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Substitution of natural river bed material by artificial granulate in physical models for bridge pier scour investigations

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ABSTRACT: The most important parameter for the dimension of bridge pier foundation is the prediction of maximum scour depth. However, the physical processes determining bridge scour are complex and not yet completely understood. This is reflected by the large number of existing approaches which, when being applied to the same boundary conditions, yield significant differences in scour depth estimates. Most of the approaches were developed on the basis of scale model experiments carried out in the laboratory. However, scaling of fine prototype sediment to adequate model sediment is complicated due to associated changes in physical and chemical properties once the scaled sediment reaches the silt and clay range. The objective of this study is the investigation of the rules for substitution of fine sediment by artificial granulates based on the sedimentological diameter D^*, the constant ratio of approach and critical velocity u/u_{crit} and the ratio of pier diameter to water depth D/h. Results of preliminary scour experiments with sand and lightweight granulates are reported. The experiments were carried out in an 8.0 m long, 0.3 m wide and 0.6 m deep horizontal flume. A single cylindrical pier model with diameter D = 0.03 m was embedded vertically in the flume centreline. The experiments outlined in this paper focus on the development of scour depth depending on the model sediment.

Keywords: Lightweight material, Scaling, Bridge piers, Maximum scour depth

1 INTRODUCTION

Bridges spanning watercourses are important civil works, especially with regard to both mobility and economy. From a hydraulic engineering perspective, the main objectives for the design of bridges are related to stability, life expectancy and safety during flood events. During periods of high discharge deep scours can develop at bridge pier foundations threatening the structural integrity of the bridges. In fact, scour processes are responsible for the majority of bridge failures and are associated with high maintenance costs (e.g., Briaud et al. 1999, Melville & Coleman 2000, Kwak 2001, Richardson et al. 2001, Dey & Raikar 2007).

Since the beginning of the last century numerous studies have been carried out to improve the understanding of the relevant processes governing scouring. The large amount of formulae resulting from these studies indicates that there are still many unresolved questions awaiting clarification.

The maximum scour depth d_s depends on bridge pier width D as well as its shape and exposure to the flow, a characteristic grain-size d, the flow depth h and the mean velocity u of the undisturbed approach flow, the fluid and sediment density ρ and ρ_S, respectively, the fluid kinematic viscosity ν, and the acceleration due to gravity g. Performing a dimensional analysis, the following dimensionless relationship can be obtained:

$$\frac{d_s}{D} = f\left(\frac{h}{D}, \frac{d}{D}, \frac{\rho}{(\rho_S - \rho)}, Fr, Re_g, K_s, K_\Theta\right) \quad (1)$$

in which $Fr = u/(gh)^{0.5}$ denotes the hydraulic Froude number of the undisturbed flow, $Re_g = (ud)/\nu$ is the grain related Reynolds number, K_s is the shape factor reflecting the bridge pier geometry, and K_θ is the pier alignment factor describing the exposure of the bridge pier to the flow. For a detailed literature review on this topic see, e.g. Melville & Coleman (2000) and Müller & Wagner (2005).

Particularly the influence of the parameters u, D, K_s, and h on the scour process is rather well known (Lee & Sturm 2009). As a consequence, these parameters are often found in existing scour equations.

As an example for the variety of different scour equations a comparative calculation was carried out with virtual data (bridge pier width D = 0.8 m, water depth h = 1.65 m, flow velocity u = 0.4 m/s, critical flow velocity u_{crit} = 0.4 m/s, clear water condition $u/u_{crit} \leq 1$, uniform sediment $\sigma = (d_{84}/d_{16})^{0.5} < 1.3$, sediment size d = 0.8 mm). The calculated maximum scour depths are illustrated in Figure 1 by using the ratio d_s/D. It is shown that the results differ between d_s/D = 0.6 to 2.6 (or d_s = 0.48 m to 2.08 m). A representative and reliable average value of maximum scour depth cannot be identified.

