Grain roughness controls on velocity and bed stress fields around a fully protruding obstacle in supercritical flow

Responses to reviewers

Response to Reviewer #1

Dear Reviewer,

We sincerely thank you for your thorough and constructive review of our manuscript. Your careful evaluation and the time you dedicated to providing detailed feedback are greatly appreciated. We are encouraged by your positive assessment of our work, particularly your recognition that the study is "technically rigorous and scientifically meaningful" and that it "fills an important gap" in understanding supercritical flow dynamics in gravel-bed channels. Your specific suggestions have substantially improved the manuscript and is now more rigorous, better organized, and clearer in its communication of both findings and limitations.

Below, we provide point-by-point responses to each of your comments, detailing the specific actions taken and the corresponding revisions made to the manuscript. Line numbers refer to, approximately, the original manuscript, and all changes are highlighted in the tracked-changes version submitted with this response.

Detailed responses

1) Line 21: “grain-dominated flow fields” is unclear. Consider revising to “flows dominated by grain-roughness effects.”
   R: We thank the reviewer for this helpful suggestion. We have revised "grain-dominated flow fields" to "flows dominated by grain-roughness effects" as recommended.
2) Line 15: The phrase “rough flat beds representing post-flood recovery conditions” needs clarification.
   R: We appreciate this comment and have added clarification. Post-flood recovery refers to the morphological state where sediment has been deposited as relatively uniform gravel sheets following high-flow events, before subsequent flows reorganize the bed into more complex configurations.
   - Original (Line 15-16): "rough flat beds representing post-flood recovery conditions"
   - Revised: "rough flat beds representing post-flood recovery conditions where sediment has been deposited as relatively uniform gravel sheets"
3) Line 108: Clarify that the hydraulic conditions described here refer to inflow boundary conditions.
   R: Thanks! We have clarified that the hydraulic conditions described refer to the approach flow (inflow) conditions upstream of the obstacle.
   - Original (Line 108): "Our primary experiments were conducted with a flow depth (h) of 1.76 cm and mean velocity (V) of 0.70 m/s"
   - Revised: "Our primary experiments were conducted with approach flow conditions characterized by a flow depth (h) of 1.76 cm and mean velocity (V) of 0.70 m/s"
4) Sediment feed: The text should explicitly state that no sediment was fed during the mobile-bed test, so scour developed from local hydraulics alone.
   R: We thank the reviewer for highlighting this important methodological detail. We have added explicit clarification that no sediment was fed during the mobile-bed experiment, confirming that scour development resulted entirely from local flow-induced erosion.

We added: "No sediment was fed during the experiment; scour development resulted entirely from local flow-induced erosion around the obstacle."

5) Line 158: I do not see a definition of SST. Please define upon first use.
R: Thanks for catching that. We have added the full definition of SST (Shear Stress Transport) at first use.
    - Original (Line 158): "the k−ω SST-DES turbulence model"
    - Revised: "the k−ω Shear Stress Transport (SST)-DES turbulence model"
6) Line 165: The use of a 0.7 m inlet-to-obstacle computational length seems short for supercritical flow. Please justify that this distance is sufficient to establish stable inflow hydraulics and discuss any limitations.
R: We appreciate this important methodological question. The 0.7 m streamwise domain (with obstacle at 0.38 m from inlet) was selected based on preliminary simulations confirming that velocity profiles achieved fully developed conditions before reaching the obstacle. For supercritical flows over rough beds, the high momentum and bed roughness promote rapid flow development. We verified that velocity profiles at 0.35 m matched those at 0.38 m (within 2%), confirming adequate development length. This is consistent with findings that supercritical flows require shorter development lengths than subcritical flows due to reduced upstream influence propagation. We have added discussion of this justification and acknowledged this as a potential limitation. We added: "Preliminary simulations verified that velocity profiles achieved fully developed conditions by 0.35 m from the inlet (within 2% of profiles at the obstacle location), consistent with the reduced upstream influence characteristic of supercritical flows. While longer domains would further ensure complete flow development, computational constraints and the verified profile stability support the adequacy of our domain length."
7) Lines 175–185: Please elaborate on how SfM warping was minimized or corrected. Was a local coordinate reference frame used? What was the workflow for aligning imagery and GCPs?
R: We thank the reviewer for requesting additional methodological detail. We have expanded Section 2.3 (Bed surface elevation representation) to include information about warping minimization, the local coordinate reference frame, and the georeferencing workflow. Specifically, we now describe: (1) establishment of a local coordinate reference frame using 12 control points, (2) the iterative optimization procedure for camera alignment and GCP refinement, (3) lens distortion correction during camera calibration, and (4) final error metrics (RMSE < 0.3 mm, mean reprojection error of 0.15 pixels). These additions provide the methodological transparency needed for reproducibility.
8) Consider including a table summarizing all hydraulic parameters (Q, h, Fr, roughness condition, obstacle dimensions) for both physical and numerical runs. This would help with readability and reproducibility.
R: We thank the reviewer for this excellent organizational suggestion. We have added Table 1 summarizing all hydraulic parameters across experimental and numerical configurations.
9) If different Froude numbers were used across experiments, briefly justify the rationale and state limitations of interpretation.
R: We appreciate this question regarding the different Froude numbers. The smooth bed case has a higher Froude number (1.94) compared to the rough bed cases (1.68) because identical discharge was applied but the reduced friction on the smooth bed resulted in higher velocities and lower flow depths. This approach isolates the effects of grain roughness on flow dynamics while maintaining comparable

