EXPERIMENTAL INVESTIGATIONS ON THE STABILITY OF RIPRAP SLOPE PROTECTION LAYERS ON OVERTOPPABLE EARTH DAMS

Rüdiger Siebel

Institute of Hydraulic Engineering, Universität Stuttgart, Germany,

ruediger.siebel@iws.uni-stuttgart.de

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Abstract : In Germany small dams (< 10 m) on flood retention reservoirs are often provided with an overtoppable dam section for flood relief. In case of overtopping a protection of the dam body is absolutely mandatory as the mainly cohesive dam material is not capable to withstand the affecting erosive forces of the flow. There is a big number of possibilities how to protect the dam whilst overtopping. Some of the most common construction types of slope protection layers for a sufficient dam protection such as riprap and placed stones, have been tested in large scale physical models at the Hydraulic Laboratory at the University of Stuttgart. Thereby different experiments for the failure scenarios "erosion of single stones", "sliding of the protection layer" as well as "disruption of the protection layer" have been conducted and analysed aiming to find some design criteria for the construction of such dams.

INTRODUCTION

In Germany a big number of new flood retention reservoirs are mapped for the following decade to obtain a sufficient protection against an increasing number of flood events with an increasing intensity. Due to environmental and landscape architectural reasons state authorities commit themselves more and more to decentralised flood protection schemes, so that several small reservoirs with small dams (< 10 m) will be performed, which can easier be integrated in the environment. Most of the dams of those reservoirs are not provided with conventional concrete spillways anymore, as viewable concrete structures are not considered to be "nature-orientated". Instead of that, earth dams can be designed as partly or completely overtoppable for flood relief.

Without a slope protection on the downstream face of the overtopped zone, the dam would get eroded immediately, starting at the toe of the dam. Thus, it is absolutely necessary to protect the soil, e.g. by a protection layer. As the safety of the complete dam structure mainly depends on the safety of that protection layer, the conditions under which the protection layer will fail, must be known. Amongst a big number of possible construction types for slope protection layers the nature-orientated single-layer placing of regular (cuboidal) or irregular shaped stones as well as the multi-layer rockfill (riprap) were the construction types which have been investigated in large scale model tests in the Hydraulic Laboratory of the University of Stuttgart.

Fig. 1 - Possible failure scenarios of protection layers on overtoppable earth dams
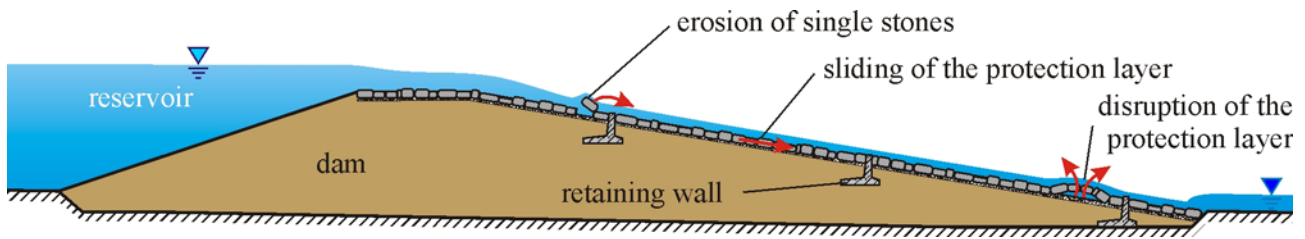
The hydraulic loads that occur during overtopping induce some reactions of the slope protection layer and accordingly of their single elements. In the worst case those reactions lead to a failure of the protection layer. The possible failure scenarios for the above mentioned construction types are the erosion of single stones, sliding of the protection layer and disruption of the protection layer (mainly due to lifting forces) are shown in Fig. 1. Another failure scenario due to washing out of the fine material underneath the protection layer can be avoided by using filter laws for the recommended filter underneath the protection layer. Thus, this failure scenario is not subject of this paper. For each of the other failure scenarios model tests with different configurations and instrumentation have been conducted, aiming to lead to a comprehensive design criterion for all possible failure scenarios.

