ABSTRACT

The major concepts and first experimental results of measurements characterising the pressure and velocity above and within a porous gravel layer are presented. With the goal of a more detailed understanding of the process new measurement techniques were applied in extensive systematic investigations of the flow within a gravel layer in a laboratory flume at the Federal Waterways Engineering and Research Institute (BAW) in Karlsruhe.

Miniaturised piezoelectric pressure sensors measured turbulent pressure fluctuations inside the gravel layer. Two fiberoptic endoscopes are used in a stereoscopic arrangement to acquire image sequences of the flow field within a single gravel pore. The images are processed by a 3-D Particle-Tracking Velocimetry (3-D PTV) algorithm. In addition to measurements of the pore flow within three gravel pores, an extended experimental setup enables the simultaneous observation of the near-bed flow field in the turbulent open-channel flow above the gravel layer and of grain motions in a sand layer beneath the gravel layer. The interaction of the free surface flow and the pore flow can be analysed for the first time with a high temporal and spatial resolution.

One of the main aspects is the question of bed stability. Since the well known Shields approach is based on mean quantities it is only valid for stationary flow conditions and uniform bed material. The appreciable amount of scatter in the experimental measurements of the Shields curve indicates that the highly time-dependent dynamical processes in the turbulent boundary layer above river beds have to be taken into account explicitly. The long-term goal of this project is to quantify the influence of turbulent velocity and pressure fluctuations on the bed stability of waterways. The obtained experimental data provide new insight into the damping behaviour of a gravel bed and can be used for comparison with numerical, analytical and phenomenological models.

The second major aspect draws attention to the influence of unsaturated submerged soil conditions, which describes a novel geotechnical phenomenon. In engineering practice submerged soils are commonly considered to be saturated and consequently the pore fluid may be regarded as incompressible. At shallow water depth the commonly used two-phase model is not in accordance with natural conditions. Even small quantities of gas bubbles change the stiffness properties of the pore fluid dramatically and the soil behaviour changes into a model of a three-phase system (gas, water and solids). In response to external fluctuating pressures, the gas bubbles in the pores experience a volume change, thus causing local transient flow. The latter must be consistent with the permeability law of the submerged soil. It could be shown, that time varying pressure loading contributes to soil deformation and erosion. Special flume experiments have been performed using wave and current loading focusing on the bed deformation due to sand motion at the interface between external water current and underlying soil. The phenomenon of scouring is taken into consideration.

Keywords: bed stability, scouring, sand waves, porous gravel layer, transient pore water pressure, unsaturated submerged soil, pressure sensor, 3D-PTV, endoscopic image analysis
1 INTRODUCTION

The current challenges in the planning of river regulation and maintenance measures at German federal waterways essentially lie in the prediction of the follow-up movement or morphodynamic changes of the river bed. The success or efficiency of regulation works or hydraulic constructions such as groynes, weirs, or embankments is strongly influenced by the stability of the river bed and the artificial geotechnical armouring layer, respectively. Abrupt pressure changes due to negative surge waves, wave loading and pressure fluctuations of the turbulent current have effects not only on the stability but further on the deformation behaviour of embankments and beds of navigable waterways. Against this background the destabilization processes of the bed, which directly take place at the water/soil interface and adjacent subsoil region, play an important role (Wenka & Köhler, 2006).

Over the last century a lot of research work has been carried out in order to gain insight into the theoretical background of river bed stability. However up to now no satisfactory, physically founded conception and its practicability has been established to answer definitely the question of river bed stability. The understanding of the individual processes, the functional chain of cause and effect is not developed far enough to predict destabilisation. With the goal of a more detailed understanding of these destabilisation processes new measurement techniques were applied in extensive systematic investigations of the flow within a gravel top layer and an underlying sand layer in a laboratory flume at the Federal Waterways Engineering and Research Institute (BAW) in Karlsruhe.

