The paper was published in the proceedings of the 11th International Conference on Physical Modelling in Geotechnics (ICPMG2026) and was edited by Ioannis Anastasopoulos. The conference was held from June 8th to June 12th 2026 in Zurich, Switzerland.

Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Mitigation of boundary-induced bias in image-based analyses for large soil deformations

G. Morales
Department of Civil and Environmental Eng., Universitat Politècnica de Catalunya, Barcelona, Spain
gerardo.morales@upc.edu

N.M. Pinyol
Department of Civil and Environmental Eng., Universitat Politècnica de Catalunya, Barcelona, Spain

Centre Internacional de Metodes Numerics en Enginyeria, Barcelona, Spain

nuria.pinyol@upc.edu

M. Alvarado
Universidad Santiago de Cali, Colombia mauricio_alvarado@cun.edu.co

ABSTRACT: Image-based measurement of large soil deformations has become increasingly important in geotechnical physical modelling. The hybrid Eulerian-Lagrangian PIV-NP method provides an effective framework for measuring soil motion under large-strain conditions by combining numerical particles with Eulerian velocity fields. However, its reliability can be compromised by systematic biases near material boundaries, particularly when image masking introduces undefined (NaN) nodal information. This paper analyses the formulation-based origins of these border-induced errors and proposes two practical correction strategies: (i) geometric filtering of numerical particles based on mesh element definition, and (ii) a local nodal velocity replacement scheme to handle NaN values prior to interpolation. Validated against synthetic benchmarks with analytical kinematic solutions, the results demonstrate that these strategies effectively suppress artificial strain localization and boundary noise. The proposed corrections significantly enhance the robustness of PIV-NP for modelling flow-like landslides and large-deformation phenomena without altering its core computational framework.

1 INTRODUCTION

Over recent decades, Digital Image Correlation (DIC) and Particle Image Velocimetry (PIV) have been extensively used for displacement and velocity measurement in geotechnical experiments. The hybrid Eulerian-Lagrangian PIV-NP method (Pinyol & Alvarado, 2017) was developed to overcome the limitations of Eulerian-based PIV when dealing with large-displacement problems. This is achieved through a dual discretisation: (i) a support mesh, whose nodes coincide with the centres of the PIV subsets to store the velocity field at each time step; and (ii) a set of numerical particles (NPs) distributed within the mesh elements, representing discrete portions of the soil mass.

The PIV-NP method provides a digital representation of the soil, where the NPs act as entities that track material motion by interpolating nodal velocities via linear shape functions. Accumulated displacements and strain fields are provided. Beyond kinematics, these NPs can function as data carriers for additional experimental variables, providing a comprehensive, high-resolution representation of the experiment involving soil in motion. This was recently demonstrated by Morales et al. (2025), who integrated PIV-NP with short-wave infrared (SWIR) images to map the evolution of the degree of saturation.

The application of PIV techniques and the subsequent PIV-NP post-processing exhibit inherent challenges associated with material boundaries (as evidenced in Di Carluccio et al., 2025). These limitations arise from a combination of experimental constraints, image-processing requirements (Take, 2015), and the specific interpolation schemes adopted during the Lagrangian mapping.

This work analyzes the mechanisms of border-induced bias in PIV-NP and proposes two complementary correction strategies. Their performance is validated through synthetic benchmarks with analytical kinematics, covering the primary deformation modes in geotechnical physical modelling.

2 BORDER-INDUCED ERRORS AND CORRECTION STRATEGIES

The PIV-NP method inherits boundary-related challenges intrinsic to its Eulerian-Lagrangian formulation. In geotechnical physical modelling, large deformations typically require image masking to isolate the soil mass, which introduces undefined (NaN) velocity values into the Eulerian support mesh. As numerical particles (NPs) approach these boundaries, the linear interpolation scheme, which relies on nodal information from the enclosing mesh element, encounters these NaN values. This results in either the premature termination of particle trajectories or, more critically, a systematic border-induced bias that distorts the displacement field and triggers artificial strain localisation at the edges of the deforming mass.

