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**A review of Soils, Structures and Hydraulics: Expertise
and Applied Research (SSHEAR) project**

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ABSTRACT

Scouring processes are a major cause of instability and destruction of structures (bridges, earthworks and buildings) especially during major floods. The consideration of these erosion phenomena remains too empirical, especially because they are particularly complex and involve many disciplinary fields: soil mechanics, fluid mechanics, structures... With a view to going beyond this empiricism, to develop knowledge and finally to improve diagnosis, warning and management methods, the SSHEAR project (“Soils, Structures and Hydraulics: Expertise and Applied Research”), supported by ANR (French “National Research Agency”), has combined 6 partners with these skills. Its objective is to improve knowledge on scour mechanisms and to develop innovative tools for observation and modeling at the scale of both experimental models and full-scale structures.

INTRODUCTION

Structures in an aquatic environment can be threatened by erosive phenomena. For instance, bridge piers that are subjected to scour under the effect of hydrodynamic forces that may be intermittent or continuous (Briaud 2008) may threaten the structure. Eventually, scour can impact the bearing capacity of the structure and lead to its ruin. However, the mechanisms involved in this erosive process are very difficult to assess, especially on a real scale. Moreover, the report “Evaluation of Bridge-Scour Research” (Sturm et al. 2011) underlines the critical need for laboratory hydraulic experiments and models to improve the understanding of scour

processes in contact with structures. The report also calls for in-situ studies and in-situ devices to evaluate the flood phenomena, assess measurement uncertainties, and calibrate models.

In France, over the past 40 years (since collapse of the Wilson Bridge in 1978), the policy of monitoring and preventive and corrective maintenance of railway and road structures has been strengthened. In the case of railway heritage, there is thus an exhaustive inventory of the infrastructure built on aquatic sites. The principles of survey are organized into various actions of periodic inspection visits to the structures, associated analysis and diagnosis actions, and reinforced monitoring based on the punctual implementation of instrumentation and/or investigations, particularly bathymetric investigations. However, there is no rigorous sensitivity classification.

In order to go beyond this empiricism and move forward on improving knowledge, the partners of the French ANR SSHEAR (“Soils, Structures and Hydraulics: Expertise and Applied Research”) project have endeavored to develop a multidisciplinary and multi-scale approach.

SCIENTIFIC AND TECHNICAL APPROACH

The French ANR SSHEAR project proposed an original multidisciplinary approach to analyzing scour from 2015 to 2019. The disciplinary fields covered included the physics of submerged granular environments, civil engineering (soil mechanics, free surface hydraulics) and scientific calculation (two-phase model) to meet the expectations of facility managers (rail and road).

Six partners have thus formed the consortium and brought, each in their respective fields, their scientific expertise, technical skills and complementary experience: soil and fluid mechanics anchored in practice (Ifsttar – Univ Gustave Eiffel), geotechnical engineers, hydraulic engineers, sedimentologists (Cerema), physicists (FAST Laboratory), railway (SNCF Réseau) and road infrastructure managers (Vinci Autoroutes) and a technological research institute (Railenium).

The project was divided into four tasks represented on Figure 1.

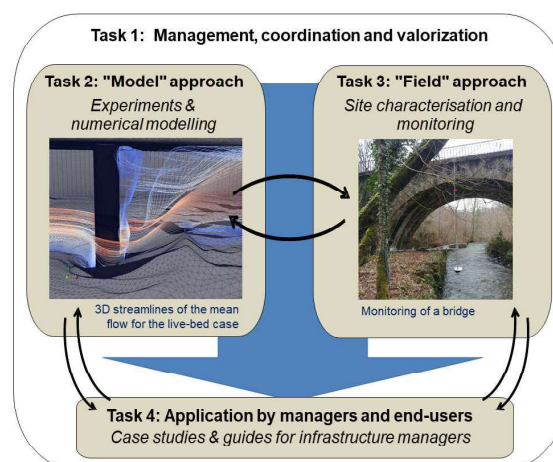


Figure 1. Task organizational flowchart of the SSHEAR Project.

Task 1 – Management, coordination and valorization – aimed at the running of the project and the good articulation of the actions by favoring synergies between partners as well as the communication around the project and the valorization of the results (web site: <https://sshear.ifsttar.fr/>).

