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Experimental study on wave-induced soil mechanical processes influencing bed load transport of fine sand

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ABSTRACT

We investigate the effects of wave-induced water pressure fluctuations and subsequent momentary soil liquefaction on bed load transport of a sandy bed in the framework of bank and bottom stability of waterways. It focuses on the soil mechanical processes of seepage, vertical drag force and vertical soil displacement influencing bed load transport. The experimental study is carried out with the river bed simulator, a closed-conduit flume with a soil sample container modelling a quasi-saturated sandy river bed. The sediment surface is subjected to steady state flow inducing small sediment movement as well as water pressure fluctuations. An absolute pressure decrease at the sample top inducing liquefaction results in an increase of sediment movement intensity determined through image analysis of the bed surface. The results show that the liquefaction process and the vertical soil displacement are both relevant factors influencing the sediment movement intensity.

INTRODUCTION

The bank and bottom stability of waterways such as the river Rhine is important for safe and easy navigation conditions. The bed of navigable rivers is subjected to free flow and ship-induced waves causing destabilizing forces on the banks and bottoms. The free flow conditions cause sediment transport.Water pressure fluctuations induced by waves act on the river bed surface altering the stress conditions in the permeable bed (Hsu & Jeng 1994). This is accompanied by transient seepage and liquefaction in near-surface areas (De Groot 2006). This contribution aims at understanding the interactions between soil mechanical processes in the river bed and bed load transport at the verge of incipient sediment motion.

Figure 1 shows the simplified river bed model of the investigated problem. We consider a sandy bed as a deformable two phase porous medium consisting of the permeable particle skeleton and the compressible pore fluid. The river bed is subjected to water pressure fluctuations from vessels inducing liquefaction in a near-surface area, characterized as states of transient suspension and resolidification. At the same time, seepage occurs and the sediment surface moves vertically (e. g. Biot 1941). These processes are superposed by a constant free flow boundary condition with “small” bed load transport (Vanoni 1964) qualified as stable.

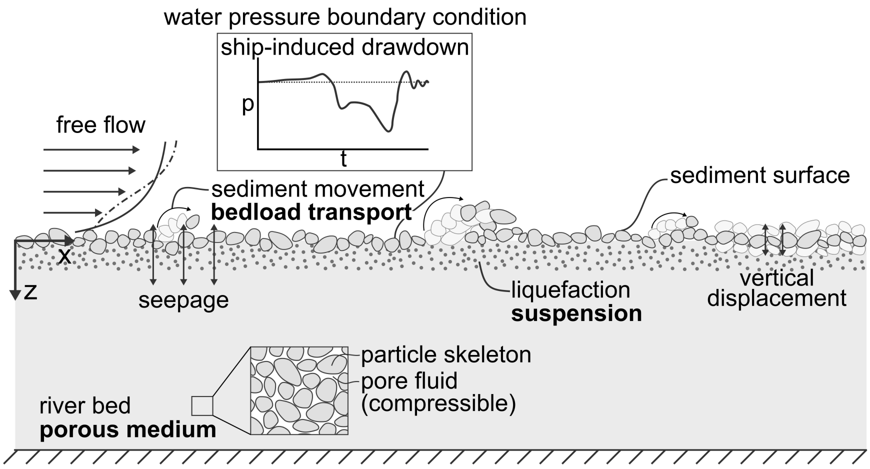

Figure 1. River bed model.

Sediment entrainment is governed by the lift and drag forces from the stream flow acting on the sediment surface. Wave action induces seepage in the quasi-saturated bed which can be accounted for as an additional vertical drag force. The seepage flow also influences the boundary shear stress of the flow (Lu et al. 2008). During the state of suspension the particle contact forces get partially lost and therefore the resistance to particle entrainment. And finally, the sediment surface moves vertically, exposing the particles differently to the stream flow. While in this study the described soil mechanical phenomena are assessed by measurements, there is no data available concerning the nature of the flow profile and boundary shear stress.