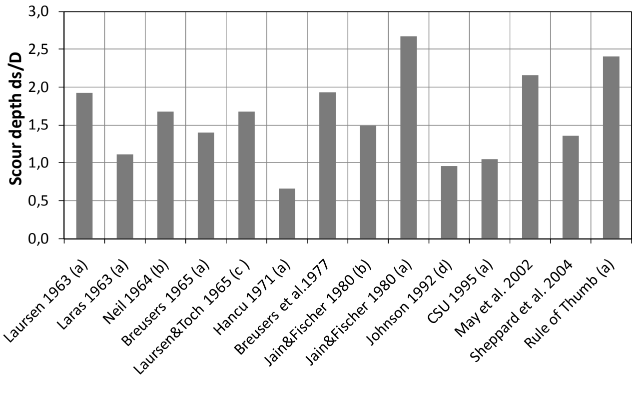

Figure 1. Dimensionless maximum scour depth d_s/D calculated with several approaches for a given hydraulic and geometrical situation (Source: (a) Melville & Coleman 2000; (b) Johnson 1995; (c) Breusers et al. 1977; (d) Hoffmans & Verheij 1997).

Due to the fact that most of the approaches were derived using data from investigations with hydraulic physical models, it is important to consider sediment scaling. Often, fine prototype sediment cannot be scaled geometrically without reaching the silt and clay range. Therefore, natural fine sediment may be scaled using artificial lightweight material. Hughes (1993) provides a detailed overview on how prototype sediment can be scaled using lightweight material. In the so called lightweight models, the geometrical length scale determines the combination of model sediment density and grain size. Substitution of sediment by lightweight material inevitably results in a geometrical distortion of the model (Hughes 1993, Ettema 2000) which further results in distortion of the flow variables. Thus, it is very difficult to quantify morphological features in distorted models.

However, it is not clear in as much such a distortion becomes significant in short sedimentological models. On the other hand, one way to minimize distortion effects in bridge-pier scouring studies could be scaling the sediment with the sedimentological diameter D^* and keeping the ratio of pier width to flow depth D/h as well as the ratio of mean approach velocity to critical velocity u/u_{crit} of the sediment constant. The latter parameter has been identified as a key parameter in many scouring equations while the similarity of the former parameter aims to exclude blockage effects. Although scaling according to this procedure violates Froude-similarity it may still be used to reproduce scour depths. In fact, results reported in Breusers et al. (1977) indicate that for $u/u_{crit} = 1$ similar scour depths should be obtained for the same blockage ratio when different sediments are used.

The sedimentological diameter D^* includes the material properties like sediment density ρ_S and grain-size d, properties of the fluid like water density ρ and kinematic viscosity v as well as gravity g:

$$D^* = \left(\frac{(\rho_S - \rho) g}{\rho v^2} \right)^{\frac{1}{3}} d \tag{2}$$

Therefore D^* can be applied to characterize the specific material parameters (Pernecker & Vollmers 1965, Dietz 1969, van Rijn 1984, Ettmer 2004, Hentschel 2007). Using D^* in combination with the Shields diagram (Figure 2) the initiation of motion can be nearly described for any bed material, even for lightweight granulates.

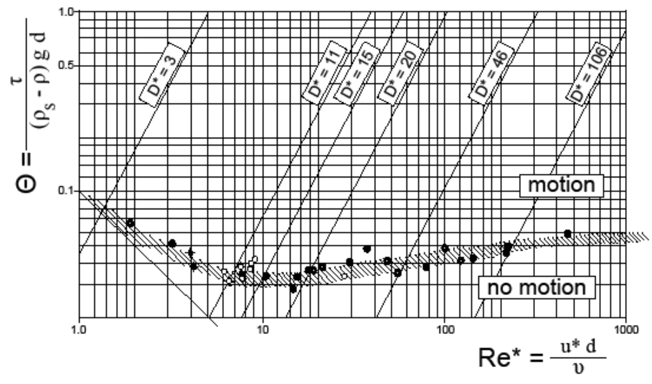

Figure 2. Sedimentological diameter D* in the Shields-Diagram modified according to Dietz (1969) (Θ = Shields parameter, τ = shear stress, Re* = grain Reynolds number, u* = shear velocity).