Task 2 – “Model” approach – consisted of two parts, experimental and numerical, aiming at improving the understanding of scouring processes, preparing the characterization and instrumentation of real structures (tasks 3 and 4) and proposing new numerical approaches for the modelling of phenomena observed in the laboratory and in the field. In particular, scour experiments were conducted on two free surface channels of very different sizes: a small hydrodynamic channel 10 cm wide at the FAST laboratory (Orsay) and a large hydraulic channel 2 m wide at the LHSV (Chatou). In the small channel, near vertical cylinder scouring was characterized by laser profilometry and flow by Particle Image Velocimetry (PIV). In the large channel, a Moiré method and Ultra-Sonic Doppler Anemometry were used for bathymetry and velocity profile characterization, respectively. On an experimental level, this work has led to the development of a new device for measuring sensitivity to sediment erosion: the Wheel Erosion Test (WET). Numerical simulations of scouring were also conducted by developing a 3D code based on an unstructured finite volume method, where turbulence is resolved by Large Scale Simulation (LES).

Task 3 – “Field” Approach – aimed at developing tools and methodology leading to a better characterization and monitoring of the sites with respect to scour processes. On the basis of a study on the databases of the management partners, 7 study sites were selected with the objective of representativeness. Conventional reconnaissance tests and complementary techniques were carried out for a better characterization of the scouring processes. This work led to the detailed monitoring of 3 “pilot” sites, including permanent instrumentation for 2 of them. Finally, the monitoring of the state of structural scour using vibration measurements was studied. This work was based on the results of task 2 and fed into task 4.

Task 4 – “Appropriation” phase by managers and end users – was based on a feedback from the managers in collaboration with the project partners, in particular for the selection of pilot sites (feeding task 3). A particular work focused on the comparison of different scour risk analysis methodologies (French, ARPSA and Japanese, RTRI). Finally, capitalizing on all the work carried out during the project, the final objective of this task was to draft a guide to present infrastructure managers with the causes, assessment methods and techniques for reducing the risks associated with scour.

OBTAINED RESULTS

Task 2: “Model” Approach

The 10cm wide channel scour experiments focused on the clear water regime, corresponding to a flow velocity that did not cause erosion of the grains making up the bed away from the obstacle. Two erosion patterns were observed and characterized: (i) a pit at the foot of the cylinder linked

to the horseshoe vortex, (ii) two pits further downstream linked to the wake vortices, of elongated shape similar to two rabbit ears (Figure 2). This last pattern, which had never been clearly reported or studied, appears for a flow velocity slightly lower than the threshold for the appearance of the usual pit at the foot, but is quickly masked by the development of this pit when the velocity becomes higher. The influence of grain size and obstacle size and the shape of the obstacle on the threshold of appearance of these two patterns and the competitive existence of these two patterns have been extensively studied (Lachaussée et al. 2018).

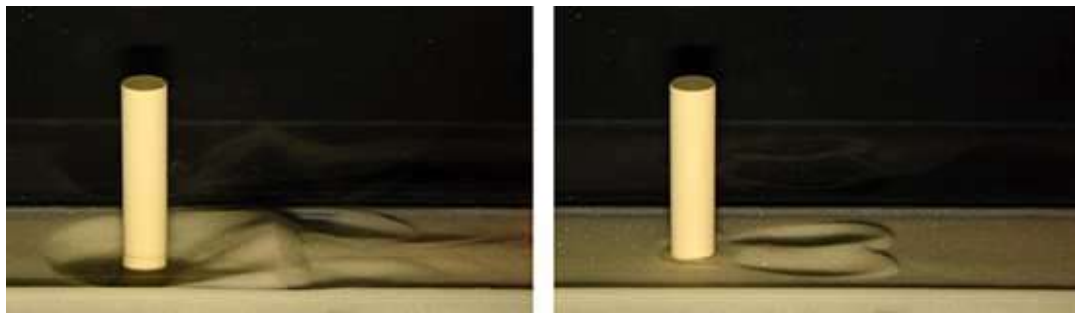


Figure 2. Two typical erosion patterns observed on a granular bed (0.3mm glass beads, $U_c=0.17\text{m/s}$) close to a vertical cylinder ($D=2\text{cm}$) submitted to a left to right water flow: (left) horseshoe vortex pattern ($U=0.94 U_c$) and (right) “rabbit ears” downstream pattern ($U=0.62 U_c$).

