82	4.06	1.90	3.19	40.96
Natural / Natural	Gravel / Coarse sand	-	-	12.5	1.00	1.13 ± 0.19	3.66	4.21	1.24	0.87	52.61
Analogue / Analogue	PET granules / Polymer abrasive	-	-	12.5	0.94	1.17 ± 0.08	8.29	2.99	0.50	2.80	37.55

2.2 Wave flume setup

The experiments are carried out in a 16 m-long, 50 cm-wide and 65 cm-high flume equipped with a vertical piston-type wave generator (Edinburgh Designs Ltd, UK) able of generating waves in shallow water and absorbing reflected waves. The wave periods that can be generated range from 1 to 3 seconds with maximum amplitudes that can reach 15 cm, whether in monochromatic waves or a frequency spectrum.

A SICK-DT500 laser sensor (SICK, Germany), mounted on a rail along the flume, was used to perform the topo-bathymetric surveys. The position of the measure is determined, with a resolution of 1 mm, by optical reading of a bar code. The surveys are performed directly through the water column, avoiding the need to drain the flume and thereby eliminating any problems associated with water removal. To account for the change in light velocity between air and water, a corrected laser velocity is applied below the water surface. The measurement accuracy of the laser is estimated at 3 mm. In addition to the topo-bathymetric surveys, profile photographs are taken through the glass of the flume to obtain a qualitative overview of the surface particle-size state and the underground configuration of the particles.

The water level variations induced by waves are measured using resistivity gauges with an acquisition frequency of 32 Hz.

2.3 Experimental protocol

The initial beach profile is built exclusively with PET granules which are reworked by wave action until they reach a state of morphological equilibrium (Fig 2). A

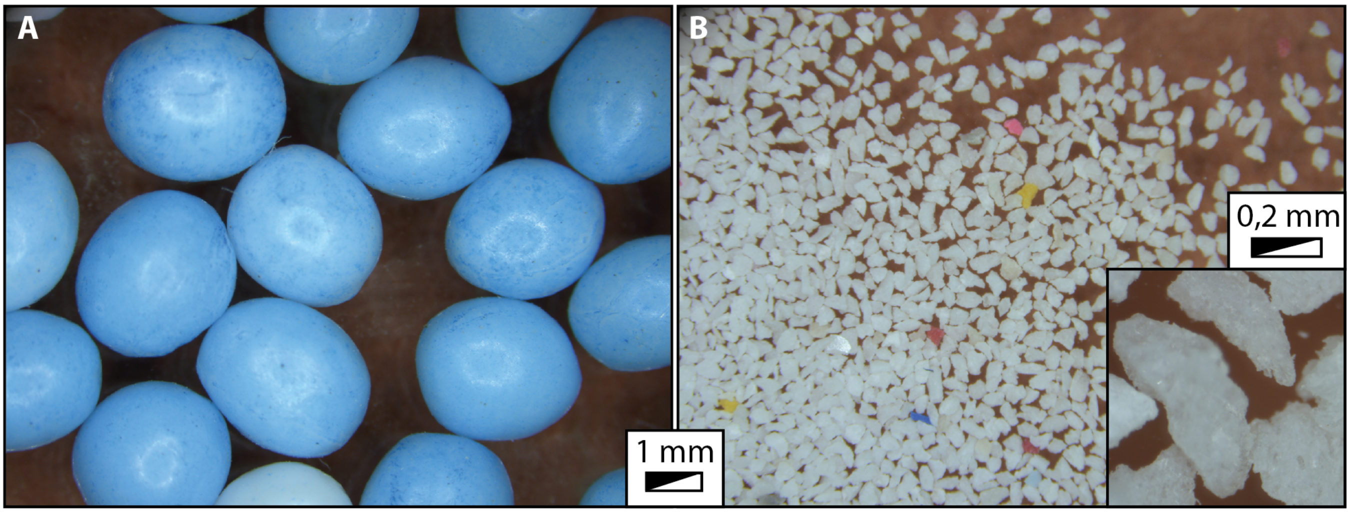

Figure 1 Sedimentary material used during the experiments: a) PET granules as gravel analogue, b) Polymer abrasive, as sand analogue.

volume of 2.3 m^3 (200 kg) is placed in front of an open-pores foam, covered by a permeable geotextile, with an inclination of 12.5% (Figs 2a, b). The foam provides structural stability and reduces the volume of PET granules required, while the geotextile is designed to prevent the passage of sediment while allowing water to flow through. The height of the initial sedimentary stock is equal to the water level in the flume, set at 30 cm. Regular waves of an amplitude of 4 cm and a period of 2 s are set up during four hours to enhance the migration of the sediment up the slope until it reaches an equilibrium state (Fig 2c, Table S1). This initial step consistently produces similar morphologies, demonstrating strong experimental replicability (Pancrazzi, 2022). Unlike most beach physical models, this initial set up includes an offshore sediment stock, and a low-thickness section at the lower boundary of the beach profile (2.2-2.6 m, Fig 2c), which allows sediment bypass to and from the offshore stock depending on wave configurations and morphodynamics, thereby simulating natural sediment transport processes.

A first phase of experiments consists in assessing the wave conditions to be used from the equilibrium state. Two wave configurations using a JONSWAP spectrum (North Atlantic wind waves) are tested: a low energy configuration with a significant wave height (H_s) of 1.64 cm and a peak period (T_p) of 1.54 s, and a higher energy configuration with H_s = 5.14 cm and T_p = 2 s (Table S1). When converted to prototype conditions using standard Froude scaling for a 1:10 geometric model, these laboratory waves correspond to approximately 0.16 m waves with a period of 4.9 s and 0.5 m waves with a period of 6.3 s, respectively. However, this scaling does not take into account the differences in density or in the magnitude of the settling velocity or shear velocity. The selected configurations, even though they are undersized compared to what can be expected on a real scale, enable the reproduction of processes and morphologies comparable to those observed in nature. For this phase, the beach is exclusively composed of PET granules. In order to represent the tidal oscillation, water level variations of 5 cm over cycles of 50 min are applied throughout the entire phase, with three tidal cycles imposed for each configuration (Fig 3). The experiments do not replicate the prototype ratio of the tidal cycle period over the wave period. Thus, the experimental beach profile is subjected to fewer waves during the water level variation cycle. However, it appears that the low density of the analogue sediment enhances sediment transport, allowing the beach to adjust rapidly and reach a near-equilibrium profile at each water level stabilization stage. This accelerated response supports the use of shortened tidal cycles within the practical constraints of the laboratory setting. The aim was therefore not to replicate natural timescales, but to capture the dynamic response of the profile to repeated water-level changes and to investigate relative trends in sediment transport and morphological evolution. Topo-bathymetric surveys and side photographs were collected at both high and low water levels to document these adjustments.