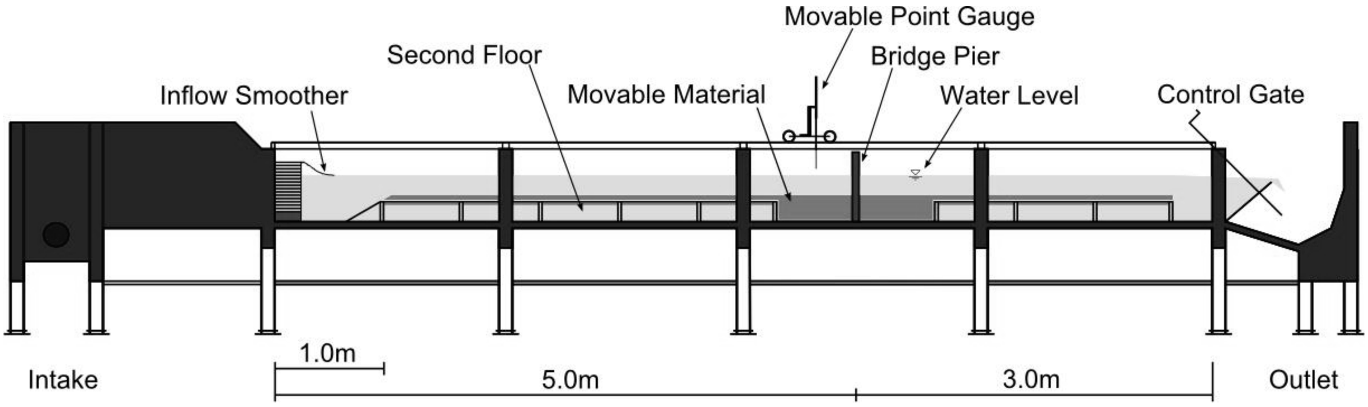

Figure 3. Experimental set up of the flume.

Until today there exist only few publications reporting bridge scour experiments with lightweight material. Yu et al. (2003) tested different formulations with regard to their applicability for lightweight sediment and found a bad agreement between calculated and measured scour depths. This indicates that the density of the sediment is generally not taken into account in the commonly used scour equations. Therefore, the purpose of this study is to explore if natural sediment can be subsitituted with uniform lightweight material in bridge pier scouring studies using the sedimentological diameter D^*, a constant ratio u/u_{crit} and the geometrical ratio D/h as boundary conditions for sediment scaling.

2 EXPERIMENTAL SETUP

2.1 *The flume*

The experiments were carried out in an 8.0 m long, 0.3 m wide and 0.6 m deep horizontal flume with smooth side walls in the laboratory of the Leichtweiß-Institut für Wasserbau at Technische Universität Braunschweig. In order to keep the material effort low, a false floor with a 0.12 m deep and 1.2 m long recess starting 4.5 m downstream of the inlet was created (Figure 3). The recess was filled up and the whole flume was covered with movable bed material resulting in a 3 cm high layer of movable sediment along the total flume length. A single cylindrical pier with a diameter of D = 0.03 m was embedded vertically in the centre of the recess area.

A constant water supply was ensured by a high level tank and the discharge was measured with an inductive flow meter at the intake pipe of the flume. The water level was adjusted by a control gate at the end of the flume.

Scour depths were measured with a point gauge during water flow (accuracy of ±0.1 mm). The point gauge was mounted to a carriage and could be moved along the entire flume length and width so that maximum scour depths could be recorded. Visual observations as well as test experiments without measurements during water flow showed that there was no remarkable influence on the scour process due to the point gauge measurements.

2.2 *Bed material*

The experiments were carried out with four different materials, as presented in Figure 4. The lightweight material consisted of Acetal with ρ_s = 1390 kg/m³ and Polystyrene with ρ_s = 1040 kg/m³. The plastic granulates were characterized by uniform shapes (see Figure 4 and Figure 5) with a grain-size of 2.60 mm and 2.74 mm, respectively. Moreover, two uniform natural sediments (ρ_s = 2650 kg/m³) with different grain-sizes were used. The finer sediment, hereafter referred to as Sand0.8, had a grain-size of d_{50} = 0.82 mm, and the coarser material, referred to as Sand1.6, of d_{50} = 1.6 mm.

