SCOUR PROCESSES AROUND A COLUMN ON A SLOPED BEACH INDUCED BY BROKEN SOLITARY WAVES

Alexander Schendel, Leibniz University Hannover, Germany, schendel@lufi.uni-hannover.de
Stefan Schimmels, Coastal Research Center, Germany, schimmels@fzk.uni-hannover.de
Mario Welzel, Leibniz University Hannover, Germany, welzel@lufi.uni-hannover.de
Philippe April Le Quéré, University of Ottawa, Canada, papri010@uottawa.ca
Ioan Nistor, University of Ottawa, Canada, inistor@uottawa.ca
Abdolmajid Mohammadian, University of Ottawa, Canada, majid.mohammadian@uottawa.ca
Nils Goseberg, Technische Universität Braunschweig, Germany, n.goseberg@tu-braunschweig.de
Clemens Krautwald, Technische Universität Braunschweig, Germany, c.krautwald@tu-braunschweig.de
Jacob Stolle, Institut National de la Recherche Scientifique, Canada, Jacob.Stolle@inrs.ca

INTRODUCTION AND MOTIVATION

Tsunamis continue to pose an existential threat to lives and infrastructure in many coastal areas around the world. Numerous studies have been conducted in recent decades to better understand the hazards and eventually mitigate risks resulting from tsunamis (Nouri et al., 2010; Palermo et al., 2013; Chock et al., 2013; Goseberg et al., 2013; Nistor et al., 2017; Stolle et al., 2018). One of these hazards is the emergence of deep scour holes around critical infrastructure and other buildings deemed community-essential, which affects their structural integrity and stability, rendering them unusable. Despite its importance, scour is still given limited and simplified consideration in foundation design guidelines related to tsunami hazards (ASCE-7 Chapter 6).

One reason for this is the complexity of the transient scour process induced by tsunami waves, which is still poorly understood despite intensive research in recent years. Previous studies have shown that the scour process is influenced by a multitude of parameters such as sediment properties (Lavictoire et al., 2014), structural geometry (Mehrzad et al., 2016), flow depth (Tonkin et al., 2003) or wave period (McGovern et al., 2019). Many other parameters such as soil stratification, sequences of individual long waves, or the soil's pore water content, affecting the scour development, have yet to be investigated.

This novel experimental study aims to improve the understanding of the time-variant scour process induced by single and consecutive broken solitary waves at large scale. **The main objectives were:**

a) High resolution acquisition of flow and spatio-temporal evolution of the scour processes around a square column including the drawdown phase.
b) Determination of the effect of consecutive waves on scour.
c) Comparison of maximum scour depth at selected instants of time during tsunami action.

EXPERIMENTAL SETUP

The study was carried out in the Large Wave Flume (GWK) of the Coastal Research Center, Germany. The GWK is 307 m long, 5 m wide and 7 m deep. A sandy beach (median diameter d_{50} = 0.35 mm, geometric standard deviation of $\sigma_g = \sqrt{d_{84}/d_{16}}$ = 1.46) with a slope of 1:20 was built on which an acrylic glass, square column (width 0.6 m), was installed. Time-history of the water level was recorded offshore and around the column using resistance and ultrasonic wave gauges. Flow measurements were carried out by ADVs and inductive flow meters. The transient scour development at the column was monitored by a video-camera system placed inside the transparent structure, while the spatial scour pattern was measured using a 3D laser scanner between individual tests. Solitary waves were generated with a non-linearity parameter (H/d) between 0.15 and 0.24 and wave periods between 7.6 s and 10.1 s. Overall, five tests have been carried out in which each wave was repeated up to four times. The test conditions are summarized in Table 1 and more detailed information on the experimental setup is found in April Le Quéré et al. (2022).

Table 1 - Test conditions.

Test	Number of waves N [-]	Water depth d [m]	Wave height H [m]	Wave period T [s]
T01b	4	3.0	0.73	7.7
T02b	4	3.2	0.74	10.1
T03	4	3.2	0.48	8.5
T04	4	3.2	0.62	7.6
T05	3	3.4	0.74	7.7

Between the individual waves, and after the water was partially drained from the surface of the beach around the column, the spatial scour pattern was measured using the 3D laser scanner. This measurement took approximately one hour. While most of the water within the sandy beach seeped back to the SWL during this time, a partially saturated soil must be assumed for the subsequent waves, which represents a different boundary condition compared to the first wave.