The second phase of experiments consists in combining the two sediment sizes, PET granules and polymer abrasive, which are referred to as ”gravel” and ”sand”, respectively, in the rest of the paper. Once the equilibrium state is reached with the gravel, 15 kg of sand are placed at the bottom of the beach profile (Fig 2c). Further additions of fine particles are made when a new equilibrium state is reached. At the end, 35 kg of sand are integrated in the system which corresponds to 15% of the total sediment weight. The wave conditions used during this step are similar to the one of the high energy configuration: H_s = 5.06 cm and T_p = 2.12 s (Table S1). The experiment was carried out over approximately 14 hours (835 minutes in total) under constant water level conditions, allowing the beach to reach a new equilibrium after sand insertion. It was then extended by an additional 4 hours, during which five cycles of water level variations (±5 cm every 50 minutes) were applied, replicating the conditions of the first phase (Fig 3). Topographic profiles acquired at three times during the test sequence (145, 835, and 1075 min) are used to illustrate the morphological evolution of the beach. These profiles are referred to as M-t145, M-t835, and M-t1075, respectively.

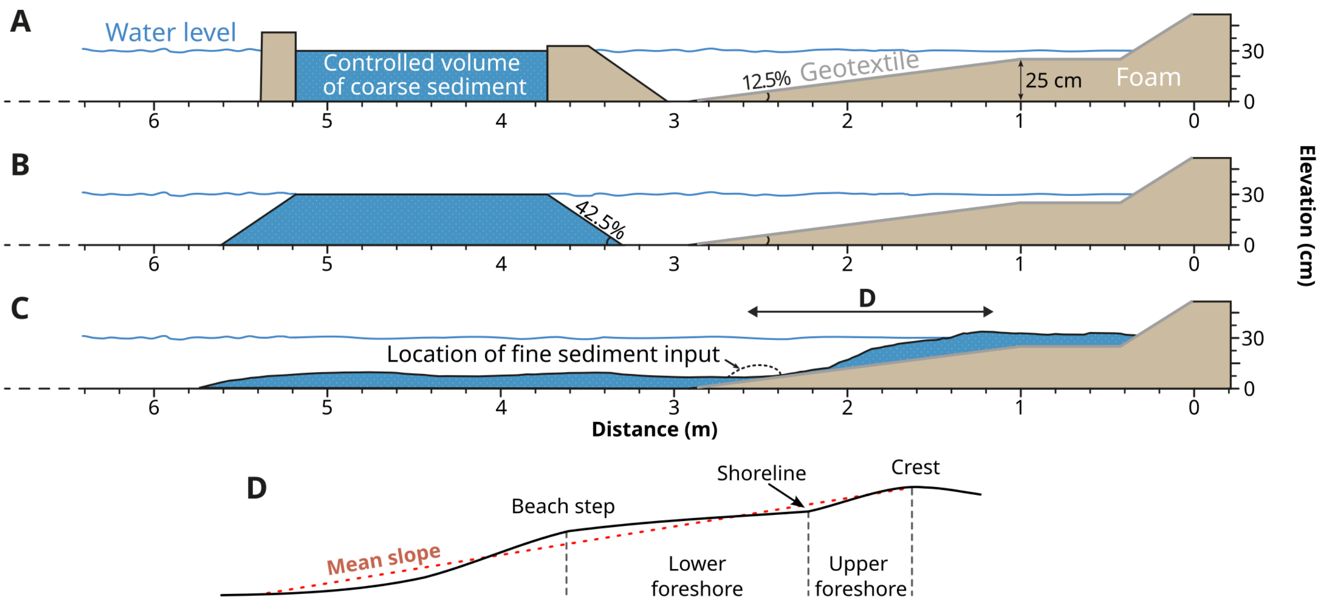

Figure 2 Experimental setup of the beach profile in the flume: a) Insertion of PET granules (gravel analogue) in front of the foam (2.3 m^3), b) Shims removal, c) Morphological equilibrium state from where the experiment begins, with indication of the location where the polymer abrasive (sand analogue) is placed, d) Classification of the beach profile sections.

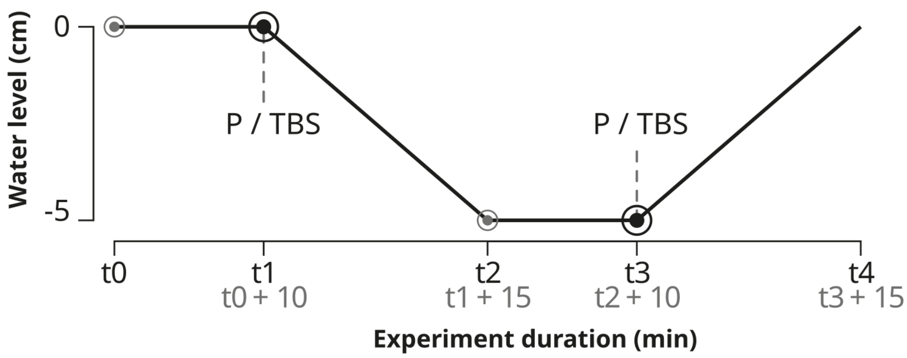

Figure 3 Water level variation protocol. P: photographs, TBS: Topo-bathymetric survey.

3 Results

3.1 Initial beach morphology

The initial morphology of the beach, once the equilibrium state has been reached, is characterised by a width of 1 meter and an average slope of 22.8% (Fig 4 and Table 2). The height of the beach crest is 3 cm above the mean water level, and it protects a sequence of paleo-crests similar to a beach ridge sequence. The volume of the sedimentary stock that is no longer reworked by waves, and therefore cannot migrate towards the upper beach profile, remains at the bottom of the beach where it forms a topographic flat at an average depth of 22 cm. The transition between the upper beach and the offshore flat, observed between 2.2 and 2.4 m in Fig 2c, is marked by a thin layer of particles, approximately 2 cm in thickness.