Studies show that steady state seepage has an effect on the boundary shear stress (Baldock & Holmes 1998). In the presence of vertical upward seepage for example, the shear stress at the sediment surface is reduced (Lu et al. 2008). Cao et al. (2016) quote that the effect of vertical upward seepage on sediment entrainment depends on the amplitude of the seepage force and influences the sediment transport rate significantly if the seepage velocity is relatively high. Also, seepage has an impact on turbulence intensities which is however not clearly understood (Lu et al. 2008). Most studies as quoted above focus on steady state seepage conditions. Others investigate the influence of wave action inducing sediment transport alone. Baldock and Holmes (1998) for example show that the vertical hydraulic gradients in the bed caused by waves with periods of 1 s have no influence on incipient sediment motion. Further experimental investigations accounting for wave action use a thin layer of sediment (e. g. Nielsen 2001). This does not account for the wave-induced instantaneous liquefaction and vertical soil displacement. Especially the sediment surface heave and settlement is not considered in the mentioned references or other by the authors known studies.

The present experimental investigation accounts for fully developed flow and transient wave action at natural scale and focuses on the analysis of soil mechanical processes in a larger soil sample. This means that pore water pressures, vertical stream and drag forces, liquefaction, and the vertical soil displacement at the surface are studied. It is the aim of this contribution to understand the influence of the soil meachanical phenomena on the sediment movement intensity as a measure of transport rate on a time-resolved scale.

THEORETICAL FRAMEWORK

Introduction. The theoretical framework aims at describing the physical processes on the basis of a continuum approach of the soil, the suspension (liquefaction) and the sediment surface movement. The soil model description is based on the mixture theory for a two phase medium consisting of the solid and the fluid fraction with homogenized characteristics. The volume fractions are defined by the porosity n and the respective velocities of the solid and fluid phases are v_s the particle velocity within the bed and v_f the seepage velocity. The sediment movement of the sample surface is addressed as a change in movement intensity per unit area.

Porous medium. The stable sand bed is described as a two phase porous medium consisting of a deformable and permeable soil matrix and a compressible pore fluid as a homogenized mixture of water and small gas bubbles (Pietruszczak 1996, Ewers and Karl 2017) which is denoted as a quasi-saturated porous medium. Seepage flow through the soil matrix is governed by Darcy's law (Biot 1941) with its vertical stream force defined as a function of the pressure gradient

$$f_s = \frac{\Delta p}{z} = \frac{v_f \gamma_w}{k} \qquad \text{(Equation 1)}$$

with k the permeability and γ_w the unit weight of water. It is noted that natural waves induce horizontal and vertical hydraulic gradients and seepage (De Groot 2006). For the case of quasi-saturated beds, the horizontal component of the hydraulic gradient is much smaller than the vertical component. Therefore, in this contribution only the vertical components inducing momentary liquefaction are accounted for. This corresponds to the simplified modelling of waves as one dimensional pressure fluctuations. The porosity of the sandy soil ranges between minimum and maximum bulk density and its limit state is defined as the loss of vertical effective stresses when the minimum bulk density of the soil is reached. It corresponds to the stream force equalling the bulk density of the soil skeleton under buoyancy $\gamma' = (1-n)(\gamma_s - \gamma_w)$ and is described as the transition from the solid porous medium to a liquefied state of suspension (Ewers 2019).

Dense suspension. The number of contact forces between the particles is reduced so that the particles do not form a solid soil matrix anymore (Jurisch 2021). The porosity approaches minimum bulk density but can still be larger (not all contact forces between particles have to disappear). The suspension is characterized by a suspension density and hydrostatic suspension pressure. Hoef et al. (2005) present a framework for the drag force relation. For dense arrays of particles the Kozeny-Carman equation is valid. It is a function of the relative velocity of the two phases and the changing porosity

$$f_{d,z} = \frac{180\eta_0}{d^2}\frac{(1-n)^2}{n^3}(v_f - v_s) \qquad \text{(Equation 2)}$$

with d the mean particle diameter and η_0 the viscosity of the fluid. It is only valid in the limit of zero particle Reynolds number (Hoef et al. 2005) which is assumed for this contribution.