Special miniaturised piezoelectric pressure sensors were developed to measure turbulent pressure fluctuations inside and upon the gravel layer. Two fiberoptic endoscopes were used in a stereoscopic arrangement to acquire image sequences of the flow field within a single gravel pore. The images were processed by a 3-D Particle-Tracking Velocimetry (3-D PTV) algorithm, which yields the three-dimensional reconstruction of Lagrangian particle trajectories. In addition to the measurements of the pore flow within three gravel pores, an extended experimental setup enabled the simultaneous observation of the near-bed 3-D flow field in the turbulent open-channel flow above the gravel layer and of grain motions in a sand layer beneath the gravel layer. With the newest developments in the measuring technique it became possible to get deeper insight into these processes, which led to the destabilisation of the river bed. The combined employment of optical flow measuring techniques and miniaturised piezoelectric pressure sensors directly above and within a gravel bed proved to be an excellent tool, to receive a synoptic view of the interacting processes (Detert et al., 2004a; Klar et al., 2004a).

The experimental setup was implemented in a 30.1 m long and 0.9 m wide stretch of a laboratory flume at the Federal Waterways Engineering and Research Institute (BAW, see Fig. 1). In the flume, a sand layer of \( H_S = 0.5 \) m was covered by a porous gravel layer with a

![Figure 1: Sketch of the laboratory flume at BAW (Detert et al., 2004b / left) and streamwise cross-section with typical observation areas for detection of sand motion (1), endoscopic 3-D PTV (2) and 3-D PTV (3) (Klar, 2005 / right)](image-url)
varying thickness of \( H_P = 0.04 - 0.20 \) m. The medium grain diameter of the nearly uniform gravel was \( d_{mD} = 10.2 \) mm. The critical shear stress \( \tau_{0c} \) for this material can be calculated to \( \tau_{0c} = 8.8 \) Pa, using Shields equation with

\[
Fr_c = \frac{\tau_{0c}}{\Delta \rho \cdot g \cdot d_{mD}} = 0.06
\]

The mean grain diameter of the uniform sand was about \( d_S = 1.0 \) mm. With this configuration at chosen flow rates of up to \( Q_{max} = 0.275 \) m\(^3\)/s and water depths of \( H_A = 0.20 \) m or \( H_B = 0.40 \) low mobility conditions at the bed were reached. The investigation area was located in the middle of the flume, hence influences of inlet and outlet conditions were negligible.

### 1.1 BED DESTABILISATION AND INCIPIENT MOTION

The concept of Shields (1936) based on the critical shear stress \( \tau_{0c} \) to describe the transition from a stable to a moving bed is still in practical use, albeit several new approaches or formulae have been developed to improve this concept, e.g. Zanke (2003) or Vollmer (2005). Furthermore, a large number of mainly empirical approaches were published to predict erosion in non-uniform flow regions like piers, groyne heads or due to jets etc. However, up to now no satisfactory, physically founded description has been established to answer definitely the question of bed stability (Detert et al., 2005).

The detection of the so-called “bursting phenomenon” in turbulent flows (Kline et al., 1967, see Fig. 2) generated new interest in the study of the structures of the boundary layer turbulence by means of flow visualisation and with application of more modern and highly resolving measuring methods. These coherent turbulent structures caused by horizontal eddies, which gradually lifts from the bottom stretching into a hairpin vortex and finally degrading in the “ejection” phase play an important role in the pressure peaks acting on the river bed. The majority of turbulence production occurs, when these low speed streaks are lifted away from the bottom-layer in a violent ejection and during inrushes of high speed fluid from the outer layer back towards the bottom.

![Visualisation of bursting phenomenon in the flume of BAW (Köhler et al., 2004)](image)

Emmerling (1973) observed pressure peaks, which amounted to about the sixfold of the middle pressure fluctuation. Raudkivi (1982) for instance presented the following correlation between the pressure variance \( \text{rms}(p) \) and the bed shear stress \( \tau_0 \)

\[
\text{rms}(p) = C \cdot \tau_0
\]

with the factor \( C \) reaching a mean value of 3.0 and ranging between 0.5 and 5.0. After Emmerling (1973) the maximum of \( p \) can even reach up to \( 18 \cdot \tau_0 \). Thus, loads from \( \text{max}(p) \)
appear to be more than one order of magnitude larger than the critical Shields parameter $\tau_{0c}$.