3.2 Beach morphology (Phase 1 – Unimodal sediment)

The beach morphology during the low-energy wave configuration (LEP) is similar to that of the initial profile (IP), as shown in Fig 4. The beach width remains similar (ca. 100 cm), as does the average slope, which is around 24% (Table 2). Both profiles differ in shape of the bottom section, between 150 and 225 cm. The IP has a slightly convex profile, while the LEP is flatter, with a step visible at 170 cm, coinciding with the position of the shoreline at low water level.

With the high-energy wave configuration, the beach profile (HEP, Fig 4) adopts a slightly lower average slope of 20.2% ($R^2 = 0.99$) compared to the one observed in the LEP (Table 2). The beach crest is 2 cm higher and has moved back 2 cm. The increase in crest elevation is accompanied by a steeper beach face, which in this case is around 36.6% instead of 20%. The beach profile is 15 cm wider and has a more complex shape, characterised by a sequence of two pseudo-horizontal “terraces”: a main one in the upper part, between 150 and 175 cm (about -2 cm water depth), and a smaller one between 190 and 195 cm (around -8 cm water depth). Unlike the LEP, which display a notch, the HEP does not provide any clear morphological evidence to infer the shoreline position at low water. Beach widening is promoted in this wave configuration by the transfer of sediment from offshore

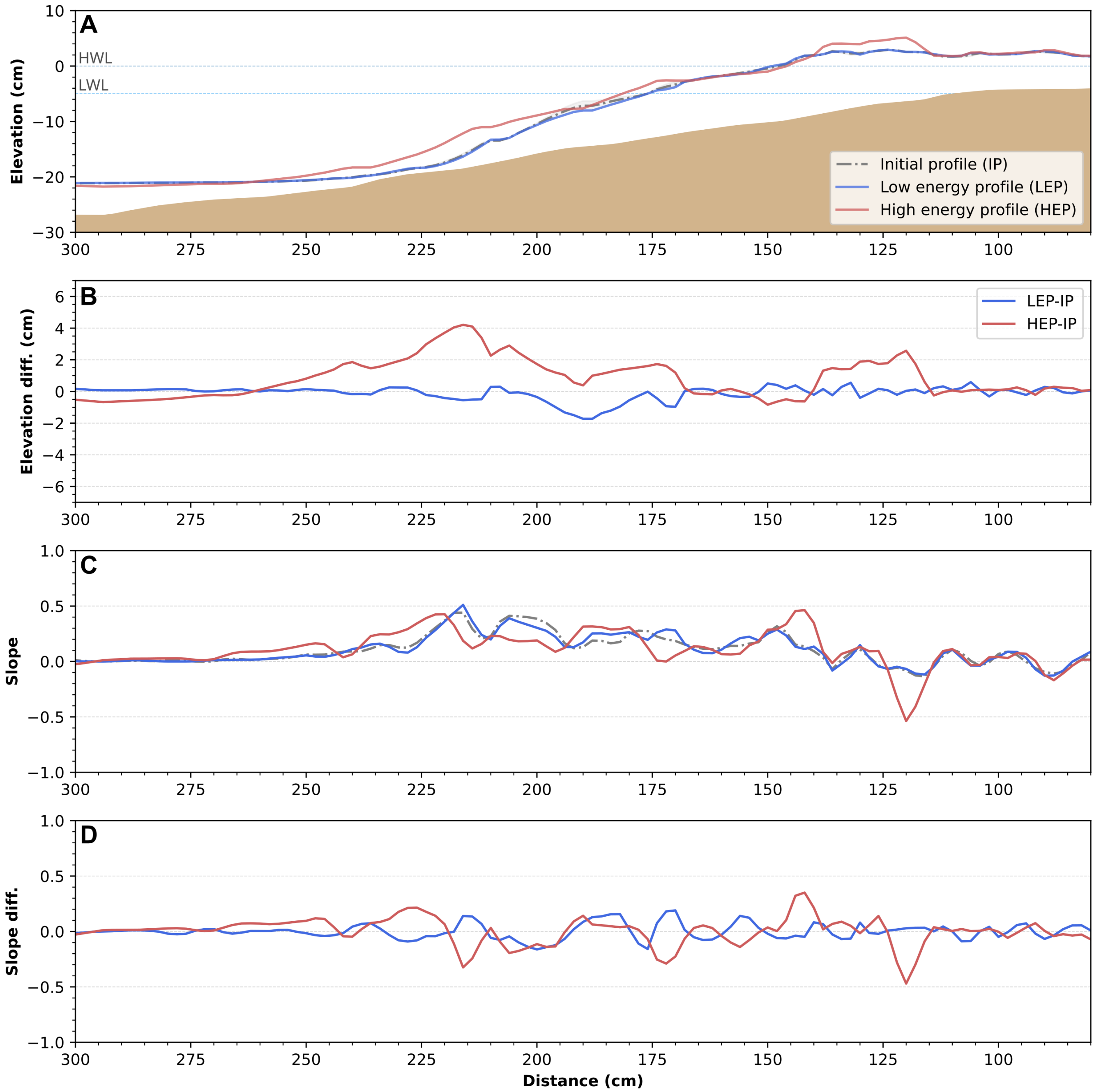

Figure 4 Beach morphology characteristics at three different states: (1) initial equilibrium state (IP), (2) low energy configuration (LEP, blue lines), and (3) high energy configuration (HEP, red lines). a) Elevation, b) Elevation differences, c) Slope, d) Slope differences. IP corresponds to an average profile of the initial morphological states, with a variance envelope.

(distance > 260 cm) to the beach profile, with accretion particularly visible in the lower foreshore between 190 and 260 cm (Figs 4a, b). In terms of sediment volume, around 0.2 m^3 of PET granules were transported, corresponding to approximately 8.5% of the initial stock.

3.3 Beach morphology (Phase 2 – Bimodal sediment)

The incorporation of sand at the bottom of the gravelly profile has a rapid impact on the beach morphology, as shown by the topographic profile at 145 min (M-t145, Fig 5). Although the beach crest height remains similar, the beach face becomes steeper (ca. 57%, Table 2) and the shoreline moves back 20 cm (M-t145, Fig 5a). The foreshore morphological irregularities, visible on the reference profile, are smoothed out, which makes the break point step less prominent (Fig 5a). After 835 min, the beach face keeps a steep slope (ca. 43%, Table 2) and retreat only by 1 cm (M-t835, Fig 5a). The crest position, however, has shifted: it has moved landward by 10 cm and increased in height by about 2 cm. The underwater morphology remains almost unchanged, with the main difference being the reappearance of a step at a depth of 4.5 cm (i.e. 55 cm from the shoreline). The main morphological change on the beach profile occurs at the back-shore, between 95 and 115 cm, where a certain (unquantified) amount of PET particles is deposited by overtopping/overwash.

