ARTIFICIAL REPRODUCTION OF THE SURFACE STRUCTURE IN A GRAVEL BED

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Abstract

Sediment transport experiments are performed by a number of institutes, mostly related to hydraulic engineering. Results are usually comparable in a statistical way, but hardly reproducible, since the initial conditions will never be the exact same for different experimental setups.

To solve this problem, it is possible to manufacture several artificial copies of a naturally developed streambed that can be transported to any location for further research. Hence, several institutes with different facilities or divergent research interests can work on the exact same channel bed and therefore compare and merge their results for a broader investigation.

A highly promising technique to reproduce the surface structure in a gravel bed has been performed, using a liquid two-component silicone rubber to manufacture a negative imprint of the stream bed. Subsequently, a two-component pouring resin forms an almost exact copy of the original gravel bed using the silicone form. The flexible silicone creates a true three-dimensional copy of the original bed structure. Protruded particles are almost fully enclosed and even smaller, partially hidden particles are entirely reproduced in the final cast.

This method was just recently used to move the surface structure of an armor layer experiment from the Leichtweiß-Institute for Hydraulic Engineering in Braunschweig (Germany), to the Department of Marine Technology at NTNU in Trondheim (Norway). The aim for the further experiments at those facilities is to estimate the physical effects of flow fluctuations over an armored riverbed, regarding coherent turbulent structures with a PIV (Particle Image Velocimetry) system. First insights in this study are presented.

Introduction

Fundamental research on sediment transport is often performed in straight hydraulic flumes. Discharge, water depth, bed slope and sediment mixture are adjustable parameters. This makes the boundary conditions for such experiments reproducible to the greatest possible extent. Still, the actual results of different experiments with the same prerequisite conditions can differ tremendously.

It would be impossible to develop an identical channel bed for two different experiments, neither in the same flume, to repeat an experiment with slightly different conditions, nor in another laboratory to work on it simultaneously. As long as a statistical analysis of steady flow situations is performed, the results of two different experiments should match. But if it comes to problems of incipient particle motion or unsteady flows, two statistically comparable streambeds might not be similar enough to reach equivalent results.

As an example: Turbulent flow structures over an armor layer during highly unsteady events might cause the incipient motion of single particles. To investigate such processes, it is necessary to monitor individual particles on the streambed surface and compare their behavior for different flow situations. Then again due to the particle motion, the armor layer would be destroyed with each individual experiment. It would not be possible to redevelop the exact same preconditions for subsequent test runs.

To overcome this problem, researchers often use artificial streambeds consisting for example of “spherical roughness element beds” (Dwivedi, Melville, Shamseldin, & Guha, 2011) or combinations of real and artificial stones (Hoan, Stive, Booij, Hofland, & Verhagen, 2011). Others tried to include a “model stone” equipped with miniature pressure sensors (Hofland & Battjes, 2006) or even a whole set of pressure-resistive sensors shaped like cobble stones (Detert, Nikora, & Jirka, 2010) into a non-moving bed.

It seems therefore that artificial streambeds might be a worthwhile alternative for laboratory experiments to achieve valuable results. The challenge is to produce streambeds with similar characteristics as in natural riverbeds. While spherical or other artificial bed elements might be a good approximation and for sure imply several advantages, molding techniques provide a nearly exact copy of any desired surface structure.

In 2003, (Buffin-Bélanger, Reid, Rice, Chandler, & Lancaster) successfully developed a casting technique to reproduce a coarse-grained river bed. Some difficulties, mostly concerning the molding material used within this method were documented in (Buffin-Bélanger et al., 2003) and (Chandler, Buffin-Bélanger, Rice, Reid, & Graham, 2003). Most of those difficulties could be avoided using the subsequently described technique, mainly due to the use of a different molding material and the abandonment of an additional rigid mold.

The following method was used to reproduce several duplicates of an armor layer surface structure in a laboratory flume of the Leichtweiß-Institute for Hydraulic Engineering in Braunschweig (Germany). Later, those copies were transported to the Department of Marine Technology at NTNU in Trondheim (Norway) for further research.

To avoid misunderstanding in the description of the reproduction technique, the word “molding” will be used to describe the manufacturing of the negative silicone imprint, derived from the original bed surface, while the expression “casting” indicates the later performed production of the positive streambed duplicates made of casting resin.

Molding the original surface structure

Preparation

To define the relevant area, a wooden frame is set in position upon the armor layer before pouring the molding mass. The open room between frame and bed has to be closed to assure that no material is wasted. Some sand around the frame, retained by a plastic foil attached to the frame is fully sufficient for that.