To mitigate these effects, two complementary correction strategies are proposed: (i) *Fully Defined Elements (FDE) Filtering*: An initial geometric constraint is applied where NPs are only initialised or updated within mesh elements where all bounding nodes possess valid velocity vectors. This ensures that the Lagrangian mapping is never performed using incomplete nodal data. (ii) *Local Velocity Replacement*: A boundary-handling algorithm identifies nodes affected by masking and dynamically replaces NaN values with the average value calculated from neighbouring nodes prior to interpolation

3 VALIDATION

The combined effectiveness of the proposed strategies is evaluated using synthetic benchmarks (rigid body motion, axial and shear strain). A synthetic rigid body rotation case is presented. This case is particularly demanding for the PIV-NP method, as the curvilinear trajectories near the masked boundaries increments the interpolation errors. As shown in Figure 1a, the original PIV-NP implementation exhibits a significant "erosion" of numerical particles and a chaotic displacement field near the borders. This is a direct consequence of the interpolation scheme encountering NaN values from the masked region, which introduces a systematic bias and artificial strain localization. In contrast, the application of both corrections strategies (Figure 1c) restores kinematic consistency. The numerical particles successfully maintain their trajectories up to the material interface without loss of information or artificial distortion. Quantitative assessment confirms that these corrections reduce the mean displacement bias at the borders by over an order of magnitude, ensuring that the tracked motion strictly adheres to the prescribed analytical solution.

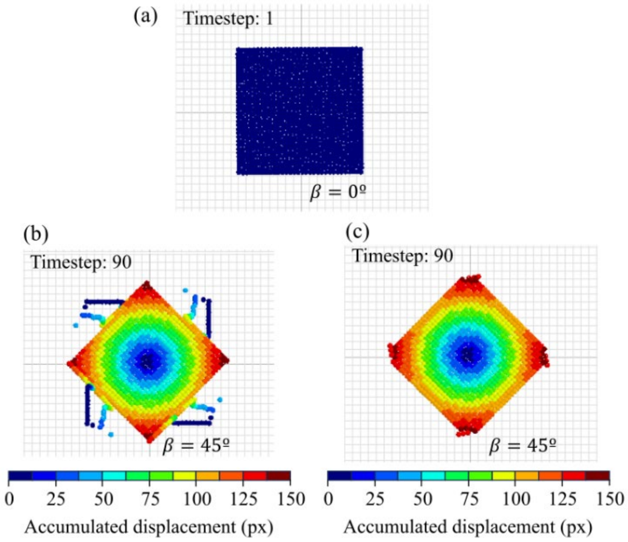

Figure 1. PIV-NP interpretation of rigid body rotation: (a) initial state; (b) original version with border-induced bias; (c) result with combined correction strategies.

CONCLUSIONS

This work identifies the origin of border-induced bias in PIV-NP, attributed to the interpolation of undefined (NaN) values following image masking. The proposed strategies successfully suppress numerical erosion and artificial strain localisation. Their implementation ensures kinematic consistency in large-deformation problems, significantly enhancing the method's robustness for geotechnical physical modelling

ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by SENACYT (Panama), the Serra Húnter Program (Generalitat de Catalunya), and Project PID2022-141429OB-I00, funded by MCIN/AEI/10.13039/501100011033/FEDER.

REFERENCES

Morales, G., Pinyol, N. M., Alvarado, M., & Alonso, E. E. (2025). Digital image-based measurement of degree of saturation on moving soil. *Canadian Geotechnical Journal* 62, 1–7. https://doi.org/10.1139/cgj-2023-0760

Carluccio, G. di, Aviles, L.A., Pinyol, N.M., & Alonso, E. E. (2025). Modelling Wetting Collapse, Failure and Deposition of an Unsaturated Slope with Material Point Method. *Int. J. Numer. Anal. Methods Geomech.* https://doi.org/10.13039/501100011033/FEDER

Take, W.A., Beddoe, R.A., Davoodi-Bilesavar, R., & Phillips, R. (2015). Effect of antecedent groundwater conditions on the triggering of static liquefaction landslides. *Landslides* 12(3), 469–479. https://doi.org/10.1007/s10346-014-0496-7