Figure 3: Head of micro pressure sensor compared to gravel $d_{50} = \sim 10$ mm (Klar et al., 2004a / left) and Positioning of two sensors on a lattice compared to a floppy disc (Detert et al., 2004a / right)

The principle of the Miniaturised Piezoelectric Pressure Sensors is based on the piezoresistive effect. The initial point is an element of silicium, with implanted resistances in its bending panel. Fig. 3 shows two photographs of the encapsulated head of the pressure pickup. The sensors were locally fixed on a grid to keep them on an accurately defined position. The differential pressure is measured in reference to atmospheric pressure, with compensation of temperature. For water resistance, the housings of the sensors are encapsulated with slowly hardening epoxy resin and sealed up with clear varnish. The maximal dimensions of the sensors are as small as $2 \times 1.2 \times 1.2$ cm$^3$, with a shape similar to a larger gravel grain. Due to signal conditioning by the purpose-built amplifier the guaranteed maximum measurable frequencies are 100 Hz. Hence, measurements of pressure fluctuations up to the estimated Kolmogorov-scale-frequency of 50 Hz (Nezu & Nakagawa, 1993) were possible. To avoid aliasing effects, the measurements were performed at a rate of 500 Hz simultaneously by up to ten pressure sensors over two minutes. Pressure sensors were located at vertical positions of $y/d_{MD} = 1.0$ (above), $y/d_{MD} = 0.0$ (at top) and at various positions within the gravel layer (see Fig. 4). On each of the three artificial gravel pores a sensor was adapted to gain simultaneous insight in pressure and velocity changes, respectively.

Figure 4: Sketch of experimental setup, dimensions [cm], not scaled (Detert et al., 2004a)
1.2 SAND WAVES AND SCOURING

River and sea bed erosion leads to morphodynamic changes, which contribute to the formation of ripples, dunes and even large transport bodies. The reason for the development of such sand bed deformations is to be explained by the hydraulic current erosion taking place at the bed. The shear stress $\tau$ acting at top of the bed is not capable alone of creating such dune and ripple effects. Greater influence factors are the pressure fluctuations caused by the turbulence of the free water current, which is of course also coupled with the interaction of the pore water flow due to seepage inside the sediments. A typical example for such interaction taking place between the influencing external water current above the bed and the induced internal pore water flow inside the soil sediments may be observed with the phenomenon of scouring. Such actions obvious take place in the intermediate areas around and behind obstacles and constructions standing in the current. In the research activities up to now these interaction phenomena did not receive enough attention. The effect of transient pore water pressure changes $\Delta u(z,t)$ (see Fig. 5, lower part) induced in the subsoil of river and sea beds exposed to external flow characteristics should be observed closely. This leads compulsorily to a novel and necessarily different way of looking at how the formation and further development of sediment transport in sandy soils takes place. Pressure changes in the soil induced by extreme pressure fluctuations of the water current above the soil represent in their interactive effects a superposition of pressure differences resulting in changes of the bed form and the actually acting flow type at the soil/water interface. Due to the coupling of these effects small scale transport phenomena receive their importance which should conclusively make the macro scale changes at the sea bed describable and accountable in a physical sense.

Figure 5: Oscillating water level and its influence on the unsteady pore water pressure response in a sandy subsoil of a river bed as a function of soil depth, elapsed time and local point x, which might change the erosion process at the sand bed due to external flow fluctuations (Köhler et al., 2004)

The schematic diagram of Fig. 5 shows the development of sand waves, which was originally demonstrated by Yalin (1977). His schematic view (Fig. 7.10 b, page 221) is here additionally expanded by the action of current induced pore water pressures inside the subsoil of the bed. The change in bed roughness at the point between the solid and movable bed
results in discontinuities at actually acting current characteristics, which lead necessarily to scouring. This process is reproduced along the flow direction in x whilst the wave form levels off within a certain distance. This again causes changes in water level of the external water flow above the deformed sea bed producing long waves which at the beginning do not coincide parallel with the sand bed deformation. The amplitudes of the deformed water level and the deformed bed differ in the range of about $\lambda/4$ of the wave length $\lambda$ (see Fig. 5 e.g. local sections 2 and 4).