If the streambed lies in a tilting laboratory flume, it should be brought into a horizontal position. If not, this step will be done during the duplicate casting later on.

Molding

To produce a negative imprint of the original surface structure, a liquid two-component silicone rubber was poured over the desired surface. This material can be processed cold and is not known to be harmful to health if it comes to contact with human skin. The use of gloves is nevertheless recommended. After mixing the two components, it hardens within less than one hour until it reaches an ultimate tensile strength of 2.36 MPa at a maximum elongation of 292% (source: www.trollfactory.de). The resulting, flexible silicone form gives the opportunity to produce riverbed duplicates with a rigid casting material. The form can later be detached from the final product without destroying either of them. Hence, the silicone form can be used to produce several artificial streambeds. According to the supplier, it remains flexible over up to twenty years or more if hermetically sealed.

The producible area is generally only limited by the difficulty to physically handle the resulting silicone form and bed duplicates in matter of size and weight. Although the silicone compound should be poured within 6-8 minutes after mixing the two components, it is no problem to produce very large silicone forms. To do this, smaller amounts of the material can be poured step-by-step and will connect seamless. Even if the earlier poured material already cured.

Figure 1 *left* shows the wooden frame before pouring the silicone. To close the gap between frame and bed, plastic foil is attached to the bottom edge of the frame and pinned down by some sand. Figure 1 *right* displays a small section of the finished, cured and cleaned silicone form which is a negative imprint of the original bed surface.

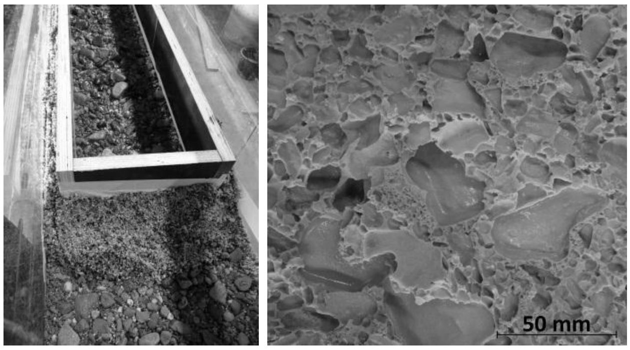

Figure 1: *left:* frame set on top of the streambed, ready to pour the silicone ; *right:* detail of the negative silicone imprint, later used as casting form

In this attempt, the original bed surface was an armor layer, developed at a constant discharge of 28.9 l/s within a 5 m long and 30 cm wide laboratory flume at the Leichtweiß-Institute for Hydraulic Engineering in Braunschweig (Germany). The mean bed slope was 0.5% and the mean grain diameter was 3-5 mm with a maximum grain size of 31.5 mm. Since the boundary areas along the glass walls might be influenced by the wall shear stress, only the inner 20 cm of the flume were regarded as freely developed and therefore chosen to be reproduced. The length of the molding area was chosen to 160 cm, to achieve riverbed duplicates that are easy to handle in size and weight as well as easy to transport. To cover all exposed grains in this section of 20 cm x 160 cm, 10 kg of silicone compound has been used.

The liquid silicone has a viscosity comparable to warm honey, so it is able to infiltrate several centimeters into the substrate underneath the streambed surface. This would cause additional work in cleaning the sand grains from the silicone form and would also imply some loss of material. To prevent the silicone from infiltrating too deep into the sand, the first layer of silicone was poured slightly time delayed. In other words: Approximately 5 minutes of additional mixing-time, increased the viscosity of the liquid silicone to an optimum before pouring. The silicone was still fluid enough to adapt even the finest sand grains within the surface structure.

During the curing process of the silicone mold, no visible shrinking of the material was observed.

Cleaning the silicone form

After the curing process, the wooden frame can be removed. Since all exposed grains were covered during the molding process, the top surface of the silicone mold should now be completely flat and the imprint of the wooden frame should be clearly apparent in the mold. The elastic silicone can be removed from the streambed by folding or rolling it together and lifting it up.

Overlaying parts of the mold, which cured underneath the boards of the wooden frame, can be removed. A sharp knife, e.g. a box cutter, is suitable to cut along the clearly distinguishable edges defined by the inner border of the frame.

All grains have to be removed from the silicone. Coarse particles can be easily removed with bare hands while a blunt piece of metal turned out to be a very helpful tool for finer gravel. Sand grains can be chipped off the form while the silicone is bended to open the pores. A compressed-air pistol can also be used. Since the form should be completely dry before filling it with pouring resin later on, water was not used to wash the form. Bending and massaging the silicone helps to feel encased particles with the fingertips.

