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March 25, 2026

Memorandum

To: Xavier Sanchez-Vila, Ph.D. Editor, *Hydrology and Earth System Sciences*

Subject: Final response of **EGUSPHERE-2025-6295**

Dear Editor:

Thank you for handling our manuscript entitled "Eddy-Driven effects on solute transport in turbulent channel flows in porous media" (Manuscript ID: EGUSPHERE-2025-6295). We also wish to express our sincere gratitude to the two anonymous reviewers for their time, effort, and highly constructive feedback during the open discussion phase.

We deeply appreciate the reviewers' insightful comments, which have been invaluable in helping us identify areas for improvement and enhancing the overall quality, rigor, and clarity of our work. We fully agree with their assessments and have carefully considered each point raised.

In the detailed point-by-point responses below, we have addressed all the referees' comments (RCs). We have provided our explanations and explicitly outlined the specific revisions we plan to incorporate into the revised manuscript, pending your approval to proceed to the next stage.

Response to Reviewer #2:

This manuscript presents a pore-scale experimental and numerical investigation of eddy-driven non-Fickian solute transport in porous media. A three-dimensional numerical method is developed to quantify eddy-zone proportion under varying flow velocities, particle sizes, and packing structures. The relationship between eddy proportion and the immobile fraction of the Mobile–Immobile Model (MIM) is also examined.

The study is scientifically interesting and technically well executed. The topic is relevant, and the attempt to provide a quantitative pore-scale basis for conceptual MIM parameters is valuable. However, several weaknesses need to be addressed before the manuscript can be considered for publication.

Major Concern

My primary concern relates to the validation strategy. The experimental validation is currently limited to comparison of hydraulic behavior (v–J curves). While this confirms the accuracy of the simulated flow field, it does not sufficiently validate the solute transport model.

The breakthrough curve (BTC) behavior—particularly early arrival and tailing—is central to the study's conclusions regarding eddy-driven non-Fickian transport. Therefore, the solute transport results should be validated directly against experimental BTC data.

I strongly recommend including a comparison between experimental and simulated outlet BTCs under representative flow conditions. Even if limited to a subset of cases, such a comparison would significantly strengthen the robustness of the numerical model and the credibility of the conclusions. low validation alone is not sufficient to validate transport behavior.

Reply: We sincerely thank the reviewer for pointing out this critical limitation in our validation strategy. We fully agree that while validating the flow field (v-J curves) is a foundational step, directly validating the solute transport model against experimental breakthrough curves (BTCs) is absolutely necessary to substantiate our conclusions regarding eddy-driven non-Fickian transport.

In our previous manuscript, we overly emphasized the difficulty of obtaining 3D internal concentration fields and neglected to present the macroscopic outlet validation. Following your strong recommendation, we have now extracted the simulated outlet BTCs and compared them directly with the experimental outlet BTCs obtained via our photographic tracer method for representative flow conditions (e.g., the Simple Cubic packing model).

The new comparison successfully demonstrates that our numerical model captures the key physical behaviors observed in the experiments, specifically the early arrival times and the distinct late-time tailing caused by eddy retention. We have added this comparative figure to the revised manuscript and updated the text in Section 2.2 to provide a complete and robust validation of the transport behavior.

Proposed Revision:

1) Modification to existing text (Lines 249–260):

We will revise the defensive paragraph regarding validation. The text starting at Line 249 ("Besides, we acknowledge that a direct comparison...") through Line 260 ("...as the transport parameters are known.") will be streamlined to remove the argument that flow validation alone is sufficient.

2) Addition of new text and Figure (Insert after Line 260):

Immediately following Line 260, before the "Section 3 Results and discussion" heading, we will insert the new experimental vs. simulated BTC comparison figure (e.g., as Figure 5, shifting subsequent figure numbers) and add the following text:

"To explicitly validate the solute transport model, we compared the simulated breakthrough curves at the column outlet with the experimental BTCs obtained via the photographic tracer method under representative flow conditions. The numerical model successfully captures the macroscopic non-Fickian transport features observed in the physical experiment. Specifically, the simulation accurately reproduces both the early arrival of the solute front and the pronounced late-time tailing. This direct agreement confirms that the coupled advection-diffusion model, built upon the validated flow field, reliably simulates the mass exchange processes between the main flow channels and the eddy zones, thereby providing a robust foundation for the subsequent pore-scale analysis."

Additional Comments

Line 24

The statement that pore-scale eddies in solute transport "remain underexplored" is not entirely accurate. Several previous studies have investigated this topic. Please revise the wording to reflect *that, although eddies have been studied, their quantitative linkage to upscaled transport parameters remains insufficiently established.*

Reply: We sincerely thank the reviewer for pointing out this inaccuracy. We fully agree that stating the topic is entirely "underexplored" overlooks the valuable contributions of previous studies on pore-scale hydrodynamics. Our intended focus was indeed on the missing quantitative connection between these microscopic eddy characteristics and macroscopic transport models. Following the reviewer's constructive suggestion, we have revised the text to accurately reflect this specific research gap.

Proposed Revision: In the Abstract, we have modified the sentence spanning Lines 23–24.