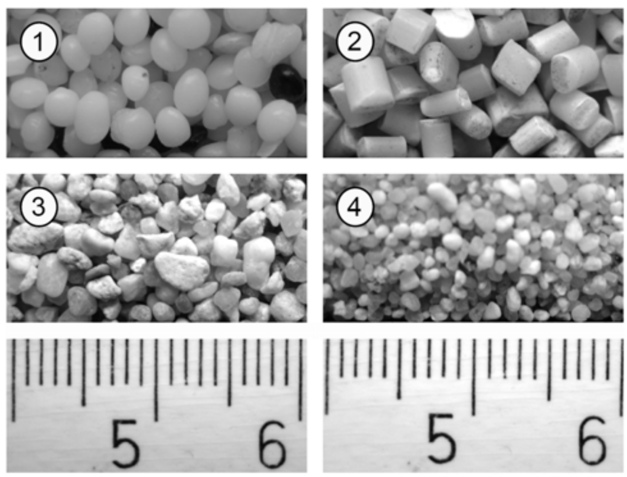

Figure 4. Experimental material; (1) Acetal, (2) Polystyrene, (3) Sand1.6, (4) Sand0.8.

The parameters characterizing the bed materials are summarized in Table 1. Table 1 also includes the shape factor $SF = c/(a\ b)^{0.5}$ (a = longest axis, b = mean axis and c = shortest axis). Although the shapes of the granulate seem to be quite different from natural quartz sand (Figure 4 and Figure 5), the shape factors are close to the natural shape factor of sand, which can be assumed to $SF \approx 0.7$ (ASCE 1962, Garde & Ranga Raju 2000, Zanke 1982).

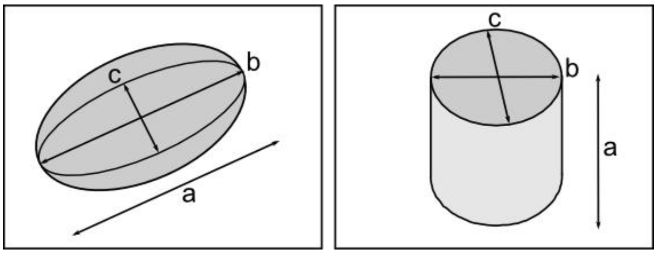

Figure 5. Left hand side Acetal, right hand side Polystyrene.

The tested materials are different with respect to their densities and grain-sizes, but the sedimentological diameter D^* of Sand1.6 and Acetal and of Sand0.8 and Polystyrene, respectively, is fairly similar (Table 1). This is an important aspect to test the assumption that D^* includes all relevant sediment properties and can be used as scaling parameter. The critical velocity u_{crit}, defining the flow velocity for which single grains sporadically start moving was determined in previous experiments carried out in the same flume by Ettmer (2004).

Table 1. Material properties.

		Sand1.6	Acetal	Sand0.8	Polystyrene
ρ_S	[kg/m³]	2650	1390	2650	1040
d	[mm]	1.60	2.60	0.82	2.74
D^*	[1]	40	41	21	20
SF	[1]	0.70	0.71	0.70	0.75
σ	[1]	1.29	1.00	1.30	1.00
u_{crit}	[m/s]	0.323	0.194	0.288	0.078

2.3 *Experimental procedure*

The material was filled into the flume without additional compaction or consolidation. After the pier was adjusted, water was filled very slowly into the flume up to a water level of 0.1 m so that any movement of the loose bed material was avoided. Following the filling process, the discharge was increased to the desired value while the water depth was kept constant by adjusting the control gate at the end of the flume. The experimental time started when the grains at the pier started to move.

Both a longitudinal and transverse bed and water level profile, respectively, was measured with the point gauge after 15 min, 30 min, 60 min, 120 min, 240 min, 480 min and after 1440 min (see Figure 6). In the longitudinal direction, the bed levels were recorded with intervals of Δx = 2 cm starting 14 cm upstream of the pier and ending 90 cm downstream of it. The transverse profile was recorded over the entire flume width with Δy = 2 cm at the pier location. Each experiment was repeated several times to ensure the reproducibility (see Section 3, Figure 7).