There are three situations where the silicone form itself has to be manually adjusted to improve the casting result:

A) In case that a larger grain is almost entirely encased in the silicone and only visible through a rather small hole in the mold, it is recommended to enlarge this hole. The reason for this is that in the later produced resin duplicate, the contact area between this particle and the rest of the streambed will be as small as the hole in the silicone form. Thus, it might be a very fragile connection.

B) If larger, protruded particles on the original surface touch each other above ground, the area underneath will appear as a bridge-like structure in the negative silicone form. It is recommended to disconnect this bridge with a clean cut. Otherwise it will be ripped apart and might be destroyed during the later detachment of form and product.

C) In case that some material infiltrated into the sand layer, a porous silicone structure will occur. This entire structure has to be carefully removed until coarser particles, which represent the actual streambed surface, are revealed.

Casting streambed duplicates

Preparation

The wooden frame, used for the silicone mold can be reused as a frame for the further cast of the streambed duplicates. An additional base plate should be attached to close one side of the frame and create an open box with the dimensions of the silicone form.

This box is now placed on an even surface with the open side up. The clean and dry silicone form is placed inside the box, structured side up.

If the form was taken from a horizontal surface or the laboratory flume was tilted to a horizontal position, the artificial riverbed can now be cast. If not, the mean bed slope has to be leveled out by lifting the upstream end of the box.

The preparation of the silicone form with a mold-release agent is not necessary since the silicone tends not to connect to most other materials.

Casting

Generally any rigid casting material can be used to fill the silicone form, as long as it does not exceed 180°C during the curing process. However a two-component polyurethane pouring resin (PUR) showed excellent characteristics for the purpose.

After mixing the resin with the curing agent, it has to be poured into the form within 3-4 minutes before it cures. To capture the entire surface structure and to provide a certain stability of the casting product, the silicone form should be covered by several centimeters of resin. Approximately the same amount of resin and silicone is necessary to do that (in this case 10 kg).

Its high fluidity allows the resin to fill even the smallest pores within the silicone form and creates a surface structure, true to the original. To prevent air bubbles at the surface of the final product, a small brush can be used to relieve trapped air within the first minute after pouring the resin into the form. After that, the form should be kept steady and not be moved, since the resin cures within minutes and fully hardens after 1.5 hours. During the curing process, the material warms up. To be sure that the casting is fully cured, it is recommended to wait until it cools down to room temperature, before removing the silicone form.

After the curing process, a small gap between the frame and the riverbed will be visible. This indicates a shrinking of approximately 1%. It should be noted that this inaccuracy only occurs in the copying process from the original bed to the streambed-copy. Since all produced copies come from the same form and consist of the same material, those should all be similar to each other.

Figure 2 *left* shows the wooden casting frame, filled with 10 kg casting resin in the natural white color that it develops during the curing process. Figure 2 *right* pictures the detaching of the rigid cast and the flexible form.

Figure 2: *left:* filled casting form ; *right:* detaching

The used casting resin contains monomeric isocyanate (MDI). So the casting should be performed in a room with ventilation or a big hall and protective gloves as well as glasses should be worn.

Alternative casting materials are described in (Buffin-Bélanger et al., 2003). Low priced alternatives could be plaster or concrete but those were not been tested.

Detaching and finishing

Before the streambed duplicate can be detached from the silicone form, it is necessary to unscrew the wooden frame. The remaining composite of form and cast should be placed on a table with the cast side up. Since the corners and edges can be quite sharp, it is reasonable to remove all burrs before proceeding with the detachment.

Now the whole piece can be turned upside down to bring the flexible silicone side on top. Starting at one corner, the silicone form can now be carefully removed from the cast. Rolling it from one side to the other seems to be the easiest way to do this (see fig. 2 *right*). Special attention should be paid at parts, around strongly overhung structures where the silicone form has to be supported to not be destroyed.

Also along the top edges of the artificial streambed, some burrs and overlaying parts will occur. These should be removed using ideally a hand-held milling cutter.

The first cast might breach some minor structures of the form that should have been treated manually during the cleaning of the form. The subsequent casts almost don't penetrate the silicone form at all, so that it can be used several times. It could be estimated to use one silicone form between ten and fifty times over several years, if treated with care.