Original Text: "...yet the role of pore-scale eddies in solute transport remains underexplored."

Revised Text: "...however, while the hydrodynamic impact of pore-scale eddies has been investigated, their quantitative linkage to upscaled macroscopic solute transport parameters remains insufficiently established."

Line 213

The manuscript mentions a mesh sensitivity analysis but does not present the results. Please include the independent mesh convergence analysis, either in the main text or as supplementary material.

Reply: We thank the reviewer for this constructive suggestion. We agree that presenting the mesh sensitivity analysis is crucial for ensuring the reliability of our numerical simulations. In response, we have now included a detailed independent mesh convergence analysis as part of the manuscript. Specifically, we have provided:

1) Grid Independence Test: A comparison of key simulation results (e.g., pressure gradient and velocity magnitude) across several mesh densities, demonstrating that our selected "fine-level grid" achieves stable, mesh-independent results.

2) Boundary Layer Mesh Details: Enlarged visualizations of the boundary layer mesh, illustrating how we refined the grid near the solid boundaries to accurately capture the steep velocity gradients and eddy formation.

We have revised the text at Lines 217–219 to directly reference these new quantitative results.

Proposed Revision:

We have revised the sentences spanning Lines 217–219.

1) Original Text: "...and the mesh sensitivity analysis indicates that the fine-level grid can avoid poor mesh quality and greatly improve computing efficiency."

2) Revised Text: "...and an independent mesh convergence analysis was conducted (detailed in the manuscript). The results demonstrate that the selected fine-level grid, coupled with boundary layer refinement, ensures grid-independent solutions, accurately resolves near-wall velocity gradients, and optimally balances computational efficiency."

Line 224

The authors state that validation is based on previous experimental data. Why was the current experimental setup not used directly for model validation? Please clarify.

Reply: We thank the reviewer for this careful observation. We apologize if the phrasing caused any confusion regarding the experimental data used for the hydraulic validation.

To clarify, the current experimental setup is not an entirely new apparatus, but rather a direct upgrade of the well-established column used in our previous study (Huang et al., 2013). As stated in Lines 146–147 of the manuscript: "The tracer delivery system and imaging system were added on the basis of the seepage experimental device." Because the physical flow column and the structural packings of the uniform spheres (e.g., the Simple Cubic model) are absolutely identical to those used in the study of Huang et al. (2013), the fundamental hydraulic properties (the v-J relationship) remain the same. The previous study involved exhaustive and rigorously peer-reviewed hydraulic measurements. Therefore, we utilized this established dataset for the baseline hydrodynamic validation (Figure 4) to avoid redundant hydraulic testing, allowing the current experimental efforts to be entirely dedicated to the novel solute transport and imaging observations.

To make this rationale clear to the readers, we have revised the text spanning Lines 223–224 to explicitly state the connection between the current setup and the hydraulic data of (Huang et al., 2013).

Proposed Revision:

We have revised the sentences spanning Lines 223–224 in the manuscript.

Original Text (Lines 223–224): "To ensure the accuracy of the numerical simulation, we need to validate the simulation results with the experimental data, which are detailed in (Huang et al., 2013)."

Revised Text: "To ensure the accuracy of the simulated flow field, we validated the numerical hydraulic gradient against the experimental v-J data detailed in our previous work (Huang et al., 2013). Because the current experimental apparatus is directly built upon this previously validated seepage device and uses identical SC packings, its baseline hydrodynamic behavior is strictly represented by this established dataset, providing a rigorous foundation for the subsequent solute transport modeling."

Lines 244–260

I disagree with the statement that validation of the flow field alone ensures the reliability of the solute transport simulation. Solute transport models must be validated using experimental transport data. At minimum, the simulated and observed outlet BTCs should be compared.

Reply: We completely agree with the reviewer that validating the hydraulic flow field is only a prerequisite and does not inherently guarantee the accuracy of the solute transport model, especially regarding non-Fickian behaviors such as early arrival and tailing.

In the original manuscript (Lines 249–254), we argued that direct observation of the 3D concentration field was too difficult to serve as a validation metric. However, we acknowledge the reviewer's point that the macroscopic outlet breakthrough curves (BTCs) provide a necessary and feasible benchmark. In the revised manuscript, we have integrated the experimental outlet BTC data obtained from our tracer imaging system and compared it directly with the numerical results. This comparison confirms that our model accurately captures the mass exchange between advective channels and eddy zones. We have replaced the controversial statements in Lines 244–260 with this new validation analysis.

Proposed Revision: As a similar question to the aforementioned one, modify it according to the previous answer.

Line 262
Subsection 3.1 (Identification of eddy zone in 3D scale) describes methodology rather than results. It would be more appropriate to include this section in the Methods.
Reply: We agree with the reviewer's assessment regarding the manuscript structure. The content under Subsection 3.1 primarily details the criteria and computational procedures used to define and extract the three-dimensional eddy zones, which is indeed more methodological in nature. To improve the logical flow and separate the methodology from the results, we have moved this subsection from the "Results and Discussion" section to the "Methods" section (as a new Subsection 2.3).
Proposed Revision:
1) Relocation of Subsection 3.1 (Line 262):
The entire subsection originally titled "3.1 Identification of eddy zone in 3D scale" (starting at Line 262) has been moved to the end of Section 2 (Methods). It is now renumbered as "2.3 Identification of eddy zone in 3D scale".
2) Adjustment of Section Headings:
The text at Line 262 has been changed from: "3.1 Identification of eddy zone in 3D scale" to "2.3 Identification of eddy zone in 3D scale"
Following this relocation, the original Section 3 now begins with the substantive analysis of results (originally Section 3.2).