Wave and seepage effects on sediment entrainment. Bed load transport is governed by the stream flow and its boundary shear stress as well as the sediment characteristics, especially the particle size. In this contribution the visual classification of the sediment movement refers to Vanoni’s (1964) approach. Instead of the bed load transport rate, we consider the sediment movement intensity as a continuum based qualitative measure.

Sediment threshold models are mostly based on the analysis of lift and drag forces entraining the particles. The triggering forces have to overcome the weight and resistance forces of the particle resting on the sediment surface and its angle of repose. Figure 2 shows a simple model of the forces acting on a single particle resting on a rough surface (Dey and Papanicolaou 2008). The streamwise drag force ($F_{D,x}$) is caused by the pressure force of the flow and the skin frictional resistance. The lift force normal to the flow direction (F_L) is caused by the velocity gradient of the flowing fluid. The resistance force of the particles is governed by the submerged weight and the friction forces c. f. the contact forces between particles.

Taking into account the soil mechanical processes during wave loading, further forces come in addition to this simplified conceptual model and modify the drag and lift forces, see Figure 2. There is a vertical drag force ($F_{D,z}$) coming from the seepage flow in the porous medium. Due to the vertical movement of the sediment surface the boundary layer may change and therefore the lift and drag forces. Additionally, the inflowing water to the main flow alters the near bed velocity profile according e. g. to Liu and Chiew (2012) which modifies the lift and drag forces from the stream flow. Finally, the resistance force of the particles is altered through the vertical drag force and the possible loss of the frictional contact forces while liquefaction takes place. In this study, the near wall velocity and boundary shear stress are not measured and subsequently there is no possibility to analyse the change in the stream flow conditions due to seepage and soil mechanical processes.

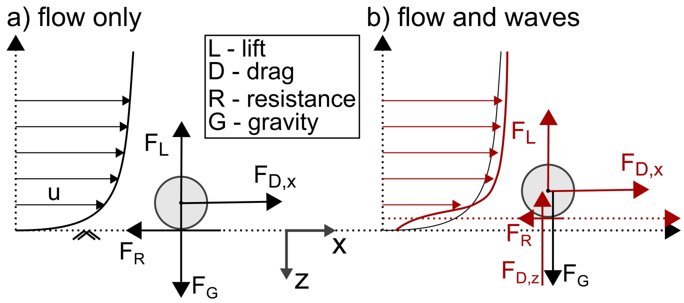

Figure 2. Forces Acting on a Spherical Sediment Particle at the Bottom of an Open Channel a) after Dey and Papanicolaou (2008) and b) the modifications with soil mechanical interaction processes.

It was chosen to not disturb the flow by incorporating a flow measurement device. Also, the impact of seepage on the flow conditions is well understood. As a consequence, the interdependency between boundary shear flow and seepage, liquefaction and soil displacement cannot be derived directly in this study.

EXPERIMENTAL SET-UP

Testing facility. The presented tests have been carried out with the river bed simulator of the Federal Waterways Engineering and Research Institute (BAW), see Figure 3. It is a recirculating closed-conduit flume with a soil sample container of 1.2 m depth. The flow is created by a pump in the rear of the facility and the water is moved through a flow damper followed by an 8 m long inlet section. Arriving at the rectangular 0.4 x 0.2 m² test section with the 1.5 m long erosion surface, the flow profile is fully developed. The faciltity is connected to a pressure system described in Kayser et al. (2016) with a pressure range from ~1.25 to 3 bar absolute for this facility. The absolute pressure is applied to the fully filled closed-conduit and can be varied time-dependently in order to simulate wave-induced water pressure fluctuations at natural scale that act on the sediment surface of the soil sample. This means that oscillatory flow is omitted for the sake of seperately analysing the effects of flow and simplified waves by superposition.

Measurements. The river bed simulator is equipped with a magnetic flow meter after the pump, measuring the discharge and respectively the mean velocity in the test section. Also the discharge at the pressure system connection is measured. Based on an algorithm programmed by Fabian

Karl (BAW) the seepage velocity v_f at the sediment surface is computed. The algorithm mainly accounts for the volumetric deformation of the facility and the air volume in the conduit.