EXPERIMENTS ON EROSION OF SINGLE STONES

Erosion of the single stones of protection layers on overtoppable earth dams can not be directly compared to erosion processes in river beds as the form of the stones are more sharp-edged and with that the retaining grouting forces are much higher than on round shaped stones. Moreover, due to the steep slopes, the supercritical flow over the protection layer with a high air entrainment and low flow depths is different than typical subcritical river flows. The own experiments as well as comparisons of the work of other authors have shown that calculation of the bed-load transport according to Meyer-Peter and Müller (1940) as well as according to Einstein (1950) overestimate the erosion rates by a factor of 10 to 100. Calculations of the beginning of transportation according to Shields (1936) result in much lower flow velocities than the own experiments have shown.

The single stones of riprap or of placed stones on protection layers are exposed to highly fluctuating positive and negative hydrodynamic pressures, which increase with an increasing flow velocity. If the resulting lifting forces F_l of a single stone exceeds the gravitation force G_s and other retaining forces together, the stone gets unhinged from the protection layer and then transported to the toe of the dam.

In case of a single-layer placing of stones such an erosion should absolutely be avoided as thereby the texture of the protection layer will be destroyed and with that most probably the whole protection layer itself. Indeed, in some experiments it could be observed, that if one stone gets eroded neighbouring stones take the affecting forces parallel to the slope (Rathgeb 2001) but that can not be ensured in any case. In fact, it must be assumed that the hole in the protection layer leads

to a zone of high turbulence and with that to an increasing hydraulic load on the neighbouring stones.

Erosion on multi-layer rockfills can be tolerated until a certain degree, as due to the multitude of possible stone sizes, forms and positions there are always some stones on the top layer which can easily be eroded even with relatively small specific discharges $q < q_E$. Those stones, which are normally unfavourable located in the flow, get transferred into a stable state of equilibrium and stay in that position if the discharge does not increase. This so-called "initial erosion" does not impact the safety of the protection layer and thus, the safety of the dam structure. From a certain specific discharge $q > q_E$ on, real erosion occurs, that results in the failure of the slope protection layer. In this case the forces affecting on a big number of stones are too high to keep the stones in a stable position. They will be eroded to the toe of the dam. Moreover, the first eroded stones can cause a chain reaction in which other stones get displaced from their positions. It could be watched that such an erosion process results in erosion channels in which the discharge concentrates, what even increases erosion.

Several investigations on the stability of riprap protection layers have been accomplished during the last decades. However, most of them had different backgrounds than overtoppable dams, such as e.g. rough ramps (Whittaker and Jäggi 1986, Hassinger 1991). Other authors made theoretical approaches for the erosion stability of the single stones (Hartung and Scheuerlein 1970, Olivier 1973, Knauss 1979, Dornack 1999). Only a few investigations are based on model tests (Linford and Saunders 1967, Abt and Johnson 1991, Robinson et al. 1997). The results of those investigations are limited to the specific boundary conditions of the tests and validity is only given within a certain range.

The experiments concerning the erosion of single elements of the protection layer were performed in a flume with a length of 7.2 m and a width of 1.5 m, whose slope could be adjusted from 1:26 to nearly 1:3. A thin layer of concrete has been placed on the bottom of the flume in which some single stones have been pressed as long as that was not hardened yet. Therewith, it could be guaranteed that no sliding of the subsequently installed 16 cm thick protection layer can occur.

Due to just a very low erosion rate, first tests with stones of a medium size $d_{50} \approx 18$ cm on a slope of 1:6 did not lead to satisfactory results, so that some more tests with smaller stones of a medium size $d_{50} \approx 8$ cm and slopes from 1:3 to 1:15 have been performed. The experiments were carried out three times for different specific discharges q and different slope angles α. In addition, time was one of the input parameters, as the mass of the eroded stones has been determined within the corresponding time windows after 5, 15, 30 and 50 minutes duration of the experiments.