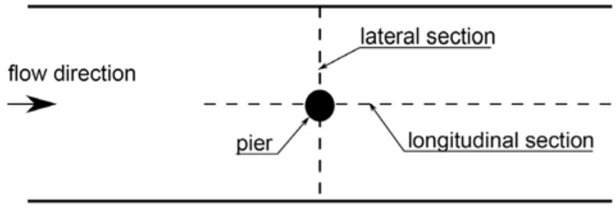

Figure 6. Top view of measurement section.

2.4 *Hydraulic conditions*

In order to keep D/h = const. the water depth was held constant with h = 0.1 m in all experiments. Thus, the mean flow velocity u had to be adjusted so that $u/u_{crit} \approx 1$ for each material (Table 2). The flow was subcritical and turbulent throughout the experiments.

Table 2. Hydraulic conditions.

		Sand1.6	Acetal	Sand0.8	Polystyrene
D^*	[1]	40	41	21	20
discharge	[l/s]	9.7	6.2	8.6	2.3
u	[m/s]	0.323	0.202	0.288	0.078
u/u_{crit}	[m/s]	1.0	1.04	1.0	1.0
$Fr = u/(gh)^{0.5}$	[1]	0.33	0.20	0.29	0.08

3 RESULTS AND DISCUSSION

Figure 7 shows exemplarily the development of the maximum scour depth for the repeated Sand0.8 experiments for each single run (symbols) as well as the development of the averaged maximum scour depth (dashed line). The depth of the bridge pier scour scatters slightly with a maximum deviation of 0.7 cm after a run time of 120 min. However, the scour depth is fairly similar after 1440 min (maximum deviation 0.4 cm). This shows that the results are reproducible.

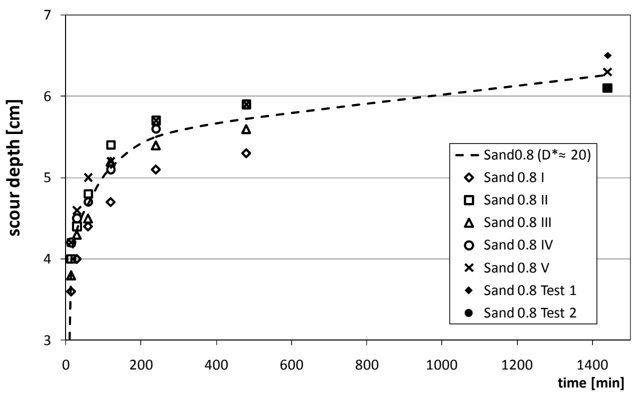

Figure 7. Reproducibility of scour depth for Sand0.8.

Similar results regarding the reproducibility were obtained for the experiments with Sand1.6, Acetal and Polystyrene. The scour depth measured in the experiments with lightweight materials scattered more during the scour development than for the sand experiments but the scour depths at the end of a run the scour depths were similar again. The observed scatter may partly be caused by some characteristics of lightweight material which have to be considered when performing experiments. For example plastic particles with a cylindrical shape (here polystyrene) tend to interlock with each other forming clusters (Figure 8). The particle interlock can have a significant influence on the scour development if a cluster is blocking or accelerating the erosive process around the pier.

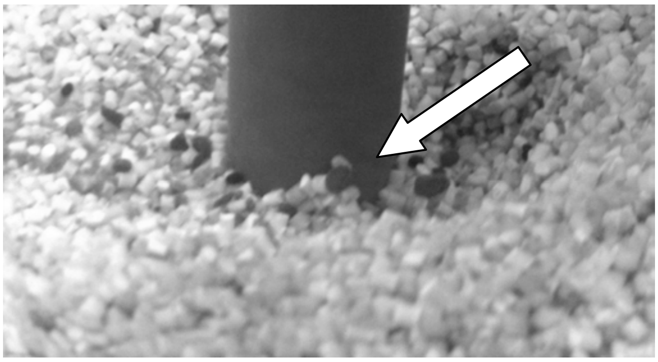

Figure 8. Cluster (Polystyrene) due to particle interlock (flow from right to left).

In the following the averaged maximum scour depths are used to analyze the scour evolution dependent on the different bed materials and hence with respect to the influence of sediment density and grain-size, respectively. In a second step the time series of the maximum scour depth are used to evaluate the applicability of the parameter D^*, combining sediment density and grain-size, as a sediment scaling parameter.