In addition to these experiments carried out on physical processes, tests were conducted in larger hydraulic channels (16m long, 2m wide) on model structures at the Laboratoire Hydraulique Saint-Venant (LHSV). Concrete model piers with or without foundation pads (representing bridge supports) were tested and accelerometers on the piers completed the model measurements (Figure 3). It was then possible to analyze the vibration response of the structure at different stages of the scouring processes (Larrarte et al. 2019b).

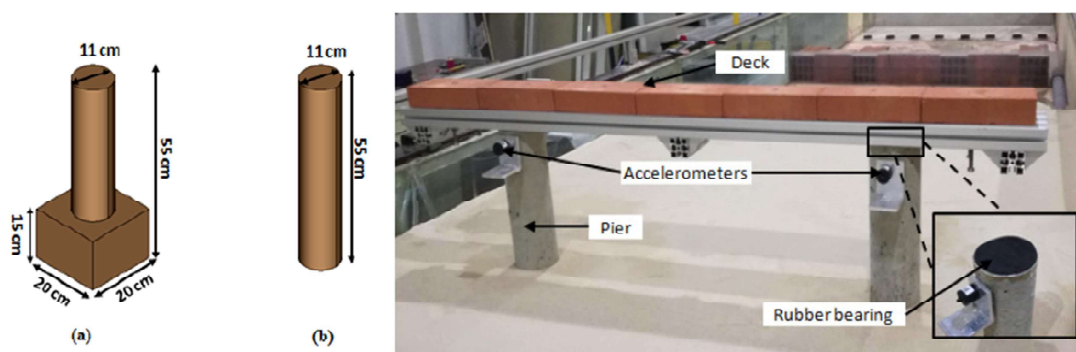


Figure 3. Model structure and its various foundations in a large hydraulic channel.

On the experimental work package, a new wheel erosion test (WET - Wheel Erosion Test) has been also developed, tested and validated (Figure 4). The test consists of a submerged cylindrical wheel (13cm width and 10cm diameter) that rotates around its horizontal axis over a layer of sediment. The rotation of the wheel generates a flow and consequently a stress on the soil surface which, once the minimum erosion threshold is reached, will create an erosion pit. This innovative device makes it possible to apply sediment in a controlled and realistic manner under submerged conditions (Ndoye et al. 2016).

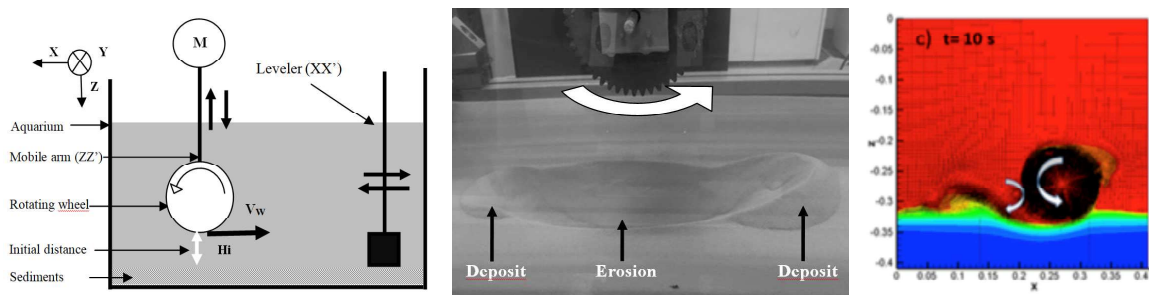


Figure 4. Wheel Erosion Test (WET): (left) schematic of the device, (center) observed erosion pattern with wheel raised after test and (right) simulation results.

Numerical scour simulations focused on the moving bed regime corresponding to flow velocities high enough for grain transport to take place not only close to the obstacle but also far from it. The 3D code is based on the unstructured finite volume method. The sigma transformation is used to take into account the deformation of the free surface. The development of the NSMP3D code (Navier-Stokes Multi-Phase three-Dimensional) was initiated in 2012 for sediment transport simulations in rivers, estuaries and coastal areas (Uh Zapata et al. 2019). The code includes advanced turbulence modeling, which is calculated either by DNS (Direct Numerical Simulation) or LES (Large Eddy Simulation), making it unique for the targeted applications (Zhang et al. 2019). Numerical modelling work has validated the 'research' code on the case of scouring of cylindrical pier (Figure 5).