For the practical reference of the experiments to the reality, it needs to be resolved what the maximum permissible erosion rate is and how it is defined. Therefore, carrying out the experiments, a value $m_{E,max}$ was defined, for which the above mentioned clearly visible development of erosion channels after 50 minutes could be watched. For the performed experiments with $d_{50} \approx 8$ cm a value of $m_{E,max} = 6$ kg/m² was chosen (Kleiner 2005). In Fig. 2, this value is shown as a dotted line.

Fig. 2 - Eroded masses m_E in 50 minutes tests for different specific discharges q_o and slopes
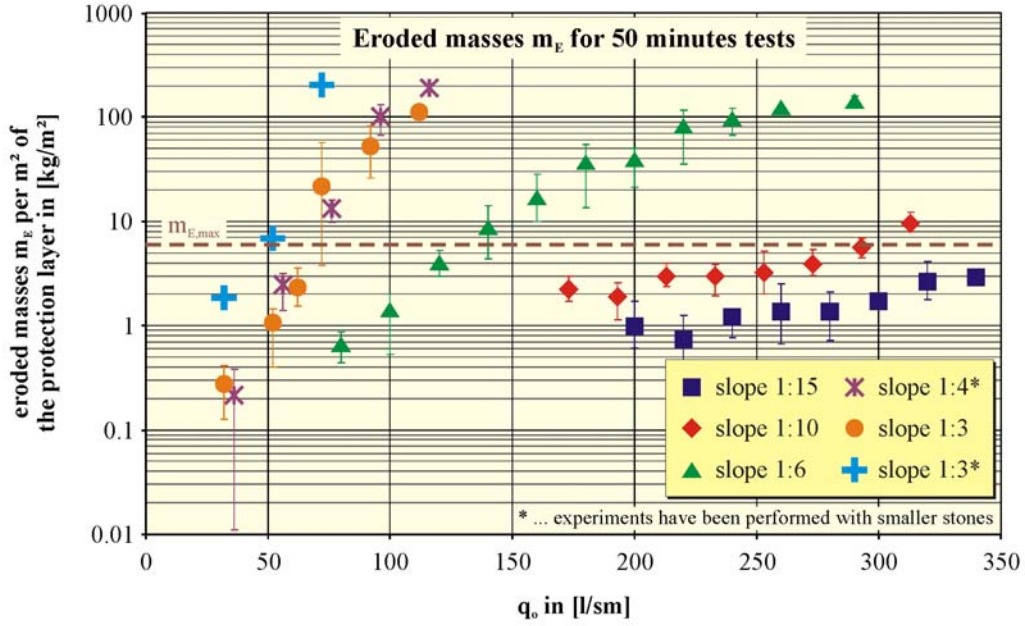

Table 1 - Maximum permissible specific discharges $q_{o,max}$ and stone diameters $d_{s,er}$

slope in [-]	$S_0 = \tan\alpha$ in [-]	$q_{o,max}$ in [l/sm]	$d_{s,er}$ in [cm]	$Fr_{s,er}$ in [-]
1:15	0.067	$q_{o,max}$ could not be reached		
1:10	0.100	282	7.3	3.29
1:6	0.167	122	7.0	1.50
1:4*	0.250	65	5.4	1.19
1:3	0.333	65	6.7	0.86
1:3*	0.333	50	5.2	0.97

* ... experiments have been performed with smaller stones

According to Fig. 2 the maximum permissible discharges $q_{o,max}$ were determined. Moreover, by weighing the eroded stones, the average stone diameter $d_{s,er}$ of the eroded stones could be identified as the density of the stones was known. Table 1 shows the most important values obtained from the experiments.

By implementing the erosion-critical stone-referred Froude number $Fr_{s,er}$, the results of the measurements can be presented in a dimensionless way and moreover, independent of the density of the stones, as shown in Fig. 3.

$$Fr_{s,er} = \frac{q_{o,max}}{\sqrt{g \, \frac{\rho_s - \rho_w}{\rho_w} \, d_{s,er}^3}} \tag{1}$$

By the help of in such a way determined values for the erosion-critical stone-referred Froude numbers $Fr_{s,er}$, an adapted smoothing function could be identified, which is shown in Fig. 3 together with the results of other authors, who dealt with this or a similar topic.