At the cross points between the deformed (continuous black line) and the fictive (dotted blue line) water level (see Fig. 5 upper part) at the time immediate past $t = 0$, the water pressure differences between both water levels are plotted along the $x$-axis (see Fig. 5 lower part), showing a sinusoidal characteristic wave form. The fictive water level describes the steady flow state at equilibrium condition ($t \to \infty$), which has not yet been reached. The yellow colour coded areas (marked with a “+” sign) describe the wave deformation with diminished wave pressure amplitudes, the blue colour coded areas (marked with a “-” sign) describe the enlarged wave pressure amplitudes along the flow direction $x$. These alternatively changed current conditions lead locally to higher and smaller velocities $v(x)$ of the external current above the deformed bed. Together with the enlarged velocities $v(x)$ the locally induced shearing stress $\tau(x)$ along the bed is also increasing. At these points of $x$ the erosion of the bed is enlarged and in contrary it will be diminished again, where the flow velocities $v(x)$ of the water current above the deformed bed will be smaller. Erosion and sedimentation may take place alternatively along the flow direction $x$ until the final dynamic flow condition is reached at equilibrium steady state condition. At the time $t = 0$ a scour develops directly behind the solid bed, which is followed up by a sand dune in a distance of $\lambda/2$ by reoccurring sedimentation of the just before eroded sand particles of the scouring area, which lies in front of the sedimentation area at about $\lambda/2$. These processes recur with the same wave length $\lambda/2$ along the flow direction $x$, in which erosion and sedimentation alternatively takes place. The so produced differences in soil levels $\Delta z_t$ at time states $t > 0$ (immediately after time $t = 0$) describe the firstly developed differences in the bed levels between the time dependent developing maximum sand level and the immediately following scoured trough level. Coupled to the changing shearing stress $\tau(x)$ the transport capacity of the external current will also change. With increasing distances $x$ from the vertical cross section 0 the described effects diminish in flow direction.

In the above mentioned sequences only forces acting outside the subsoil, such as pressure and velocity changes of the overflowing water current are taken into consideration. As soon as also current induced pore pressure fluctuations $\Delta u(t,x,z)$ inside the subsoil are taken into consideration, it will result in additional loading factors contributing to soil deformation of the sea and river bed. With increasing soil depth $z$ below the continuously deforming sea bed, the pressure spreading is delayed in time and damped in its size.

This transient pore pressure response may alternatively act as an enlarged scouring sequence as well as a diminishing scouring process. In the loading areas with positively marked pore pressure differences (+) the locally and time dependent acting upwards directed pore water flow may result in an increasing erosion potential at the river bed. Contrarily the negative marked areas (-) with down-ward acting transient pore water flow may result in an increased stabilisation of the river bed.

Both loading mechanisms leading to erosion and sedimentation are simultaneously superimposed thus in their effect it may either strengthen or reduce the result of the induced morphological process (Davis et al., 2004). In non-cohesive soils this process is always accompanied by changes of the soil structure. Whereas in cohesive soils these deformations lead either to hydraulic failure or to the detachment of thin cohesive soil layers out of a cracking bed.
2 PRACTICAL RESULTS

2.1 PRESSURE SENSORS

The analysis of the pressure signal gained by the Miniaturised Piezoelectric Pressure Sensors is less difficult than the Optical Flow Technique. To gain additional insight into the velocity regime on a less expensive and faster basis, a 1D-Acoustic Doppler Profiler (ADCP) was applied in the free surface flow proximately above the bed. A more detailed description of the measuring techniques and a first analysis of the data is given in Detert et al. (2005).

The measurement programme was designed for variation of water depth, thickness of the gravel layer as well as flow conditions up to low mobility conditions as mentioned above. Tab. 1 gives the flow conditions and mean parameters of the experimental series A01-A10 for a chosen gravel layer thickness of \( H_P = 0.10 \) m. Within this series, the bed shear stress \( \tau_0 \) was gradually increased to low mobility conditions. The criteria of instability is defined by \( \tau_0/\tau_{0c} \), with \( \tau_{0c} = 8.8 \) Pa after Shields (1936). At \( \tau_0/\tau_{0c} = 0.59 \) the transport of single grains was observed which is in good agreement with relevant studies and experiments for low mobility conditions and loose bed density (Detert et al., 2005).