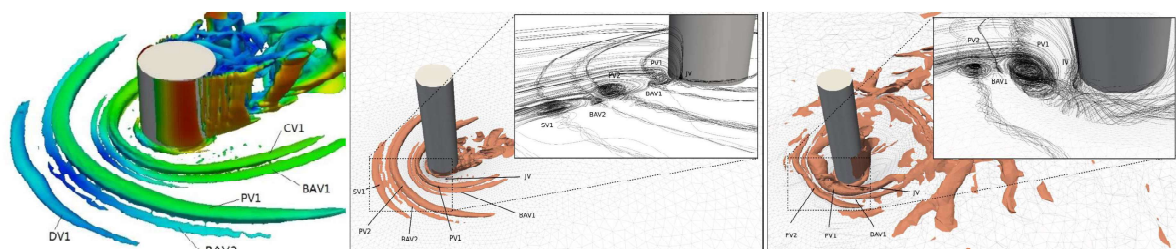


Figure 5. Coherent structures around a cylinder: (left) vorticity and (center, right) evolution of the horseshoe vortex during scouring.

Task 3: “Field” Approach

After a step of identification and characterization of representative sites affected by the scouring (Salavati et al. 2017), 3 sites were the subject of survey and in-depth monitoring: bathymetry, velocity profiles, sampling and characterization of sediments, additional topographical measurements at the level of the supports of the works, etc. These 3 sites were: (i) A71 Bridge over the Loire (6 piers located in the floodplain with 4 in the river bed), representative of structures crossing main river in the oceanic part of France, (ii) SNCF bridge over the Aurence River near Limoges in the oceanic part of France, a single masonry arch structure based on the bank of the river, very common on the secondary railway network but also on local roads, (iii) the embankment-dam along the Allier river at St Loup, where scouring is observed in a meander, representative of riverbank and its toe erosion in extrados (Figures 6 to 8).

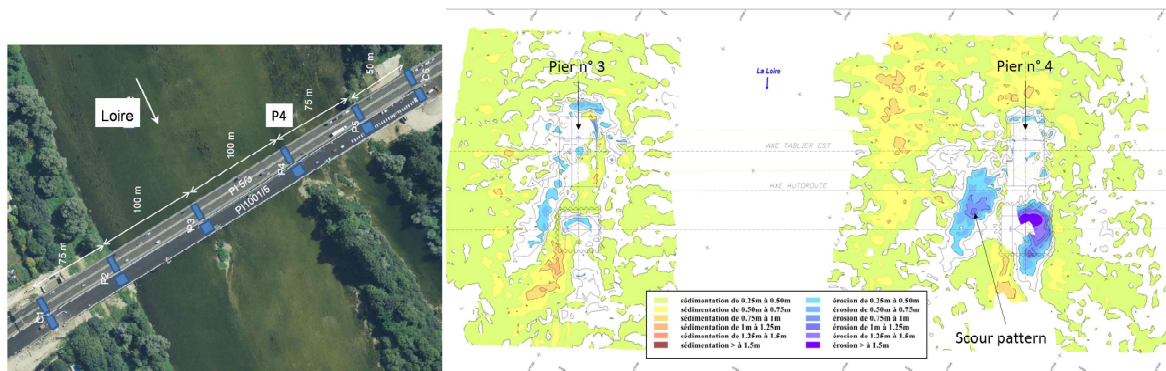


Figure 6. A71 motorway double viaduct in Orléans (France) over Loire river: (left) aerial view of the bridge and (right) bathymetric surveys comparison between January 2018 and May 2016

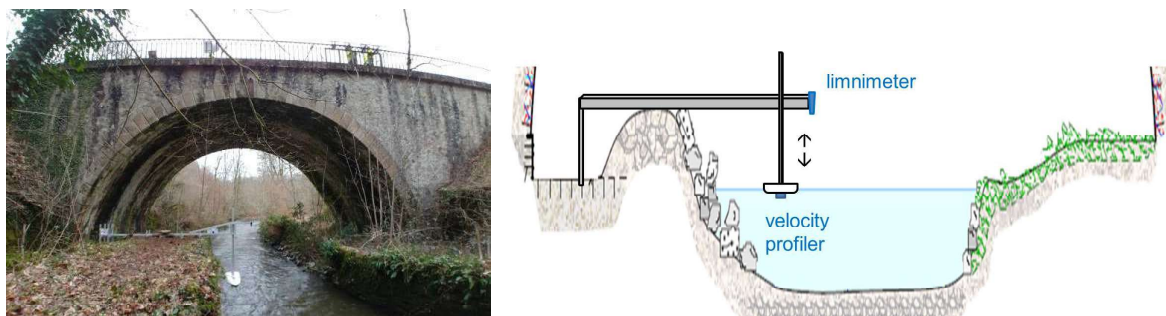


Figure 7. Site of the SNCF bridge over the Aurence River near Limoges (France): (left) view of the instrumented site and (right) scheme of the instrumentation.