The adapted smoothing function reads as follows:

$$Fr_{s,er} = \frac{q_{o,max}}{\sqrt{g\,\dfrac{\rho_s - \rho_w}{\rho_w}\,d_{s,er}^3}} = 0.258\,S_0^{-1.08} \tag{2}$$

After solving equation (2) for $d_{s,er}$ and after implementation of a safety factor $\eta = 1.6$ to cover the wide range of stone forms (this safety factor was chosen in accordance with other authors dealing with that topic, e.g. Rathgeb 2001), the design formula for multi-layer riprap protection layers can be indicated as follows (according to Kleiner 2005):

$$d_{50,req} = 1.85\,S_0^{0.72}\,q_o^{2/3}\left(\frac{\rho_w}{\rho_s - \rho_w}\right)^{1/3} \tag{3}$$

Thereby, $d_{s,er}$ was equated with the average stone diameter d_{50} and $q_{o,max}$ was equated with the specific overflowing discharge q_o. The discharge $q_o = q - q_{pl}$ instead of q may only be inserted, if a blockage of the voids (e. g. by leaves or soil material) of the protection layer can be avoided permanently, otherwise the complete specific discharge q has to be used.

Fig. 3 - Erosion-critical stone-referred Froude numbers $Fr_{s,er}$ plotted versus the slope
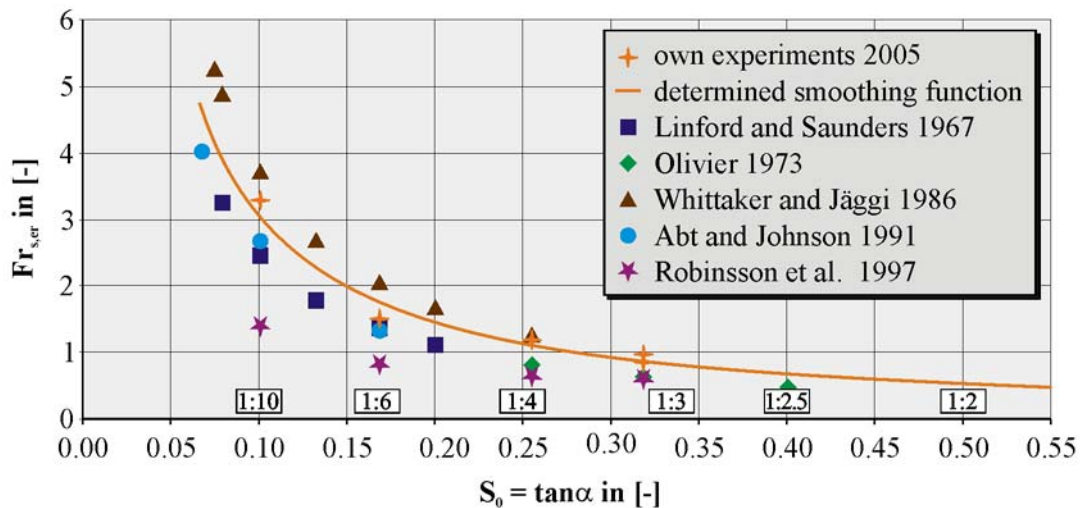
EXPERIMENTS ON SLIDING OF THE PROTECTION LAYER

The overtopping water exerts shear forces F_s parallel to the slope as well as lifting forces F_l rectangular to the slope of the protection layer. With an increasing discharge and flow velocity, the shear forces F_s increase as well as the lifting forces F_l. By increasing the lifting forces F_l, the friction force F_f of the protection layer on the filter layer decreases. When that friction force F_f is smaller than the shear force F_s the whole slope protection layer begins to slide. Sliding can be avoided by retaining structures such as sheet pile walls, retaining walls and others. So-called self-supporting protection layers do not need any retaining structure, as even for the highest possible discharge q_{max} the friction force F_f is higher than the shear force F_s and the gravity force G_{sx}.