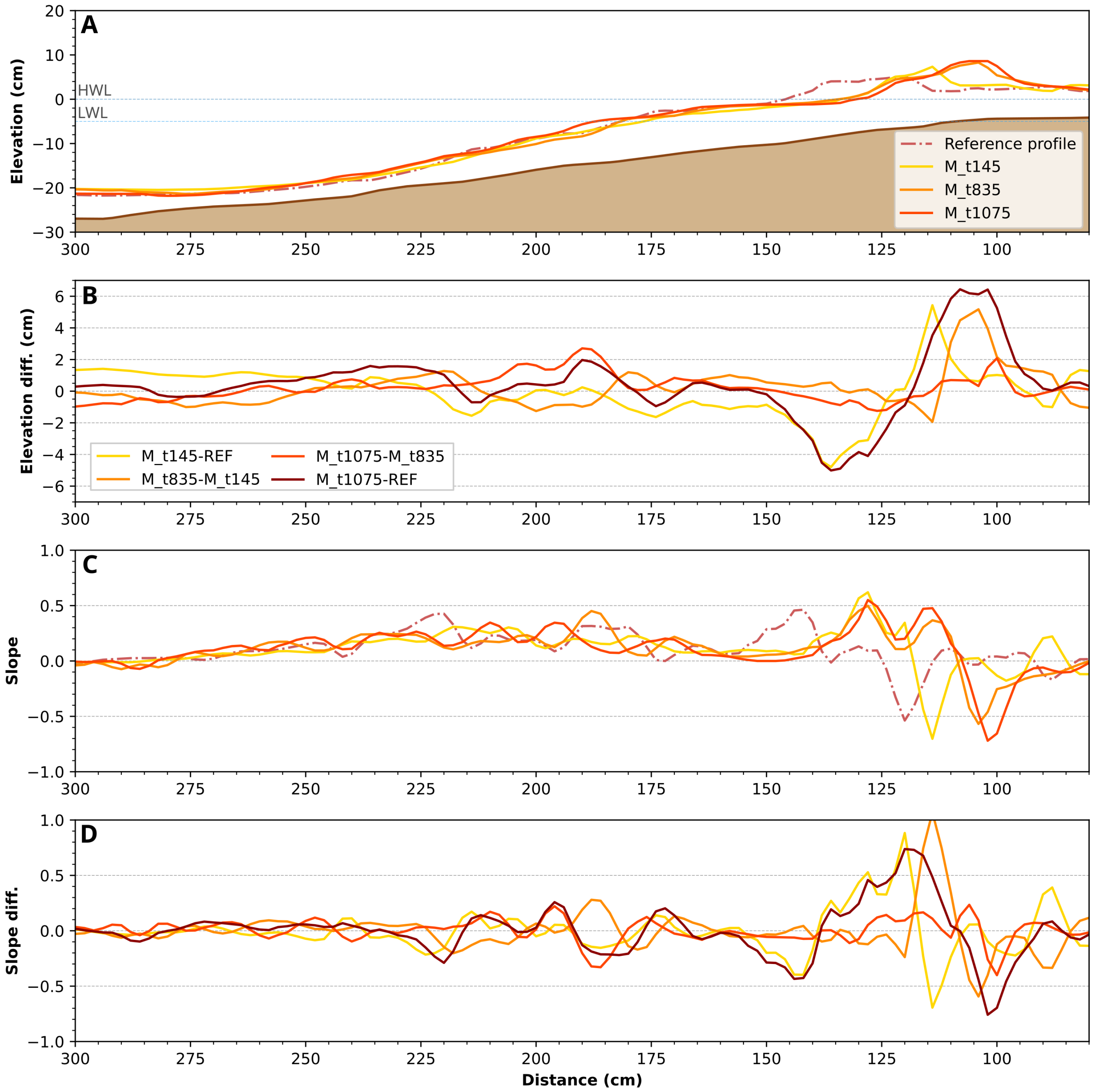

Figure 5 Morphological evolution of the beach composed of PET granules when polymer abrasive is added at the bottom of the beach profile (250 – 300 cm). a) Elevation, b) Elevation differences, c) Slope, d) Slope differences. Three profiles at different times are compared: M-t145, M-t835 and M-t1075. Water level was static water between M-t145 and M-t835, and with 5 cm oscillations between M-t835 and M-t1075. The HEP is set as reference profile.

The water level oscillations set up for the end of the experiment had no major effects on the morphology of the upper beach profile, except the deposition of some additional coarse-grained particles on the back-shore and the better delineation of the break point step 65 cm offshore (M-t1075, Fig 5).

3.4 Infiltration of fine particles

Side-view photographs show the evolution of the fine sediment from the bottom of the beach profile into the coarse-grained beach. A large proportion of the sediment (unquantified) is transported offshore as bed load, forming a sedimentary bed above the coarse particles on which ripples develop (Fig S1). The rest of the sediment gradually rises up the beach slope, infiltrates the porosity of the coarse-grained mass, and accumulates above the foam in contact with the geotextile (Fig 6). The head of the fine-grained sediment body formed within the coarse-grained mass reaches its uppermost position, between the beach step and the upper beach face, after 310 minutes (Fig 6). The fine particles then accumulate on the upper part until they form a bar-like morphology. No stratigraphical surfaces could be observed within the internal structure of the bar.

The migration of the fine particles is not progressive and fluctuates depending on their availability. During phases of sediment availability, the layer of fine particles becomes slightly thicker and progresses landward.

Table 2 Slope values for different sections of the beach profile.