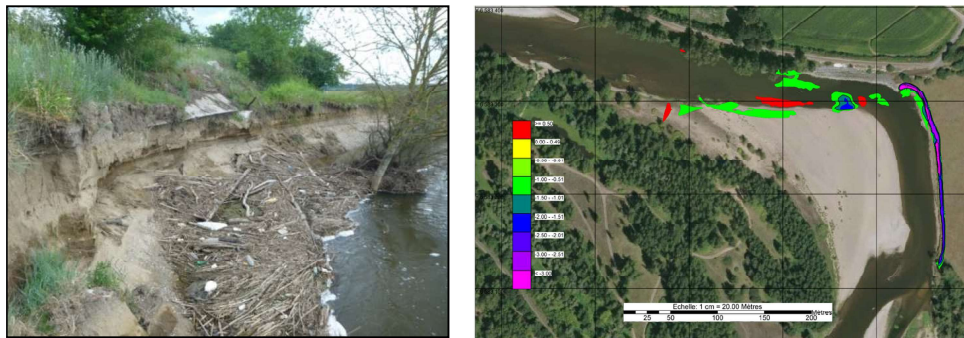


Figure 8. St Loup river bank over Allier river (France): (left) levee toe erosion view and (right) bathymetric surveys comparison between May 2018 and May 2017.

Two of these sites (bridges over the Loire and Aurence rivers) were also selected for the installation of permanent instrumentation (Florens et al. 2018, Larrarte et al. 2019a). After the definition of precise specifications, a market study and the definition of specific installation systems, these instrumentations were set up at the beginning of 2019 with autonomous energy supply and remote telemetry system (web data server). Complementary to punctual surveys (like on Figures 6 and 8), they enable continuous monitoring, over a long period, of the key parameters for understanding scour phenomena: bathymetry (sediment level) and velocity profiles (2D or 3D) (example on Figure 9). These instruments provide new data that give new light on the complexity of scouring on real scales: erosion but also potential sediment deposition, influence of turbulence, etc (Larrarte et al. 2020).

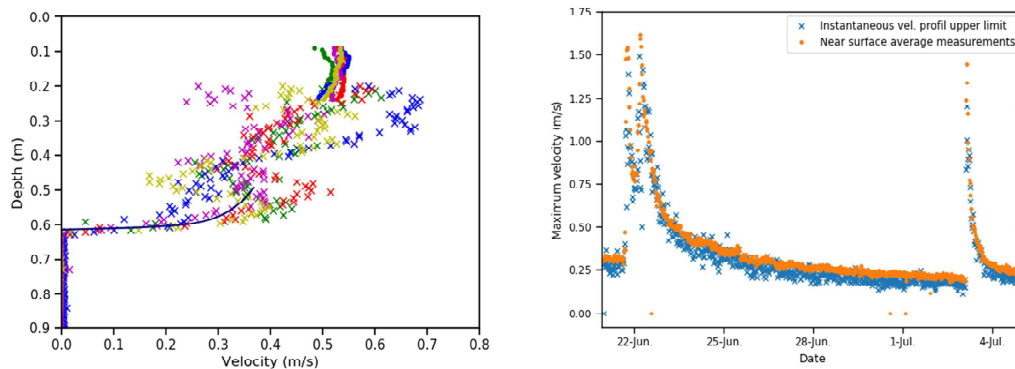


Figure 9. Measurements at the Aurence River near Limoges (France): (left) velocity profiles and fit and (right) time evolution of maximum velocities.

Soil scouring around the supports of structures modifies the conditions of the supports and can change their structural behavior. In order to detect this phenomenon and, if possible, to follow it, two paths were investigated (Boujia et al. 2019, 2020). First, the development of an auxiliary structure, corresponding to an instrumented rod, was studied (Figure 10). Then, the direct instrumentation of the structures was implemented with the aim of determining whether following the structure allows following the scour processes.