Figure 3 compares the original to the artificial streambed surface. The pictured sector shows strongly protruded areas and a high range of grain sizes, from fine sand particles up to 31.5 mm gravel. It gives an impression of the duplicate's authenticity.

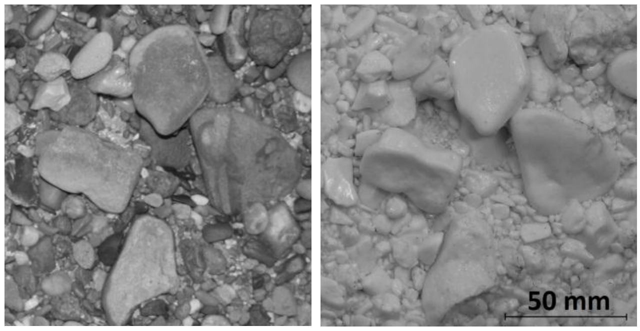

Figure 3: *left:* original surface ; *right:* duplicate

Coloring

Some experimental applications require structures in a certain color. It can be advantageous to use color codes for different bed forms, to refer to different colored structures on photographs of the experiment setup or it might simply be for esthetical reasons.

The reason to color the here described artificial riverbeds was the use of a PIV (Particle Image Velocimetry) system for the further research. This velocity measurement technique involves a flow field illumination using a laser beam, spread into a laser sheet and one or more cameras to record the reflections of the laser light scattered from small artificial tracer particles in the water. To avoid unwanted laser reflections from the streambed surface, it is expedient to color it in a dark tone. In the specific application of using a green laser, like in most PIV systems, it is possible to go even one step further and use Rhodamine B. This dry chemical compound dyes the cast in a fluorescent color that shifts the frequency of the green light into the frequency range of orange light. The unwanted reflected light (orange) can then be separated from the desired tracer particle reflections (green), using a filter in front of the PIV cameras.

The natural color of the polyurethane casting resin is cream white and would therefore cause major reflections using a laser based measurement technique. Thus, besides the natural color of the casting resin, three different techniques to darken the artificial riverbeds were tested:

A) A thin layer of black, water resistant spray paint turned out to be a quick and good solution that can be applied after manufacturing the streambed duplicates. It was not necessary to use a base coat and the spray penetrated only very minor pore structures at the surface. It covered the product surface entirely although it could be scratched off if it comes to contact with a rough object.

B) Liquid black resin dye was used to color the base material, not only the surface. Thus, even if accidentally dragged over a rough surface, the riverbed remains entirely black and no additional cover has to be sprayed on, so that the surface structure remains as close to the original as pos-

sible. 150 g of the dye have been used to color one cast of 10 kg resin.
C) Adding 50 g of Rhodamine B in powder form and 100 g of black resin dying paint to the cast, created a dark purple streambed which was ideal for the further PIV experiments. To avoid powder pockets in the final product, it is recommended to mix the rhodamine properly with the dye before adding it to the resin.

Application

The described artificial riverbed duplicates were used for a series of stereoscopic PIV (Particle Image Velocimetry) experiments in a hydraulic flume at the Department of Marine Technology at NTNU in Trondheim (Norway) which are currently in the post processing state. The aim of this study is to gain a better understanding of the highly unsteady flow over an armored riverbed, due to rapid discharge fluctuations.
This 60 cm wide flume was faced with three equivalent artificial streambed parts of each 160 cm x 20 cm. One Rhodamine B dyed streambed positioned along the central streamline to be illuminated by the laser sheet and two black pieces along the side walls. Black curtains covered the whole flume, to block all external light from the measurement area.
The laser sheet was induced from a window at the downstream end of the flume pointing upstream, expanded to a vertical plane. Two digital cameras, one positioned on each side of the flume, recorded the illuminated flow field of up to 30 cm x 14 cm with 15 double frames per second.
Figure 4 shows a perspective view on the rear part of the experimental setup. The view direction is upstream, from outside the orographic right glass wall. The vertical laser sheet illuminates the flow section along the central streamline. The measurement area, or “field of view”, matches with the laser sheet and is positioned slightly downstream of the riverbed center. Downstream the artificial streambed, the flow passes on to a smooth channel surface until it reaches the outlet weir.