Figure 9 shows the scour depth development for the natural bed material with identical density (Table 1). The figure shows that both curves are approximately parallel. However, the development of the maximum scour depth within the first 15 min is faster for the finer sediment Sand0.8 than for the coarser material Sand1.6 (see also Figure 12). As a consequence the scour of Sand0.8 is deeper than for Sand1.6 at comparable time steps. The main difference between both experiments is the ratio of pier width D and grain-size d. In case of Sand0.8 the ratio is D/d = 37.5 and for Sand1.6 D/d = 19. According to many researchers the scour depth is significantly influenced by this parameter, e.g., Melville & Chiew (1999), Sheppard et al. (2004) and Lee & Sturm (2009). Furthermore, Melville & Chiew (1999) reported that the scour depth decreases with decreasing D/d if the ratio D/d is smaller than 50. Similarly, Lee & Sturm (2009) found that the scour depth increases with increasing D/d if $D/d \leq$ 25 while it decreases for $D/d \geq 25$. For $D/d > 400$ the scour depth is independent of D/d. In this study, D/d = 11 - 19 indicating that further experiments are needed to investigate if the observed differences can be attributed to the differences in D/d.

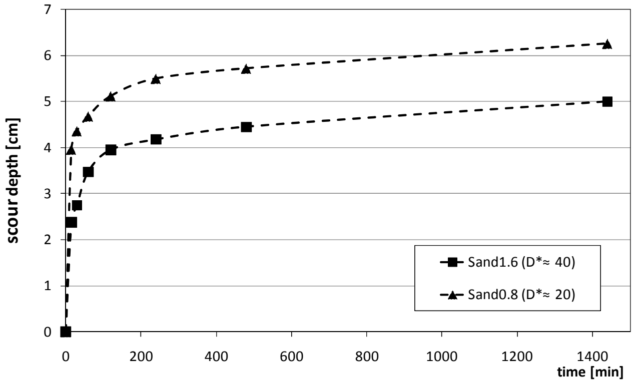

Figure 9. Development of the maximum scour depth in front of the pier for materials with ρ_S = constant, d = variable, $u/u_{crit} \approx 1$.

Figure 10 shows the scour development for the experiments with lightweight material which have similar grain-sizes but different sediment densities (see Table 1). The scour was slightly deeper in the experiments with Polystyrene which is 9.75 times lighter under buoyancy than Acetal. This result implies that the scour depth depends on the sediment density although its influence is much less than the influence of the grain-size.

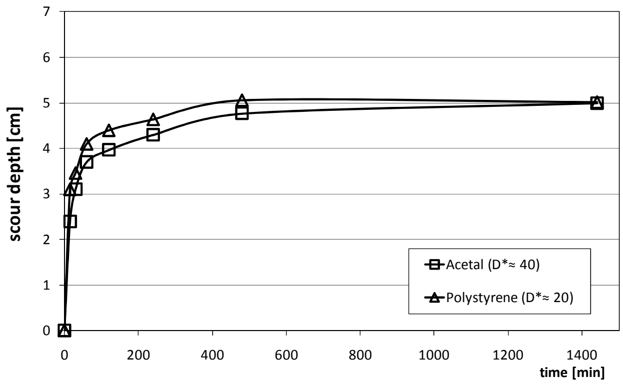

Figure 10. Development of the maximum scour depth in front of the pier for materials with ρ_S = variable, $d \approx$ constant, $u/u_{crit} \approx 1$.

The different materials were chosen so that a natural and an artificial material are comparable regarding the sedimentological diameter D^* combining the aforementioned parameters d and ρ_S (Table 2). The maximum scour depths of the four bed materials are plotted as a function of time in Figure 11. For the material with larger D^* (Acetal and Sand1.6, $D^* \approx 40$) scouring of the natural sediment is well reproduced by the artificial sediment. On the other hand the scour depths for Polystyrene and Sand0.8 ($D^* \approx 20$) differ remarkably from each other. As aforementioned, the experiments were repeated several times and the averaged scour depths are plotted in Figure 11. Hence, the observed differences cannot be attributed to scatter due to an individual time series. Besides the different values of D^*, the experiments differ with regard to D/d. For the experiments with artificial materials $D/d \approx 11$. Thus, the ratio of bridge pier width to grain-size is in the same order of magnitude for the three materials Polystyrene, Acetal, and Sand1.6 whereas D/d is at least twice as high in the experiments with Sand0.8. The results show that the ratio D/d cannot be neglected when scaling the sediment for scour experiments. However, further experiments are required to investigate the influence of D/d in combination with D^* in more detail.