		Mean slope	Foreshore	Upper foreshore	Lower foreshore
Beach profile ID	Experimental set-up	Crest to offshore flat	Crest to break point step	Beach face	Bottom of the beach face to break point step
IP	Gravel Initial state	24.41% (R^2=0.98)	13.33% (R^2=1.00)	18.36% (R^2=1.00)	13.03% (R^2=1.00)
LEP	Gravel Low energy	23.57% (R^2=0.99)	17.29% (R^2=0.97)	20.07% (R^2=0.95)	12.90% (R^2=0.96)
HEP	Gravel High energy	20.20% (R^2=0.99)	15.85% (R^2=0.85)	36.62% (R^2=0.97)	7.85% (R^2=0.94)
M_t145	Sand and gravel High energy	17.45% (R^2=0.98)	13.84% (R^2=0.86)	57.15% (R^2=0.98)	9.96% (R^2=0.97)
M_t835	Sand and gravel High energy	17.60% (R^2=0.99)	12.45% (R^2=0.83)	42.96% (R^2=0.99)	7.50% (R^2=0.96)
M_t1075	Sand and gravel High energy	16.92% (R^2=0.97)	9.66% (R^2=0.66)	45.20% (R^2=0.97)	3.18% (R^2=0.80)

The landward progression is particularly important at the beginning of the experiment, when the upper internal bar is not formed yet, then it slows down. When the bar is already formed, the accretion of fines, at the level of the bar, occurs mainly on its offshore side (e.g., 310–805 min, Fig 6). In the absence of sediment supply, the migration of fine particles is reduced, giving way to a slight downward migration (e.g., 505–700 min, Fig 6). The layer thickness reduction, resulting from this downward migration, is higher below and under the beach step, which means the fine layer thickness becomes less and less homogeneous with time. It becomes all the more irregular when there are water level oscillations (925–1085 min, Fig 6). In this scenario of oscillating water levels, the internal bar of fine particles is able to rise a few centimetres in the porous volume.

At the end of the experiment, the internal bar was approximately 40 cm wide and over 5 cm thick. Observations in cross-section of the beach show that the bar is present across the entire width of the flume (Fig 7a). The presence of fines particles is therefore not an artefact due to edge effects with the glass wall. These observations also show that the bar is massive and composed of highly compacted fine sediments, with coarse-grained particles well integrated throughout the matrix, resulting in a distinctly mixed grain-size composition (Fig 7b).

4 Discussion

4.1 Qualitative validation of morphological scaling

The present experiments do not aim to achieve full dynamic similitude, as several scaling constraints remain inherent to the use of low-density analogue sediments. Instead, the objective is to assess whether the experimental system reproduces the first-order organisation of morphodynamic processes observed in natural coarse-grained beaches. This section therefore provides a qualitative validation of process similarity, based on comparison with field observations and large-scale experiments.

The experiments conducted with PET granules alone (phase 1) reproduce several key morphological features characteristic of reflective gravel beaches, that are observed in the field (e.g., Jennings and Shulmeister, 2002; Austin and Buscombe, 2008; Masselink et al., 2010) and 1:1 scale experiments (e.g., López de San Román-Blanco et al., 2006; Polidoro et al., 2018). These include:

- a concave and steep upper beach face, and foreshore slope values consistent with the observations made on pure gravel beaches (Jennings and Shulmeister, 2002);
- the formation of a berm crest with elevation scaling with the significant wave height (e.g., Weir et al., 2006; Austin and Masselink, 2006a);
- the development of a persistent beach step at the break point, under varying wave energy conditions.

Importantly, the morphological response to wave forcing is coherent with expected behaviour: higher-energy conditions induce beach widening, crest elevation, and increased profile complexity, while lower-energy conditions maintain a more stable and uniform profile. Although sediment mobility is likely enhanced due to reduced particle density, the sequence and spatial distribution of morphological adjustments remain consistent with natural systems. This suggests that, at least at the level of process topology, the experimental configuration provides a realistic analogue of gravel beach morphodynamics.

The introduction of fine particles (phase 2) leads to a marked reorganisation of both surface and subsurface sediment structures. The formation of an internal fine-grained body within the coarse-grained matrix, its progressive landward migration, and its interaction with the beach step are consistent with concep-