RESULTS

The flow and scouring processes observed in the experiments clearly differ from most previous studies in that a gravity-driven return flow occurred during which the flow interacted with the column differently than during wave runup, causing significant scour development on the downstream side of the column.

To illustrate the differences between the runup and drawdown phase, the flow and scouring processes around the column are shown in Figure 1 for two selected instants in time. In the depicted test T03 (cp. Table 1), the flow reversal between runup and downflow occurred at

about 6.8 s after the initial wave impact on the column.
After the initial impact and the occurrence of a wall jet on the offshore face (front) of the column, water rapidly penetrated into the dry soil and began to erode sediment along the entire length of the offshore (front) column face. The formation of the lateral vortex shedding at the offshore corners of the column resulted in extensive scour development at this location (Figure 1, upper left picture). After flow reversal, the drawdown flow was blocked by the back face of the column, leading to a hydraulic jump on the onshore (back) column side. Flow separation and lateral vortices forming at the onshore corners led to scouring at these locations, analogue to the flow and scouring process at the offshore corners during wave runup.

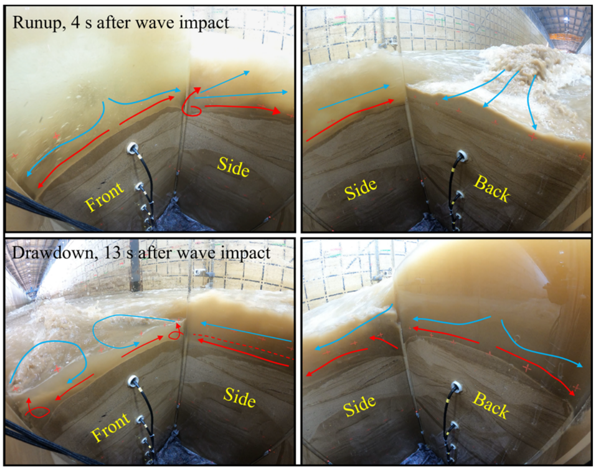

Figure 1. Flow patterns (blue lines) and scouring process (red lines) during wave runup (upper two photos) and drawdown (lower two photos) for the first wave in test T03.

Towards the end of the drawdown phase, the returning wave carried a high sediment load that led to refilling of the scour hole around the column, especially on the onshore side.
For test T03, Figure 2 presents photographs and the time-history of the relative scour depth S/D at three locations at the column side. As a result of the sediment infilling, the final relative scour depths at the end of the test were as much as 50% less than the maximum scour depth measured during the test, which is a larger reduction compared to those observed by McGovern et al. (2019) and Merzhad et al. (2016) who considered scouring over a horizontal sediment bed. In addition, relative scour depths at the end of the initial wave runup phase were 50% larger than the final measured scour depths. The discrepancy between final and maximum scour depths decreased with an increase in the inundation depth.
Overall, the scour deepened significantly less on the offshore side of the column with successive waves than on the onshore side, which is illustrated by Figure 3 by showing the scour profiles for Test T03. As the scour deepened, the shape of the scour profile on the onshore side of the structure also changed.

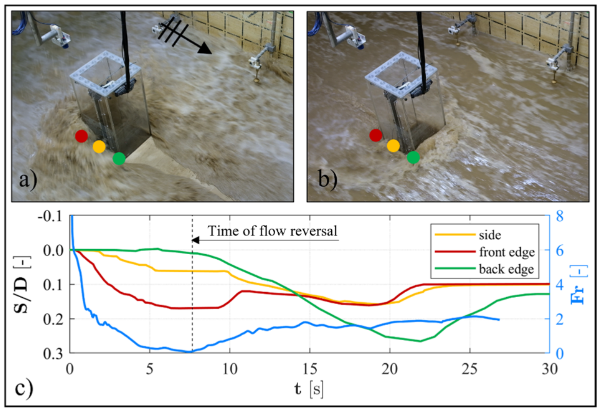

Figure 2 - Upper panels: Flow around the column during a) wave runup and b) wave drawdown. c) scour development around the column over time vs. Froude number.