Reynolds numbers. We have added clarification acknowledging that direct quantitative comparisons between smooth and rough beds should account for these Froude number differences.
We added: "…resulting in higher velocities and lower flow depths due to reduced friction (Table 1). This yielded a Froude number of 1.94, compared to 1.68 for the rough bed cases, while maintaining comparable Reynolds numbers across all configurations. This approach isolates the effects of grain roughness on flow dynamics; however, direct quantitative comparisons between smooth and rough bed cases should account for these Froude number differences."

10) Line 241: Define "deformation pattern magnitude." Is this a normalized metric, spatial derivative, or amplitude measure?
R: Thanks for noticing that. We have clarified this terminology by specifying that "deformation pattern magnitude" refers to the amplitude of water surface elevation variations around the obstacle.
    - Original (Line 241): "no clear effect on air entrainment intensity or deformation pattern magnitude"
    - Revised: "no clear effect on air entrainment intensity or water surface elevation amplitude"

11) Section 3.2: Please clarify whether the same discharge (Q) was used across flume runs and numerical simulations.
R: Thanks for the suggestion. We have added explicit clarification that identical discharge (Q = 3.08 l/s, accounting for width reduction) was used across all numerical simulations, enabling direct comparison of roughness effects. We added "All numerical simulations used identical discharge (Q = 3.08 l/s) to enable direct comparison of bed roughness effects on flow characteristics."

12) Section 3.2.2 and elsewhere: Phrases such as "provides critical insight into how developed scour geometry interacts with grain-scale flow physics" feels interpretive. In the Results section, consider reporting observations more neutrally and reserving interpretive statements for the Discussion.
R: We thank the reviewer for this organizational guidance. We have revised Section 3 to present observations more neutrally, moderating interpretive language while reserving broader interpretive statements for the Discussion. The following revisions were made:
Line 302:
    - Original: "The VOF method demonstrated remarkable success in reproducing..."
    - Revised: "The VOF method effectively reproduced..."

Lines 440-445:
Original: "This contrast reveals the profound impact of grain-scale roughness on flow turbulence characteristics...This transition from concentrated, organized turbulent structures to distributed, grain-induced turbulence reflects the fundamental shift in flow physics..."
Revised: "This contrast illustrates differences in turbulence characteristics between smooth and rough bed conditions...This transition from concentrated turbulent structures to distributed, grain-induced turbulence corresponds to the shift from large-scale coherent structures to grain-dominated flow interactions..."
Lines 459-462:
Original: "This case provides critical insight into how developed scour geometry interacts with grain-scale flow physics to produce the most complex flow patterns observed in this study."
Revised: "This case combines grain-scale roughness with large-scale topographic modifications, producing distinct flow patterns compared to flat bed conditions."
Lines 551-555:

Original: "This instantaneous analysis reveals that the apparent organization in time-averaged results emerges from statistical averaging of chaotic, continuously evolving vortical interactions, highlighting the importance of understanding both the organized mean behaviour and the underlying turbulent dynamics that drive momentum and energy transfer processes."
Revised: "This instantaneous analysis shows that the organization apparent in time-averaged results emerges from statistical averaging of continuously evolving vortical interactions."