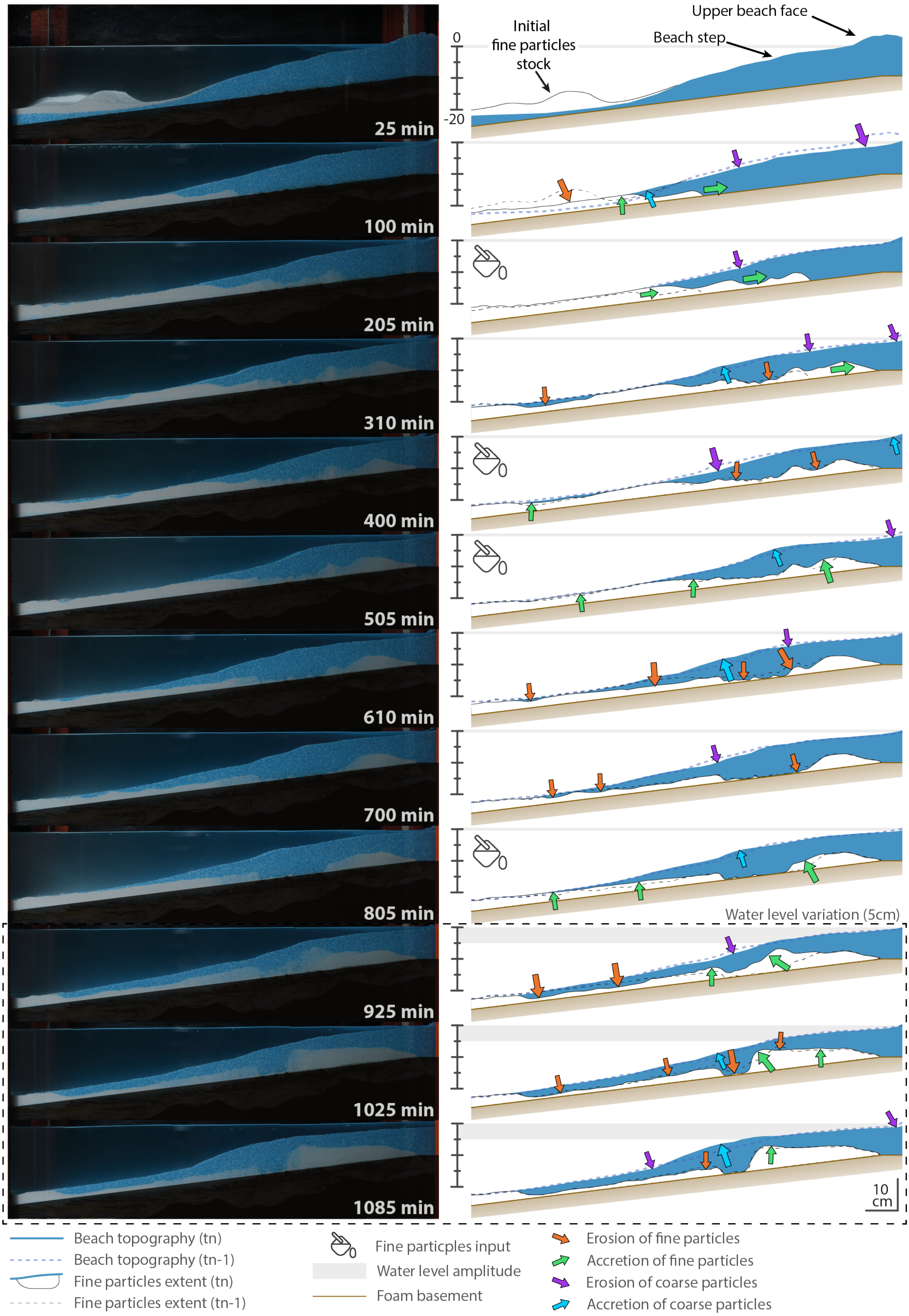

Figure 6 Schematic evolution of the fine-grained particles inside the coarse-grained beach mass.

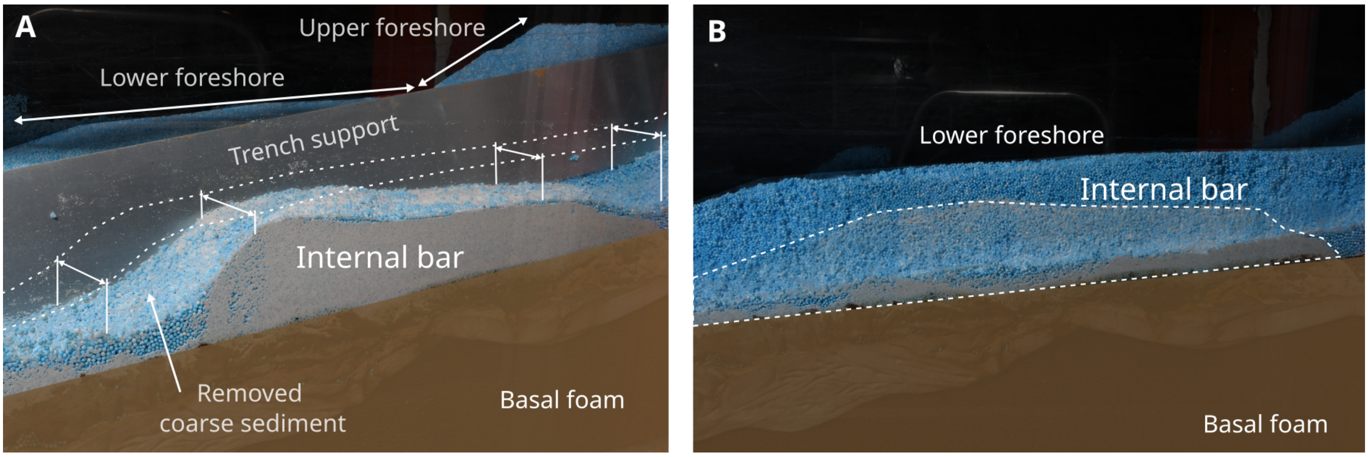

Figure 7 Side-photographs of the fine-grained internal bar: a) After removing the coarse-grained fraction, b) After excavation of the sediment up to the middle axis of the flume.

tual models of sediment mixing and subsurface dynamics in mixed sand-and-gravel beaches. In particular, the observed onshore migration of fines through the porous coarse framework is analogous to the "infiltration wave" described in previous experimental and field studies, while the development of a compact internal bar reflects processes of subsurface sediment accumulation reported in dynamic cobble berm systems (e.g., Bayle et al., 2021) and recent investigations of internal sediment structuring in gravel-dominated environments (e.g., Matsumoto et al., 2025).

The resulting morphological response (shoreline retreat, crest elevation, and modification of profile curvature) is consistent with the expected impact of reduced permeability and enhanced pore pressure in mixed sediment systems. Although these processes are interpreted qualitatively due to the absence of direct hydrodynamic measurements, their coherence with existing conceptual frameworks supports the relevance of the experimental observations.

Taken together, these results indicate that the experimental system reproduces the spatial organisation and sequencing of key morphodynamic processes, despite known limitations in dynamic scaling. The agreement with both empirical observations and conceptual models suggests that the approach captures the dominant feedbacks between sediment transport, subsurface structure, and beach morphology.

4.2 Processes involved in cross-shore variability of porosity

Hydrodynamic parameters such as run-up, flow velocity, turbulence, and groundwater circulation were not measured in these experiments. The following interpretation therefore remains qualitative and aims only to contextualise the observed sedimentary behaviour using established conceptual frameworks from the literature. No quantitative inference of unmeasured hydrodynamic processes is intended.

Fine particles added at the toe of the coarse-grained beach are rapidly reworked and transported either offshore or onshore. As a consequence, particles of the same size are deposited in different hydrodynamic environments enhancing the cross-shore variability of sediment composition. The interaction between fine and coarse particles depends on the position along the profile, and therefore on the energy to which the sediment mixture is exposed: (1) the fine particles offshore (low-energy environment) remain at the surface, completely covering the coarse particles, (2) the particles onshore (high-energy environment) predominantly infiltrate the coarse-grained material vertically downward through the interstices and then landward along the surface of the basal foam (Fig 6). Although this was the dominant pathway observed, we cannot fully exclude that a small fraction of fines transported in suspension or saltation may have been incorporated slightly higher in the beach profile; however, this process could not be quantified with the available measurements.

The depth of infiltration of the fine particles into the interstices of coarse-grained particles can primarily be defined by the size of the particles (Dfine; Dcoarse). According to the classification of Schruff (2018), who defined different infiltration behaviours depending on the ratio Df/Dc, finer particles are assumed to undergo an unimpeded static percolation if the ratio Df/Dc is lower than 0.11. This is in line with the observations onshore, but it does not apply to offshore particles that do not percolate. Thus, parameters such as the horizontal and interstitial flow, the turbulence or the gravitational processes, might also play an important role in the infiltration of fines within the coarse mass (e.g., Frei et al., 2019; Waldschläger and Schüttrumpf, 2020; Alhusban, 2024).