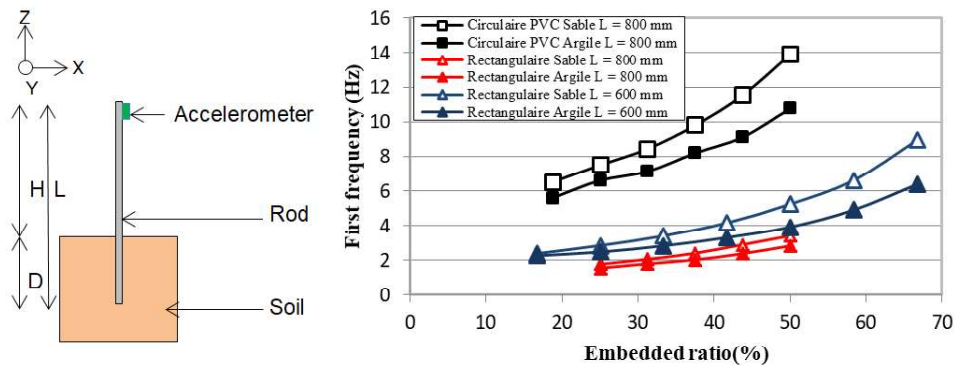


Figure 10. Tests to determine the vibratory behaviour of a rod embedded in the ground.

Task 4: “Appropriation” phase by managers and end users

The collaborative work between the project partners has enabled the identification of interesting SNCF and Vinci Autoroutes structures to be studied within the framework of Tasks 2 and 3. In parallel, working groups were regularly organized in order to establish a coherent architecture of a new guide (main deliverable for managers). These workshops allowed a fruitful exchange on the existing knowledge of the phenomenon (guides, publications, ongoing research...) and then resulted in exchanges with international organizations (RTRI in Japan and Network Rail in the United Kingdom), notably to exchange information on risk analysis methods (Takayanagi et al. 2019). The framework chosen for the content of the guide is essentially based on a risk management approach proposed in NF EN 31000 (Figure 11). Risk management using the VIP Risk approach makes it possible to study and assess each risk parameter (VIP for Vulnerability, Intensity, Probability). Aspects concerning uncertainty, climate change and prioritization of actions by managers are addressed in the guide.

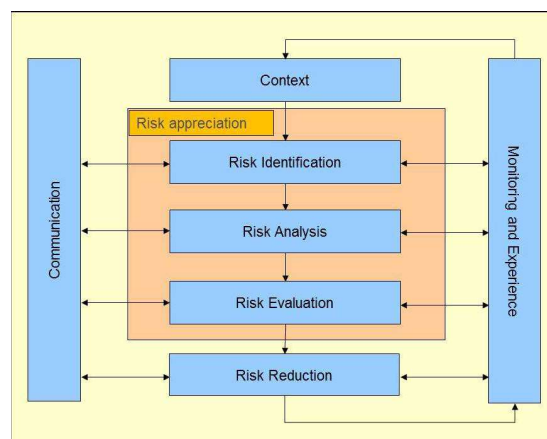


Figure 11. Risk management process (ISO 31000).

DISCUSSION, DIFFICULTIES AND CHALLENGES

Almost all of the project's initial objectives have been achieved with valorization through scientific publications and/or papers in international conferences. The ANR SSHEAR project gave also the opportunity to conduct 3 PhD studies and a total of 4 years of postdoctoral students work.

The main difficulty encountered came from a longer than expected time frame for the choice of pilot sites and specific problems related to setting up the permanent instrumentation. However, this is a common difficulty with this type of approach. Nevertheless, all the critical actions (choice of sensors, installation, preliminary tests...) having been carried out, the measures will be able to continue beyond the project with the agreement of the managers. These measurements and their analysis will enable further progress to be made in understanding scour phenomena.

CONCLUSIONS

The French ANR SSHEAR project proposed a novel multidisciplinary approach to scouring through the combined study of fundamental processes (in the laboratory) and real site investigation (including near real-time measurement and monitoring). In conjunction with the managers involved in the project, the progress achieved will be highlighted in a guide and may help to improve risk control through better knowledge of the hazard.

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