Hydro- and morphodynamic LES modelling of scour holes in rivers

Lars Paternotte[a*], Marthe Oldenhof[a], Hermjan J. Barneveld[b], Sam Bom[c], Jord J. Warmink[a]
[a]*University of Twente, Department of Water Engineering and Management, Faculty of Engineering Technology, P.O. Box 217, 7500 AE, Enschede, the Netherlands*
[b]*HKV lijn in water B.V., Botter 11-29, 8232 JN, Lelystad, the Netherlands*
[c]*Svašek Hydraulics, Kratonkade 23, 3024 ES, Rotterdam, the Netherlands*

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Introduction

Scour holes are local depressions in the river bed induced by hydrodynamic or geotechnical conditons. They have been observed in rivers around the world. These scour holes can pose a potential risk for the stability of dikes and infrastructure (e.g. Huismans et al., 2021; Barneveld et al. 2025).

Ensuring flood safety and functioning of essential infrastructure like pipelines and ferry landings requires effective prevention and management of scour holes. However, this is not straightforward, as their formation and evolution may be dependent on upstream conditions or subsurface architecture (Barneveld et al. 2025; Oldenhof et al. 2026a).

Local scour around a structure has been extensively studied for decades (e.g. Hoffmans & Verheij, 1997). However, multiple scour holes in the Rhine-Meuse system have formed over longer river sections in the absence of flow-obstructing infrastructure. Fig 1. shows an example of these scour holes along a section of the Meuse River after an extreme discharge event in July 2021 (Barneveld et al. 2025).

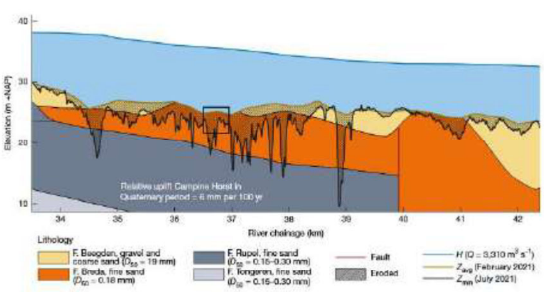

Figure 1. Scour holes in the Meuse River (dashed areas) after the 2021 flood event (Barneveld et al., 2025).

Subsurface geology was a primary trigger of the formation of these scour holes, as an easily erodible sediment layer was exposed in a hardly erodible cover layer. This type of scour hole formation has also been observed in other parts of the Rhine-Meuse river system (Sloff et al., 2013,). Fig 2. shows a schematized description of scour in a hardly erodible layer.

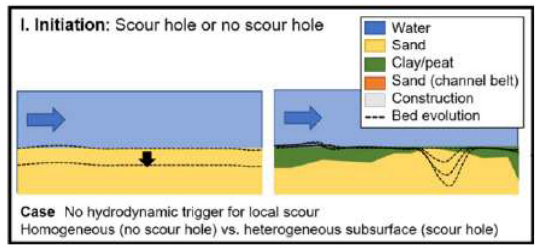

Figure 2. Example of the initiation of a scour hole in a heterogeneous subsoil (adapted from Huismans et al. (2021)).

In this research, scour holes in these heterogeneous riverbeds are studied. Better understanding of morphological development of scour holes could contribute to forming effective river management strategies.

Previous modelling studies on scour holes either only concerned the hydrodynamics in scour holes in heterogeneous subsoils or considered local scour around a structure. In this study, scour hole development in a heterogeneous riverbed is modelled both including both hydro- and morphodynamics. The aim of this study is to investigate the effects of flow conditions and subsoil composition on scour hole formation and development in rivers with heterogeneous subsoils.

Methods

As flows in scour holes are highly turbulent and have three-dimensional characteristics, a Large Eddy Simulation (LES) approach is likely to provide the most accurate estimations of flow and sediment transport. The relatively efficient open-source software TUDflow3D for process-based Computational Fluid Dynamics (CFD) modelling has been used effectively for scour simulations (De Wit et al., 2023) and is therefore also used in this study. The model is set up at an experimental scale, so results can be

* Corresponding author
Email address: l.paternotte@student.utwente.nl (Lars Paternotte)

compared quantitatively with flume measurements by Oldenhof et al. (2026b).

First, the hydrodynamics in a predefined scour hole with a fixed bed are simulated. This step aims at validating the presence of flow characteristics like flow separation, a horseshoe vortex and the downstream wake in the model.

Secondly, sediment transport and bed evolution are added to study the formation of a scour hole in an exposed sandy patch in a gravel bed river starting from a flat bed situation. The shape of the developed scour hole is compared to the flume experiments and scour holes in the field. In the field, these scour holes have mild slopes around the edges and are relatively shallow (Oldenhof 2026a).

If the model provides accurate estimates of hydrodynamics and scour hole shape, the model can be extended to investigate the effect of an extreme discharge event on the development of an existing scour hole. Moreover, model simulations with a coarse top layer at the bed and a fine layer below could provide insight into the model's capabilities to simulate the effects of bed form development on scouring potential.

Outlook

LES modelling could improve the understanding of flow processes and morphological development of scour holes in heterogeneous subsoils. This study will provide insights into the effects of (high) discharge and shear stresses and subsoil composition on scour development and the effect of bed forms on the potential for scour hole formation. Results could be used to identify locations with increased scouring potential. Moreover, it might support policy decisions on management of existing scour holes or prevention of scour holes at vulnerable locations in the river system.

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