Kinetic sieving, whereby small particles in a moving granular mixture migrate downward while coarser particles are displaced upward (c.f. Frey and Church, 2010), provides a plausible mechanism for the observed vertical redistribution. Within the swash zone, highly unsteady flows combined with repeated agitation of the sediment may create conditions favourable to this process. Its occurrence is likely intermittent and dependent on the ability of the flow to mobilise the coarse fraction. Over time, the imbrication of coarse particles and the progressive filling of pore spaces by fines may reduce interstitial connectivity and modify infiltration pathways.

The present experiments show that fine particles not only migrate downward, but also migrate onshore within the sediment matrix, a behaviour consistent with the "infiltration wave" described by Dudill et al. (2016). In the lower beach, when the supply of fine particles is significant, the coarse-sediment porosity is progressively saturated and the infiltration front migrates onshore. Conversely, when the supply decreases, the infiltration front slows down and vertical redistribution becomes dominant. Similar behaviour has been observed in physical experiments with unidirectional flow (e.g., Diplas and Parker, 1992; Wren et al., 2011; Dudill et al., 2016).

At the beach step, within the sub-surface, little to no accumulation of fine particles is observed. This absence of deposition contrasts with the accumulation immediately landward. This pattern suggests that the step acts as a transition zone in which subsurface transport pathways are modified. While the underlying processes cannot be directly resolved, previous studies indicate that the step corresponds to a zone of intense hydrodynamic activity, where onshore and offshore transport processes converge (e.g., Strahler, 1966; Masselink et al., 2010). The spatial offset between the coarse-grained step and the fine-grained internal bar indicates that these two features are controlled by distinct processes, the former being influenced by surface and near-surface dynamics, and the latter by sub-surface sediment redistribution.

No evidence was found for significant exfiltration of fine particles once they infiltrate the coarse-grained mass. Only changes in the water level allowed partial remobilisation of fines located near the surface. Periods of low sediment supply appear to favour compaction within the sediment matrix, potentially limiting subsequent remobilisation. Previous studies suggest that low-energy conditions favour infiltration, while higher-energy conditions promote exfiltration (e.g., Bergillos et al., 2016; Bayle et al., 2021; Casamayor et al., 2022; Matsumoto et al., 2025). Although not directly tested here, variations in water level appear sufficient to trigger superficial remobilisation at the timescale of the imposed cycles.

Some particles may become effectively trapped at depth where hydrodynamic forcing is insufficient to induce remobilisation (e.g., Dudill et al., 2016). In such cases, reactivation would require erosional processes capable of re-exposing these particles to the active layer (e.g., She et al., 2006; Boano et al., 2014; Zarkogiannis et al., 2018). Further work coupling morphodynamic observations with hydrodynamic measurements would be required to constrain these processes.

4.3 Impact of porosity reduction on the morphodynamics of sand and gravel beaches

The experiments carried out exclusively with PET granules showed the development of a steep upper beach face, the formation of a beach crest, and the establishment of a distinct break point step. The supply of fine particles to the initial coarse-grained beach induces a significant modification of both cross-shore and vertical sediment composition, and therefore of permeability (c.f. Quick and Dyksterhuis, 1994; Holmes et al., 1997; Mason and Coates, 2001). In the present study, the progressive incorporation of fines within the coarse-grained matrix leads to measurable changes in beach morphology, including variations in slope, shoreline position, and crest elevation.

Because fine particles are introduced at the lower part of the profile and remain largely confined below the upper swash zone, the resulting morphological adjustments are spatially heterogeneous. While the average beach slope decreases, the upper foreshore becomes steeper, resulting in a more concave upper beach. As expected, the presence of finer particles (even if not visible on the surface) contributes to the overall reduction in beach slope.

The reduction of the beach permeability associated with fine sediment infiltration modifies the interaction between waves and the beach. A decrease in infiltration capacity is expected to enhance pore pressure within the sediment, thereby influencing swash dynamics and sediment mobility (Polidoro, 2019). In the present experiments, this is expressed by a shoreline retreat and an increase in crest elevation, indicating a shift in the balance between onshore and offshore sediment transport.

In that sense, the experiments carried out represent an interesting analogue showing the transition from pure gravel to composite-type beaches (sensu Jennings and Shulmeister, 2002). This transition highlights the importance of the underlying fine-sediment permeability layer in beach morphodynamics, revealing two contrasting patterns:

1. A thinner, high-porosity coarse layer with little fine-grain support promotes higher transport rates, leading to greater beach instability (e.g., Quick and Dyksterhuis, 1994; Guillén and Hoekstra, 1996).

2. The lower mobility of the uppermost inner bar enables the fixation of the beach step and, consequently, enhances the beach stability.

A key uncertainty in assessing beach stability at this stage lies in the transport rate ratio between the two sediment fractions. Indeed, finer particles within the interstices of coarse-grained particles tend to migrate relatively slowly in comparison with the coarsest particles at the surface. Experimental results in this study show that greater amplitudes of water level oscillations, combined with increased inputs of fine material, lead to enhanced interstitial migration rates. When fine particles are not dominant, they appear to contribute to stabilisation; however, this effect may not persist if fines completely fill the interstices and reach the surface. It is also important to consider the influence of energetic events, which can swiftly redistribute sediment fractions and significantly impact the migration patterns of fine particles (e.g., Matsumoto et al., 2025).

4.4 Use of low-density particles in analogue beach models

Some considerations must be taken into account when using low-density particles in analogue models, as they necessarily imply scale effects (Henry and Aberle, 2018). According to Petruzzelli et al. (2013), the mobilisation of low-density particles is likely to be enhanced compared to natural sediments, which may affect the representation of sediment transport rates.

The experimental protocol leading to the initial beach topography illustrates how easily PET granules can be transported onshore. However, sediment mobilisation decreases considerably when the beach profile reaches a state of morphological equilibrium, suggesting that the overall profile organization is not solely controlled by this initial mobility bias.

Measurements of sediment transport modes were limited to qualitative observations. The predominant mode of transport for the PET granules includes bed load transport, with saltation and suspension observed locally, particularly around the beach step. These modes are consistent with expected behaviours for coarse-grained particles (Buscombe and Masselink, 2006), although their relative proportions cannot be quantified here. Experiments in steady currents have shown that bed-load transport for natural and low-density particles may be comparable (e.g., Lofty et al., 2023), but differences may arise under oscillatory flow conditions.