Table 1: Experimental conditions with a gravel layer thickness of \( H_P = 0.10 \) m (Detert et al., 2005)

<table>
<thead>
<tr>
<th>series</th>
<th>unit</th>
<th>A01</th>
<th>A02</th>
<th>A04</th>
<th>A06</th>
<th>A08</th>
<th>A10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_0/\tau_{0c} )</td>
<td>[-]</td>
<td>0.09</td>
<td>0.18</td>
<td>0.36</td>
<td>0.48</td>
<td>0.55</td>
<td>0.59</td>
</tr>
<tr>
<td>( Q )</td>
<td>( m^3/s )</td>
<td>56.0</td>
<td>81.8</td>
<td>120.5</td>
<td>149.8</td>
<td>173.0</td>
<td>193.4</td>
</tr>
<tr>
<td>( h )</td>
<td>[m]</td>
<td>0.201</td>
<td>0.203</td>
<td>0.207</td>
<td>0.219</td>
<td>0.234</td>
<td>0.249</td>
</tr>
<tr>
<td>( U )</td>
<td>( m/s )</td>
<td>0.31</td>
<td>0.45</td>
<td>0.65</td>
<td>0.76</td>
<td>0.82</td>
<td>0.86</td>
</tr>
<tr>
<td>( u_e )</td>
<td>( m/s )</td>
<td>0.026</td>
<td>0.040</td>
<td>0.063</td>
<td>0.078</td>
<td>0.073</td>
<td>0.085</td>
</tr>
<tr>
<td>( R_{Dc} = u_e \cdot d_{msD}/\nu )</td>
<td>[-]</td>
<td>260</td>
<td>410</td>
<td>640</td>
<td>800</td>
<td>740</td>
<td>870</td>
</tr>
<tr>
<td>( \bar{U}_{ADCP} )</td>
<td>( m/s )</td>
<td>0.31</td>
<td>0.45</td>
<td>0.67</td>
<td>0.80</td>
<td>0.86</td>
<td>0.91</td>
</tr>
<tr>
<td>( h_{ADCP} )</td>
<td>[m]</td>
<td>0.200</td>
<td>0.200</td>
<td>0.199</td>
<td>0.207</td>
<td>0.224</td>
<td>0.235</td>
</tr>
</tbody>
</table>

The non-dimensional diagram of Fig. 6 presents the dependency of measured \( \text{rms}(p) \) or \( \max(\Delta p) \) with increasing shear stress \( \tau_0 \). All curves show a more or less linear behaviour. For the positions of the gravel sensors in the vertical direction (see Fig. 4), \( y = 0 \) is defined at 0.25 \( d_{msD} \) below the uppermost gravel grains. Focusing on the two sensors at the interface between gravel and open channel flow at \( y/d_{msD} = 0.0 \) (×, +) the gradients can be calculated to a ratio of \( \text{rms}(p)/\tau_0 = 3.5 \) (3.0) or \( \max(\Delta p)/\tau_0 = 18 \) respectively. Both values agree well with the above statements and given information by Raudkivi (1982).

Figure 6: Pressure fluctuations normalised by \( \tau_{0c} = 8.8 \) Pa, Runs A01-A10 (Klar et al., 2004b)
The view inside of the pore flow provides additional information. Now, the damping of the gravel becomes obvious: Whereas the ratio $\text{rms}(p)/\tau_0$ at $y/d_{mD} = 1.0$ above the gravel can be calculated to $C = 10$, the ratio is about $C = 2.2$ at $y/d_{mD} = -1.0$. Deeper in the gravel bed no difference between vertical positions can be detected. The ratio $\text{rms}(p)/\tau_0$ is given mostly by $C = 1.8$.