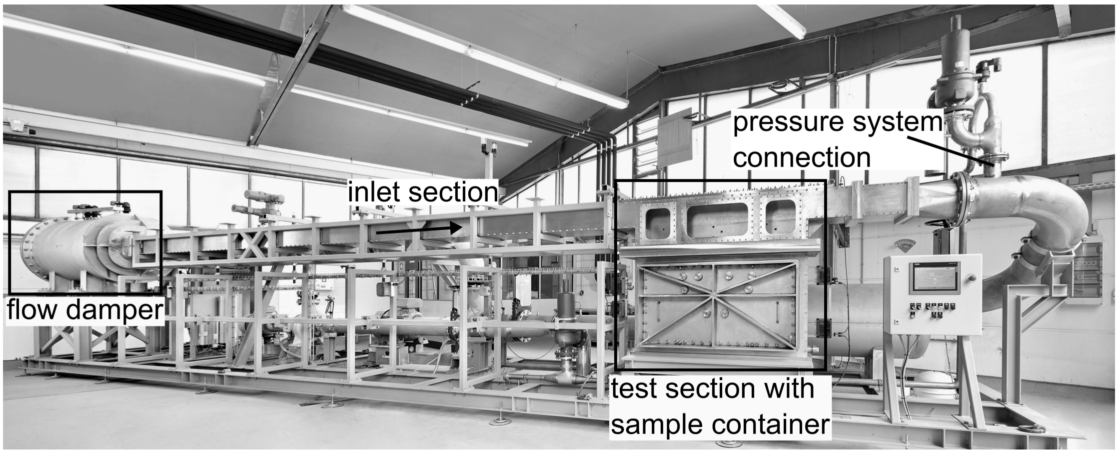

Figure 3. River bed simulator.

Absolute water pressure and differential pressure measurements are arranged at the back of the sample container measuring at a rate of 100 Hz. Figure 4 displays the measurement scheme with the absolut pressure sensor at the sample top (*pB01*) representing the absolute pressure boundary condition p_0 and a differential pressure sensor at 0.05 m depth (*pDiffB02*) for excess pore pressure data with the Darcy stream force

$$f_s(\frac{z}{2}) = \frac{pDiffB02}{z} \quad \text{with} \quad z = 0.05 \text{ m} \qquad \text{(Equation 3)}$$

The side camera records the movement of the soil in a near-surface area with a frame rate of 50 Hz. The video analysis is based on a simple tracking algorithm extracting local vertical and horizontal in-plane soil movement data in different depths. Based on the data, a variation of the initial porosity n_0 is calculated with the movement data in two depths with initial vertical distance l_0 (here about 11 mm) and differential movement Δs_z. The solid volume is assumed constant over time with $V_s \sim (1 - n_0)l_0$ and the void volume is $V_v \sim n_0 l_0 + \Delta s_z$. Then, the void ratio is

$$e = \frac{V_v}{V_s} = \frac{l_0 n_0 + \Delta s_z}{(1 - n_0)l_0} \quad \text{with} \quad n = \frac{e}{1 + e} \qquad \text{(Equation 4)}$$

Further, as the Kozeny-Carman equation (see Equation 2) is both a function of porosity (Equation 4) and the relative movement velocity $v_f - v_s$, the settlement data is numerically integrated in order to obtain the movement velocity of the solid phase with $v_s = f(s_z)$.

The top camera records an area of about 3 x 5 cm² of the erosion surface and shows the time-dependent bed load movement at a distance of ~0.8 m from the start of the erosion surface.

An image analysis technique is adopted to determine an integral sediment movement intensity I_{sm} over time by calculating the mean squared error

$$I_{sm} = \frac{1}{m}\sum_{i=1}^{m}(Y_i - \hat{Y}_i)^2 \qquad \text{(Equation 5)}$$

where $(Y_i - \hat{Y}_i)$ is the difference of RGB-values in each pixel i between two subsequent frames with m corresponding to the pixel number. It describes the similarity between two images. Thus, a higher value of I_{sm} signifies an increased transport rate. The data has a frame rate of 2 Hz. The measure shows qualitative changes of transport rate and is not comparable between different tests. Light conditions and exposure are constant for one test run but can scatter on different tests. The data shows an increase in I_{sm} and a higher data scatter for higher flow velocities.