Due to the low settling velocities, the transport of suspended low-density particles is more likely to differ from natural particles (e.g., Waldschläger and Schüttrumpf, 2019a,b; Wang et al., 2021). According to Wang et al. (2021), settling velocities of microplastics between 1 and 1.25 g/cm^3 are highly influenced by turbulence, while particles with a density greater than 1.25 g/cm^3, such as the one used here, are less influenced. Whereas the PET granules are in suspension only momentarily around the beach step, the polymer abrasive is suspended more rapidly and permanently, creating a plume similar to those observed in other experiments using this type of particles (e.g., Grasso et al., 2009; Rocha, 2016). In energetic conditions where coarse particles are mobilised, a strong mobilisation of the fine sediment fraction makes sense and has already been reported in natural cases (e.g., Bergillos et al., 2016). Due to the lack of in situ and experimental hydro-sedimentary evidence within coarse-grained foreshores, it is currently not possible to quantify the potential side-effects of a longer suspension. During the experiments, the polymer abrasive is not deposited in the swash zone, but rather remains below the beach step, migrating offshore or infiltrating in the porosity of the PET granules. The morphodynamics of the beach face is therefore presumably not directly influenced by the dynamics of the suspended polymer abrasive.

Particle aggregation is a another potential source of bias that may influence the behaviour of the polymer abrasive. The irregular shape, relatively low density, and hydrophobicity properties of these particles may promote flocculation under low-energy conditions (Waldschläger and Schüttrumpf, 2020; Waldschläger et al., 2022). Such aggregation could locally reduce migration rates, particularly within the sediment matrix. However, no clear evidence suggests that this process significantly alters the large-scale organisation of sediment redistribution.

A further effect relates to the flotation of PET granules, likely enhanced by capillarity forces associated with their hydrophobic properties (Waldschläger and Schüttrumpf, 2020). Despite being a completely unnatural phenomenon, it is not considered to have an impact on the beach dynamics as it only concerns a small amount of particles.

Given these limitations, it remains difficult to assign a precise time or energy scale to these experiments. Morphological time scaling is typically derived assuming a single sediment density (Henry and Aberle, 2018), and no established framework exists for bimodal systems using analogue materials. The present results should therefore not be interpreted in a strictly quantitative framework. Based on the processes observed, which include beach face scarping and overwashing, it is more likely that the experiments represent an energetic configuration. A wider range of wave conditions will be required to estimate the operating range of this model. Other parameters, such as water temperature and salinity, should also be considered in the future as they can have a significant impact on the behaviour of particles. Nevertheless, these results already allow us to glimpse a wide field of experimental possibilities and comparisons, as well as to qualify hydro-sedimentary processes that are difficult to observe on a 1:1 scale. The satisfactory reproduction of the beach profile suggests that properly accounting for sediment transport processes is essential to this type of model.

5 Conclusion

This study investigated the hydro-sedimentary dynamics of coarse-grained beaches incorporating finer material (such as composite beaches and mixed sand-and-gravel beaches), using reduced-scale wave flume experiments and low-density sediments. The physical modelling approach, using PET granules as gravel analogues and polymer abrasives as sand analogues, allowed for detailed observation of sediment transport and morphological evolution under controlled wave forcing and water level fluctuations. From these experiments, the following conclusions can be drawn:

1. The use of PET granules reproduced several morphodynamic features that are characteristic of natural gravel beaches, including steep upper foreshore slopes, beach crest development, and the formation of a distinct beach step. The beach slopes align with those described for pure gravel beaches in the literature. However, this reproduction should be interpreted with caution: some artefacts previously reported in the literature have been observed. While these effects did not appear to exert a significant influence on the overall morphodynamic evolution, their presence high-

lights the need for careful interpretation. The main uncertainty concerns the potential acceleration of certain processes associated with the relatively high mobility of particles.

2. The introduction of fine particles at the base of the beach profile leads to a progressive infiltration into the coarse-grained matrix and the formation of a distinct internal bar. This fine-sediment body, driven by both infiltration and wave-induced groundwater flow, migrates landward and aggrades over time. The dynamics of this internal bar likely reflect complex interactions between porosity, flow asymmetry, and sediment supply, although these hydrodynamic controls were not measured directly in this study and thus remain interpretative. Even so, the resulting behaviour highlights how changes in fine-sediment supply can influence subsurface structure and permeability within coarse-grained beach systems.

3. Fine particle infiltration induces overall a retreat of the shoreline position, an increase of the beach crest elevation, and a reduction in the beach slope. These changes alter local hydrodynamic conditions, leading to contrasting effects on beach stability: an increase in sediment transport in the swash zone leading to beach instability, and the progressive fixation of the beach step which can over the long term increase the beach stability.

While there is still much to learn about the processes occurring in the swash zone of these beaches, especially when low-density particles are used, the experiments in the study demonstrate promising performance. They also provide a first-order insight into the complexity of the processes that may take place in natural systems. Although the capacity of sand-and-gravel foreshores to dissipate wave energy is not yet well quantified, the observed dynamics suggest that such systems may contribute to coastal flooding mitigation—a hypothesis that warrants further investigation. Currently, there's no practical method of quickly and accurately quantifying the porosity and permeability in mixed sediment beaches. A deeper understanding of these beaches therefore requires not only a better understanding of the physical model itself, but also the development of new instruments giving access to sub-surface hydro-sedimentary processes.

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Land Recognition

The research was conducted indoors within the UMR 6143 M2C laboratory of the University of Caen's campus. The authors have confirmed that the lands containing their institutions and all work sites associated with this study do not have cultural or historical significance to a particular indigenous group.

Data and Codes Availability

A curated subset of the dataset supporting this study, along with two Python scripts used for figure preparation and minor data analysis, is openly available via Zenodo at https://doi.org/10.5281/zenodo.17127151. These data represent the measurements deemed accurate and internally consistent following quality checks. Due to unresolved inconsistencies in portions of the raw data, the full dataset is not included.

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Conflict of Interest Disclosure

The authors declare that they have no known competing interests.

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Declaration on Artificial Intelligence Use

The authors declare that large language models (ChatGPT and Copilot) were used incidentally to suggest edits to text originally written by the authors. No new content was generated by these tools.

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