The first results of the interaction between turbulent open channel flow and the hydrodynamic reaction in porous gravel layer were presented in Detert et al. (2004a) and Klar et al. (2004a). For the power spectral density of pressure fluctuations in the water column and at top of the gravel layer a good agreement with Kolmogorov’s $k^{-5/3}$ law for the turbulence cascade in open-channel flow was found. Further, within the gravel layer an essential damping between 1 to 3 Hz could be recognized. Below $y/d_{mD} = \sim -4.0$ within the gravel layer there was no identifiable difference in damping pressure fluctuations higher than 3 Hz. For design criteria for stable filters thinner than $4 \cdot d_{mD}$ influence of turbulence of open channel flow has to be taken into consideration.

2.2 SAND MOTION

In this section, dealing with sand motion, an exemplary result from image analysis using rigid endoscopes is presented. A comprehensive analysis of the subsoil observation in the flume experiments is compiled in the technical report of Klar (2004).

Fig. 7 shows a result of the motion detection and a typical image of the endoscopic view. In this image, a partition of the observation area into four horizontal slices is indicated. In the upper part of the image, a gravel grain can be seen. The interface between the gravel layer and the sand layer is located in slice number two.

Figure 7: Left hand side and center: Results of sand motion detection at the sand/gravel/water interface using endoscopic image analysis (Klar, 2005).
Right hand side: Partition of the endoscopic observation area into four horizontal slices (Klar, 2005).

Fig. 7 shows the results of the motion detection at the sand/gravel/water interface. The plot has been obtained by simply counting all the pixels of the image where motion had been detected. At some wave cycles, sand grains have been transported and a quasi-periodic motion could be observed. All the counts of motion have been accumulated separately for each of the four horizontal slices (see Fig. 7). The synoptic view shows that the maximum motion occurs in slice one and two, where the gravel layer resp. the interface between the underlying sand and top loaded gravel layer is located. In the left plot, the motion counts are shown as a function of the space of the whole image. The white horizontal line indicates the approximate location of the sand/gravel interface. The counts are colour coded. The colour map is shown at the top of the image: Blue corresponds to 'no motion', and red corresponds to 'maximum
motion'. The plot clearly shows that motion of sand grains occurs along the interface between the sand and gravel layer. Grain motion in the deeper sand layers (slice three and four) only occurs for single grains, which move periodically in response to the impact of the artificially generated wave amplitudes in the flume (see Fig. 1).

The effect of small amounts of gas in bubble form inside the pore water of the subsoil at shallow water conditions is to make the pore water highly compressible compared to the stiffness of the soil skeleton. The effect associated with this phenomenon during external pressure fluctuations is to make the soil vulnerable to enhanced erosion (Davis et al., 2003; Köhler et al., 1996; Spies et al., 2000).

3 CONCLUSION

A new experimental concept for the laboratory measurement of the flow in and above a gravel bed with an underlying sand layer has been developed in close co-operation between the Federal Waterways Engineering and Research Institute, Karlsruhe and the Universities of Heidelberg (Interdisciplinary Center for Scientific Computing) and Karlsruhe (Institute for Hydromechanics). The instrumental setup allowed synchronous measurements of pressure and velocity within three artificial pores and the open channel flow. Stereo camera setups with flexible fiber-optic endoscopes are used to measure the flow within three artificial pores in the gravel layer. Image processing techniques were used to extract the 3-D velocity field from the acquired image sequences. The motion of sand grains at the sand/gravel interface had been observed by three additional endoscope setups.

The new method for the measurement of pressure fluctuations in open channel flow at high temporal resolution both on subsurface and within a gravel layer has proven its functionality. The novel measuring technique using 3-D PTV and endoscopic image processing has proven its practicability to be a very good basis for future research. A detailed presentation of the method used with special focus on the image processing technique is given by Klar (2005). The hydraulic part of the research project will be compiled by Detert in his PhD thesis, to be published in 2007 at the University of Karlsruhe.

ACKNOWLEDGMENTS

The authors are grateful to Mr. M. Detert at the Institute for Hydromechanics, University of Karlsruhe and Dr. M. Klar at the Interdisciplinary Center for Scientific Computing, Ruperto-Carola University of Heidelberg for the performance of the joint research project.

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