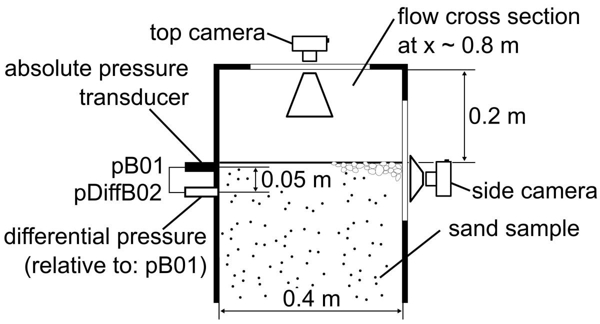

Figure 4. River bed simulator cross section with measurement equipment.

Experimental procedure. The preparated soil sample consists of a fine quartz sand with median diameter of $d_{50} \approx 0.12$ mm and a high uniformity. The hydraulic conductivity is evaluated in-situ before the test. The procedure adopted in the presented test is performed on one preparated sand sample with initial porosity $n_0 = 0.47$ and mean permeability $k = 1.14 \cdot 10^{-4}$ m/s. Here, we present a test (test-ID: 210714_gesi_fs_p1s1_07_flow1_lin3) with constant mean flow velocity of 0.184 m/s. The initial flow conditions correspond to a preliminary defined state of "small" bed load transport following Vanoni's classification and therefore characterized as stable. The pressure boundary condition is an approximated linear pressure decrease of around 20 kPa within ~30 s and a similar pressure increase after a time lapse with constant pressure of ~50 s. Within the constant pressure time the transient soil mechanical phenomena nearly completely fade away. The pressure changes can therefore be regarded as single events.

RESULTS AND DISCUSSION

The initial bed load transport of the presented test can be visually described as local movement of single grains or small groups of grains rolling over the sediment surface with long periods of rest. It can be characterized as small following Vanoni (1964). Figure 5a shows the applied pressure boundary condition at the bed surface (z = 0). The area hatched in yellow highlights the approximate range of time with bed suspension.