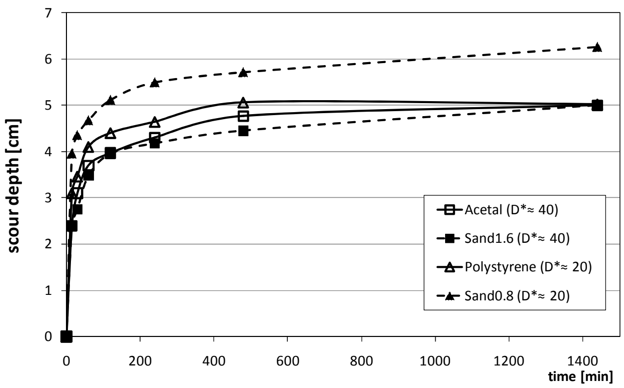

Figure 11. Development of the maximum scour depth in front of the pier for natural and artificial materials.

The development of the maximum scour depth is plotted again with a semi-logarithmic scale in Figure 12. The figure shows that the curves are more or less parallel, i.e. the time evolution of the scour depth is approximately proportional to ln(t) in both experiments with natural and artificial sediment. According to Ettmer (2004) and Hentschel (2007) sediment processes with lightweight material proceed faster than those with natural sediment. This effect cannot be observed in these experiments. It is worth mentioning that the experiments of Ettmer (2004) and Hentschel (2007) were carried out with live bed conditions whereas the experiments reported herein were clear water experiments. Thus, further experiments are required to investigate the influence of the flow intensity u/u_{crit} on time scale effects when using artificial sediment.

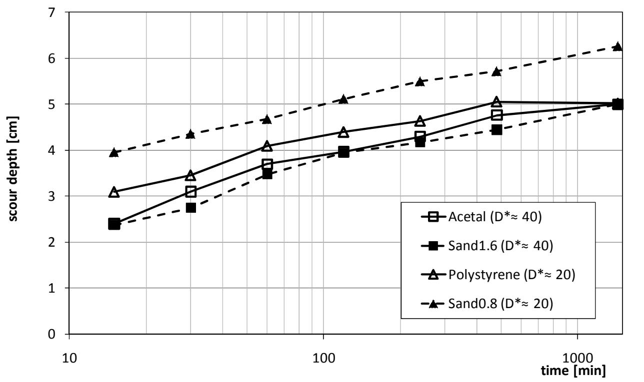

Figure 12. Development of the maximum scour depth in front of the pier for natural and artificial materials in semi-logarithmic scale.

4 SUMMARY

Laboratory experiments were carried out to investigate the applicability of the sedimentological diameter D^* as scaling parameter for fine sediment. In order to avoid cohesive characteristics of scaled sediment it is necessary to substitute natural sediment (sand) by lightweight materials. The applicability was tested by means of the development of the maximum scour depth in front of a single bridge pier. Four different bed materials were used; two kinds of sand with different grain-sizes and Acetal and Polystyrene, which had the same diameter but different sediment densities. The sediment densities and grain-sizes were chosen so that Sand0.8 and Polystyrene as well as Sand1.6 and Acetal had the same sedimentological diameter D^*, respectively.

The results of the preliminary experiments show that similar scour depth can not be achieved by using only D^* as scaling parameter. The ratio of the bridge pier width and the grain-size D/d has a strong impact on the maximum scour depth and thus cannot be neglected when scaling the sediment. Moreover the flow intensity u/u_{crit} has an influence on the temporal evolution of the scour depth. Under clear water conditions the processes showed no time dependency whereas in life bed experiments the processes develop faster with artificial bed material than with natural sediment. Further experiments are planned to quantify the effect of sediment density and of the ratio D/d in order to develop a sedimentological scaling parameter for scouring processes the constant ratio u/u_{crit} and the geometric ratio D/h.

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