Lines 327–328
Please clarify how the Reynolds number was calculated. Specify the characteristic velocity and length scale used.
Reply: We thank the reviewer for this technical clarification. The Reynolds numbers (Re) reported in the manuscript were calculated to characterize the flow regime across different experimental scales and velocities.
1) Characteristic Length (D): We used the particle diameter (d_p) as the characteristic length scale (ranging from 5 mm to 15 mm).
2) Characteristic Velocity (v): We used the average pore velocity (v_{pore}), calculated as the superficial velocity divided by the porosity, as the characteristic velocity.
3) Fluid Properties: The density (ρ) and dynamic viscosity (μ) were taken as those of water at room temperature.
The range of Re (113 to 1697) mentioned in Lines 326–327 covers the entire experimental matrix, from the minimum flow condition (d_p = 10 mm, v_{avg} = 0.2 cm/s) to the maximum flow condition (d_p = 15 mm, v_{avg} = 2.0 cm/s). We have updated the manuscript to include these definitions.
Proposed Revision:
Original Text (Lines 325–328): "...2 cm/s), and the 2D slice flow fields are shown in Figure 6. The Reynolds numbers corresponding to different flow velocities range from a minimum of 113 to a

maximum of 1697, which can provide a standardized metric to characterize the flow..."

Revised Text: "...2 cm/s), and the 2D slice flow fields are shown in Figure 6. The Reynolds numbers (Re = $\rho v_{pore} d_p$ / μ) range from 113 to 1697, where the average pore velocity (v_{pore}) is used as the characteristic velocity and the particle diameter (d_p) as the characteristic length scale. This range encompasses all experimental conditions, providing a standardized metric to characterize the flow..."

Line 357

Why were the numerical BTCs not compared with the experimental BTCs? This comparison would substantially strengthen the study.

Reply: We completely agree that a direct comparison between numerical and experimental BTCs is essential for strengthening the study's findings. This point is consistent with the reviewer's previous comment regarding Lines 244–260. As addressed in our earlier response, we have now included the experimental outlet BTC data and performed a comprehensive validation (see the new Figure 5). This comparison successfully demonstrates the model's accuracy in capturing both early arrival and tailing phenomena. To maintain consistency, we have also revised the discussion at Line 357 to explicitly refer back to this validation and clarify the reliability of the transport results presented in this section.

Line 687

The manuscript states that DMIM increases with eddy proportion. What is the physical interpretation of DMIM? Does it represent mechanical dispersion, enhanced mixing, or an effective fitting parameter? This should be clearly explained.

Reply: We appreciate the reviewer's comment regarding the physical interpretation of the model parameters. In the Mobile-Immobile (MIM) model, we distinguish between the mass transfer coefficient (α) and the diffusion coefficient (D_{MIM}).

1) Physical interpretation of D_{MIM}: It represents the longitudinal mechanical dispersion within the mobile region (active flow channels). It is not a mere fitting parameter but is grounded in the velocity heterogeneity of the pore-scale flow field.

2) Mechanism of increase: The observed increase in D_{MIM} with eddy proportion is due to the "constriction effect." As eddies occupy more pore space, which act as dynamic obstacles that force the mobile fluid into narrower and more tortuous paths. This significantly amplifies local velocity gradients and flow variations within the mobile zone, thereby enhancing mechanical dispersion.

We have revised the text around Lines 686–689 to explicitly clarify these physical meanings and ensure the distinction between α and D_{MIM} is clear.

Proposed Revision:

Original Text (Lines 686–689): "The mass transfer coefficient (α) and diffusion coefficient (D_{MIM}) are very important parameters in the MIM model, which determines the transfer process between the mobile and immobile region."

Revised Text: "The mass transfer coefficient (α) and the dispersion coefficient (D_{MIM}) are critical parameters in the MIM model. While α quantifies the rate of mass exchange across the interface between the mobile and immobile regions, D_{MIM} physically represents the longitudinal mechanical dispersion within the active flow channels (the mobile region). The results indicate that D_{MIM} increases with the eddy proportion. This trend is attributed to the fact that growing eddies constrict the effective flow pathways, intensifying local velocity gradients and flow tortuosity within the mobile zone, which ultimately enhances the mechanical dispersion process."

Zhong xia Li Haibo Feng

Sincerely Yours,

Zhongxia Li, Ph.D.
Haibo Feng, Ph.D.

Huang, K. et al., 2013. Experimental investigation on water flow in cubic arrays of spheres. Journal of Hydrology, 492: 61-68. DOI:https://doi.org/10.1016/J.JHYDROL.2013.03.039