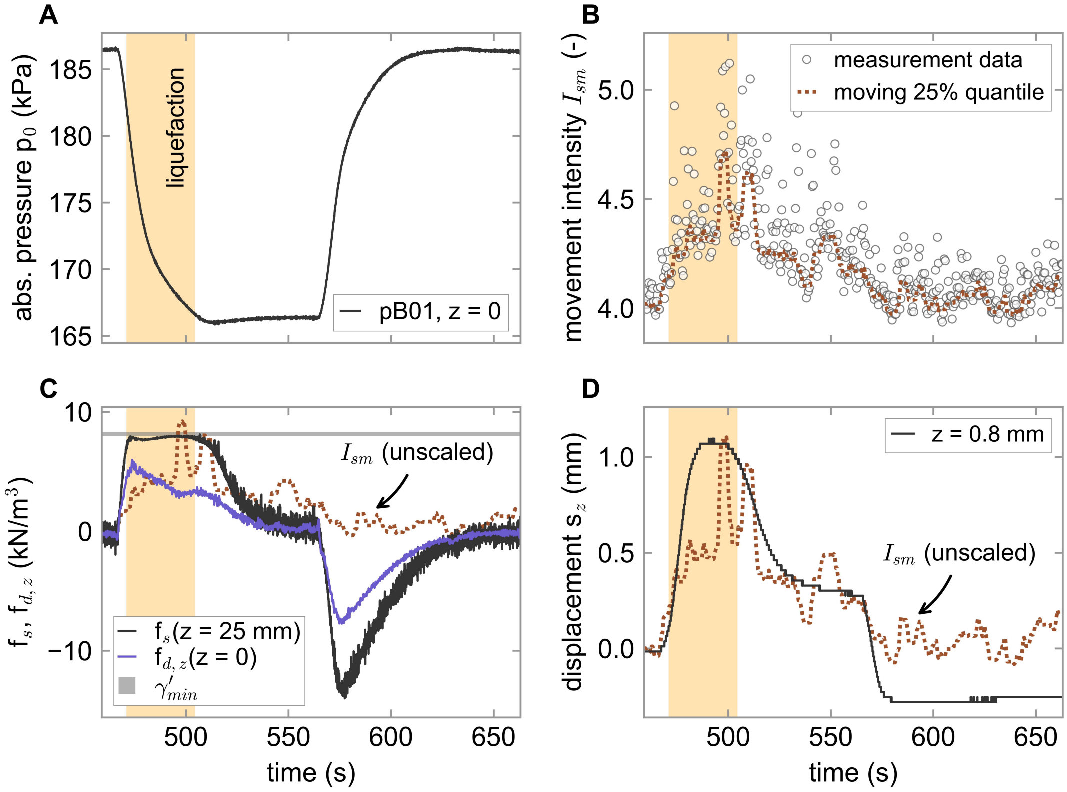

Figure 5. a) Pressure boundary condition, b) sediment movement intensity c) Darcy stream force f_s and empirical vertical drag force $f_{d,z}$, and d) vertical movement.

The sediment movement intensity I_{sm} (see Figure 5b) exhibits an increase starting with the pressure decrease and then coming down approximately to the initial intensity state. It goes along with a wider scatter during and shortly after liquefaction. No significant change in movement intensity is observed during the subsequent pressure increase. The visual analysis of the sediment motion during pressure decrease leads to the observation of bursts of movement with more general sediment motion and a merely susceptible but assumed calmer state during pressure increase.

Figure 5c focuses on the vertical seepage and drag forces. The Darcy stream force (see Equation 1) shows an immediate increase with the start of the pressure lowering and rapidly reaches the minimum bulk density of the soil γ' where it transitions to the suspension state. The solid matrix then looses its stability and becomes a dense suspension with a nearly constant suspension pressure. The vertical drag force based on Equation 2 rises quickly and then reduces slowly to zero during the constant pressure phase.

Figure 5d shows the vertical displacement of the soil sample nearly at its surface. It heaves with the onset of pressure decrease until a maximum value and then settles. Its reaction is slower than the build-up of Darcy stream force. After liquefaction and during the constant pressure phase the soil settles due to resolidification and consolidation. The pressure increase goes along with a linear settlement and a residual overall settlement at the end of the pressure boundary condition. In the background of Figures 5c and 5d the unscaled I_{sm} is shown. Vertical displacments and sediment movement intensity data have a comparable path over time. While the hydraulic processes (Darcy stream and vertical drag force) occur with a very small phase shift with respect to the pressure boundary condition, the soil particle reactions c. f. the vertical displacement and the sediment movement intensity appear to have a longer reaction time, here with their peak at a similar moment at the end of the liquefaction state.

CONCLUSION

The investigation shows the complexity of sediment transport in the presence of soil mechanical processes and presents an in-depth analysis of the soil phenomena. The lack of measurement data of the stream flow characteristics in a near bed area makes the assessment of the bed load transport influences incomplete but it shows that liquefaction is a driving force of enhanced sediment movement intensity.

The vertical displacement of the sample surface during pressure fluctuations and its correlation with the sediment movement intensity is an aspect which has been neglected in earlier studies. The results show that the sediment movement intensity increases at a similar pace as the heave of the sample surface. Also, the time resolved analysis suggests that the velocity or period of the pressure fluctuation is relevant since the sediment motion reacts with a time shift. Assumably, for very small wave periods, as in Baldock and Holmes (1998), sediment movement intensity might not be enhanced due to the phase lag of the particle reactions.

Further data analysis will focus on the influence of soil heave and settlement on the sediment movement intensity with variation of the pressure change as well as with periodic pressure fluctuations.

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