13) Lines 493–501 and similar locations: These interpretive remarks would be better placed in the Discussion.
R: We agree with the reviewer that this passage is interpretive in nature. We have relocated the content from Lines 493–501 to Section 4.2 (Bed Shear Stress Distributions and implications for river processes), where it integrates with the existing discussion of stress field characteristics. In its place, we added a brief neutral observation in the Results:
"The scoured bed configuration illustrates the compound influence of scour geometry and grain roughness on stress patterns, with maximum values occurring at locations determined by both individual grain protrusions and the scour hole's topographic features. The stress distribution exhibits the most complex spatial organization of all cases, where grain-induced localized high-stress zones are modulated by the scour hole's influence on the overall flow field, creating patterns that differ from both the organized smooth bed and fragmented flat rough bed distributions. The scour hole geometry introduces additional complexity by creating zones of flow acceleration and deceleration that interact with grain-scale stress concentrations, resulting in a hierarchical stress field where large-scale topographic effects provide the background upon which grain-induced variations operate."

14) Some claims are stronger than the evidence presented. For example, Lines 674–679 discuss ecological implications without citing supporting literature. Either provide appropriate references or soften the interpretive strength.
R: We acknowledge that our ecological interpretations require stronger literature support. We have added relevant citations and softened interpretive language where direct evidence is lacking. We have modified the text as it is described below:

- Original: "From an ecological perspective, the heterogeneous stress distributions generated by grain roughness create the microhabitat diversity essential for aquatic ecosystem function..."
- Revised: "From an ecological perspective, the heterogeneous stress distributions generated by grain roughness may contribute to microhabitat diversity that supports aquatic ecosystem function (Buffington and Montgomery, 1999; Lamouroux et al., 2004). The spatial patchwork of high and low-stress zones could potentially provide refugia for benthic organisms while maintaining areas of enhanced sediment mobility (Lancaster and Hildrew, 1993)..."

Added references:
Buffington, J.M. and Montgomery, D.R.: Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research, 35, 3507-3521, 1999.
Lamouroux, N., Dolédec, S., and Gayraud, S.: Biological traits of stream macroinvertebrate communities: effects of microhabitat, reach, and basin filters. Journal of the North American Benthological Society, 23, 449-466, 2004.
Lancaster, J. and Hildrew, A.G.: Characterizing in-stream flow refugia. Canadian Journal of Fisheries and Aquatic Sciences, 50, 1663-1675, 1993.

15) Several sections could more clearly position the results within the context of previous work on roughness effects in supercritical flow, horseshoe vortices, and obstacle-induced turbulence in gravel-bed channels.
R: We thank the reviewer for this suggestion. We have strengthened the Discussion by more explicitly connecting our findings to previous work. Specifically, we added references and contextual discussion related to: (1) roughness effects in supercritical, (2) horseshoe vortex dynamics, and (3) obstacle-induced turbulence in gravel-bed channels. These additions better position our contribution within the existing literature and clarify how our findings extend current understanding of supercritical flow-obstacle interactions in rough-bed environments.

Added references are listed below:

- Benson, A. H. (1995). The horseshoe vortex in super-critical flow. Proceedings of the 26th IAHR World Congress, 20–24.
- Dey, S., Rathore, V., Penna, N., & Gaudio, R. (2021). Hydrodynamics of flow over a gradually varied bed roughness. Physics of Fluids, 3(12), 125112. https://doi.org/10.1063/5.0074428
- Kadivar, M., Tormey, D., & McGranaghan, G. (2021). A review on turbulent flow over rough surfaces: Fundamentals and theories. International Journal of Thermofluids, 10, 100077. https://doi.org/10.1016/j.ijft.2021.100077
- Kirkil, G., & Constantinescu, G. (2015). Effects of cylinder Reynolds number on the turbulent horseshoe vortex system and near wake of a surface-mounted circular cylinder. Physics of Fluids, 27(7), 075102. https://doi.org/10.1063/1.4923063
- Kirkil, G., Constantinescu, S. G., & Ettema, R. (2008). Coherent Structures in the Flow Field around a Circular Cylinder with Scour Hole. Journal of Hydraulic Engineering, 134(5), 572–587. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:5(572)
- Tritico, H. M., & Hotchkiss, R. H. (2005). Unobstructed and Obstructed Turbulent Flow in Gravel Bed Rivers. Journal of Hydraulic Engineering, 131(8), 635–645. https://doi.org/10.1061/(ASCE)0733-9429(2005)131:8(635)
- Wu, W., & Piomelli, U. (2018). Effects of surface roughness on a separating turbulent boundary layer. Journal of Fluid Mechanics, 841, 552–580. https://doi.org/10.1017/jfm.2018.101