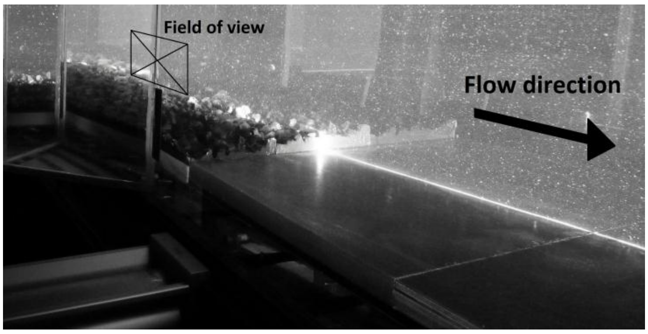

Figure 4: PIV experiment with an artificial streambed

The combination of Rhodamine B in the direct vicinity of the laser sheet and dark surfaces surrounding the field of view minimized unwanted reflections of the green laser light from other objects then the tracer particles. The result was an excellent picture quality with a very good contrast and clearly distinguishable particles.
Figure 5 shows the raw version of a PIV image taken by the camera on the orographic right side of the flume. The flow direction is therefore from left to right. The rough artificial riverbed is slightly recognizable on the lower edge of the picture but shows no reflections. Even though a larger grain in the bottom-left corner of the image is directly exposed to the laser sheet and appears as very light, no blooming effects occur and all particles in the direct vicinity of this grain are clearly recognizable. This indicates a high image quality.

Figure 5: PIV image (raw)

Within the post processing of the recorded images, steady and unsteady flow situations will be compared by performing quadrant analysis to monitor coherent turbulent flow structures.

Discussion

The here described reproduction method for gravel streambeds stands out due to the choice of exceptionally applicable molding and casting material. It enables the production of artificial streambeds, true to the original. The molded silicone form can be used several times and the casting compound is easy to process and very stable at the same time. Furthermore it is possible to be dyed in an arbitrary color. All this gives one the opportunity to send one or more streambed duplicates to project partners, or colleagues in other research institutes with related interests. Thus, several researchers in hydraulic laboratories around the world can perform physical experiments using the exact same surface structure and combine their results to a bigger picture, comparable to a CFD model sent by e-mail.
The artificial streambed can be installed in any desired flume geometry. Several duplicates can be set next to each other to tile a bigger flume base and single pieces can be shaped into smaller, maybe even bent pieces, to fit into a smaller or curved facility. The elimination of the mean bed

slope during the casting procedure appears as an advantage if the streambed copies are used as tiles to cover a flume base. Any desired bed slope can be created with an inclined substructure. To reproduce the original or any other bed slope in the experiment setup, the new bed structure can then be angled with an inclined substructure or by tilting the flume.

The riverbed duplicate is a fixed bed without any movable objects. Hence, it is not practical for actual sediment transport experiments but a combination with single movable particles is imaginable. Anyhow, for many kinds of experiments, regarding for example the flow structures and hydrodynamic forces upon the streambed, the use of a fixed bed is actually an advantage. It is an opportunity to repeat several experiments and exceed the threshold of incipient particle motion without changing the surface structure and therefore the initial experiment conditions. The use of pressure and force measurement techniques alike the ones described in (Detert et al., 2010), (Hofland & Battjes, 2006) and (Dwivedi et al., 2011) is also possible in combination with the cast streambed.

Although the surface structure of the streambed duplicate is virtually not distinguishable from the original and even the pore spaces within the armor layer are as far as possible reproduced, the highest continuous sand layer sets a boundary for the casting form. Therefore, deeper layers and pore structures cannot be captured with this technique which leaves the influence of a permeable riverbed on the surface flow unconsidered for further research.

The main application for this surface reproduction method is the creation of streambed duplicates in a gravel riverbed or laboratory flume. If larger particles appear within a river bed, the described technique might consume a greater amount of silicone which is rather heavy and expensive. It is then imaginable to divide the molding mass in a layer of silicone and a fill of expanding foam with a lower density and price, most similar to the rigid mold described in (Buffin-Bélanger et al., 2003). Further supposable structures of interest for hydraulic engineers are for example tunnel surfaces or failures in hydraulic structures and turbine elements, such as parts affected by cavitation or sand erosion. Those can be reproduced in the same manner.

Conclusion

Artificial streambeds, produced with the described technique, reflect the original surface structure to the greatest possible extent. Several duplicates can be cast using one silicone form, which provides the opportunity to share the same boundary condition for experiments at different institutes and to unite the results for a broader investigation. The possibility to shape and combine single streambed copies makes them applicable for many experimental setups, regardless of the flume geometry or the installed measurement device. Dying the resin cast in a dark color or even adding Rhodamine B reduces unwanted reflections in laser based experiments and improves the image quality in PIV measurements tremendously.

The reproduced surface structure is virtually not distinguishable from the original gravel bed.

Acknowledgements

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