Following the first wave, a conically shaped scour profile formed on the onshore face, with the greatest scour depths in the corners. After the fourth wave, the scour profile changed and exhibited a much more pointed sediment peak in the centerline of the onshore side.

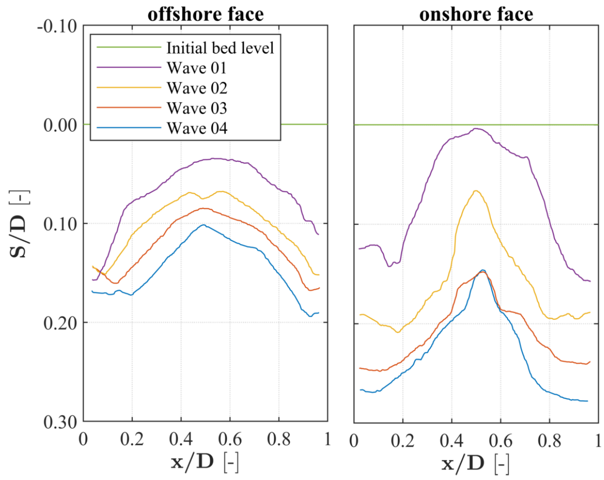

Figure 3. Test T03, development of scour over the offshore and onshore face of the structure with successive wave impact.

To further elaborate on the effect of successive wave impact on scour depth, Figure 4 shows the development of maximum scour depth with each wave for all tests. The scour depths given in Figure 4 represent the maximum final scour depth measured at the end of each test. As can be seen from Figure 2, the maximum relative scour depth during a test was sometimes significantly higher than this value.
As expected, the increase in scour depth diminished with each subsequent wave. While an increase of up to 43% was observed between the first and second wave (test T05) and an increase of up to 19% between the second and third wave (test T02b), the increase between the third and fourth wave was still up to 13% (test T01b), indicating that the equilibrium state had not yet been reached.

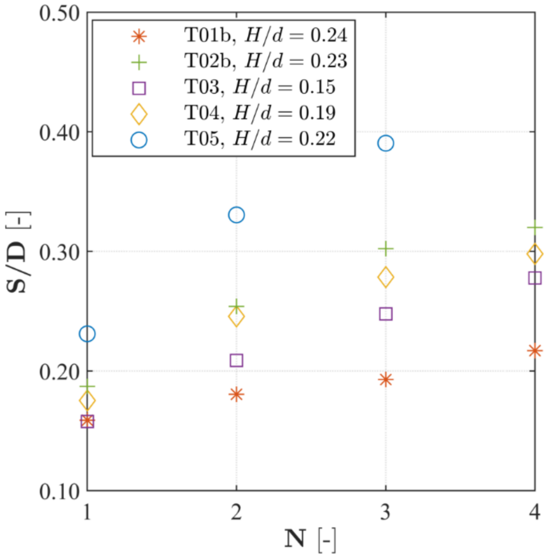

Figure 4 - Development of maximum relative scour depth (S/D) at the end of a tests vs. number of waves N.

During the subsequent interactions of broken solitary waves with the square structure, the flow field required additional time to fully develop into the already developed scour hole and to reach critical shear stresses to initiate additional sediment transport. This is the preliminary conclusion as to the causes of the decreasing relative scour depth with subsequent number of waves. In addition, the maximum scour depth increased with larger water depth which led to wave breaking occurring closer to the column. For constant water depth (tests T02b, T03 and T04), a larger wave height resulted in a deeper scour.

It should be pointed out that the results in tests with successive waves may be affected by the varying degree of saturation of the sand (see above in the description of the experimental setup) as well as by the beach profile changing with each wave due to the impact of the breaking wave.

CONCLUSIONS

This experimental study presents novel results on the spatio-temporal scour development induced by a tsunami wave. It aims at advancing the knowledge on tsunami-induced scour by providing new insights in the scour mechanism during the wave drawdown on a slope beach and by assessing the influence on scour processes of successive soliton waves. Additionally, by conducting large scale experiments scale uncertainties are further minimized and reference for an improvement of scour consideration in tsunami design guidelines is provided.

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