Response to Reviewer #2

Dear Reviewer,

We sincerely thank you for your thoughtful and rigorous review of our manuscript. Your expertise in numerical modeling and fluvial hydraulics is evident in the depth of your evaluation, and we greatly appreciate the time and effort you invested in providing such detailed methodological feedback. We are grateful for your recognition that our study "addresses an important gap in fluvial hydraulics" and that our "methodology and motivation are strong." Your critical assessment has prompted us to substantially strengthen the Discussion section, including a tiered confidence framework that systematically connects our validation approach to specific findings and explicit guidance on appropriate applications of our results.

Below, we provide point-by-point responses to each of your comments, detailing the specific actions taken and the corresponding revisions made to the manuscript. Line numbers refer approximately to the original manuscript, and all changes are highlighted in the tracked-changes version submitted with this response. Some of your comments overlap with those from Reviewer #1; where applicable, we note how revisions address concerns raised by both reviewers to ensure a cohesive and integrated final manuscript.

Detailed responses

1) Validation Limitations and Confidence in Claims - Model validation relies on qualitative visual agreement and bulk metrics. The consequences of this for specific claims (e.g., stress distributions, turbulence structures) should be more critically discussed.
R: We sincerely thank the reviewer for this thoughtful critique. The reviewer raises an important point about systematically connecting our validation approach to the confidence level of specific claims. We have substantially expanded the Discussion section to explicitly address how our qualitative validation strategy affects interpretation of different results. Specifically, we now distinguish between (1) bulk flow characteristics and domain-scale patterns, which are well-supported by our validation approach, and (2) grain-scale quantitative predictions, which should be interpreted as indicative rather than definitive. We have added a new subsection (4.1.1) that systematically links validation limitations to specific findings.
2) DES/VOF approaches may miss subgrid turbulence and struggle with non-orthogonal, complex mesh zones. No detailed grid-convergence analysis is provided for stresses/velocities at critical locations.
R: We appreciate the reviewer's detailed attention to our numerical methodology. The reviewer correctly identifies that DES/VOF approaches face challenges in highly complex mesh regions, and that our study does not include a formal grid-convergence analysis at grain crests. We have expanded Section 4.1 to explicitly address these numerical limitations and their implications. While computational constraints precluded systematic grid-convergence studies at all grain locations (which would require prohibitive computational resources given the ~13.5 million cell domain), we acknowledge this as a limitation affecting local quantitative accuracy. We have added discussion distinguishing regions where our mesh quality supports reliable predictions from regions where results should be interpreted more cautiously.
3) Guidance on when application of this modeling approach is acceptable or concerning, distinguishing domain-scale patterns from grain-scale quantitative applications.

R: We thank the reviewer for this constructive suggestion. We have added explicit guidance distinguishing applications where our modeling approach provides reliable insights from applications where additional caution is warranted. Please see the end of Section 4.1. (Based on our validation approach …)

4) The static grain and impermeable bed assumptions limit transferability to natural systems. Implications for erosion prediction, morphodynamic evolution, and ecohydraulic/biogeochemical applications are underemphasized.
   R: We appreciate the reviewer highlighting the need for more thorough discussion of our fixed-bed assumption implications. We have expanded the Discussion to address how static grain and impermeable bed assumptions affect transferability to natural systems, including implications for morphodynamic prediction, ecohydraulic applications, and biogeochemical processes (see new section 4.2.1 Implications of fixed-bed assumptions for natural system applications)