The forces affecting the protection layer during overtopping are shown in Fig. 4. They can be listed as follows:

In x-direction (unit: N/m²):

Gravity force of the stones:

$$G_{sx} = \gamma_s \, d_{pl} \, (1 - n) \sin\alpha \tag{4}$$

Friction force:

$$F_f = \underbrace{(G_{sy} - F_b - F_{dyn,y})}_{N_{res}} \tan\varphi' \tag{5}$$

Shear force F_s consisting of:

Weight of overtopping water:

$$G_{wox} = \sigma \, \gamma_w \, y \sin\alpha \tag{6}$$

Weight of water flowing through protection layer:

$$G_{wplx} = \sigma \, \gamma_w \, d_{pl} \, n \sin\alpha \tag{7}$$

Hydrodynamic force:

$$F_{dyn,x} \sim v^2$$

In y-direction (unit: N/m²):

Gravity force of stones:

$$G_{sy} = \gamma_s \, d_{pl} \, (1 - n) \cos\alpha \tag{8}$$
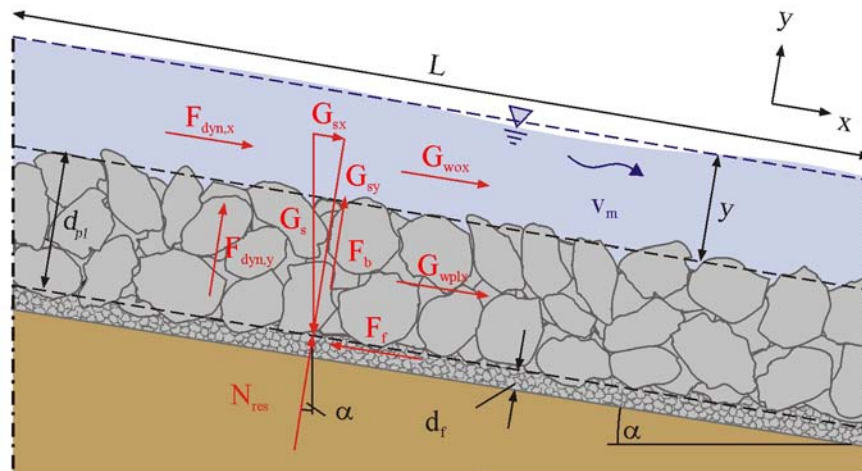
Lifing force F_l consisting of:

Buoyancy force:

$$F_b = \sigma \, \gamma_w \, d_{pl} \, (1 - n) \cos\alpha \tag{9}$$

Hydrodynamic force:

$$F_{dyn,y} \sim v^2$$

Fig. 4 - Forces affecting the protection layer during overtopping

One of the main targets of performing the experiments, was to detect the hydrodynamic forces $F_{dyn,x}$ and $F_{dyn,y}$ which could be verified on protection layers made of placed stones (Rathgeb 2001). Those hydrodynamic forces occur on highly turbulent flows due to extremely high positive and negative pressure peaks (Westrich and Rathgeb 1998).

For the experiments the above mentioned flume was equipped with a multitude of rollers in the bottom of the flume. A riprap layer, enclosed in a geogrid and placed on top of a thin metal sheet, could be applied on those rollers almost without any friction. Two load cells which have been installed in the bottom end of the flume prevented the protection layer rolling downwards. By the help of those load cells also the forces parallel to the slope were measured. Moreover the flow depth

was measured. Therefore, pressure gauges have been installed in the sidewall of the flume.

For the experiments both, the thickness d_{pl} (25 cm and 40 cm) as well as the length L (2 m and 4 m) of the protection layer, was varied. Class II stones have been used, according to the German standard TLW 2003 (diameter of the stones from $d_s = 10$ cm to $d_s = 25$ cm, respectively weights between $m_s = 2,5$ kg and $m_s = 16,0$ kg). The specific discharges overtopping the protection layer were ranging up to $q = 0.350$ m²/s.

Fig. 5 - Ratio F_{calc}/F_{meas} of the forces parallel to the slope plotted versus specific discharges q for different slope angles α (thickness $d_{pl} = 40$ cm and length L = 4 m)
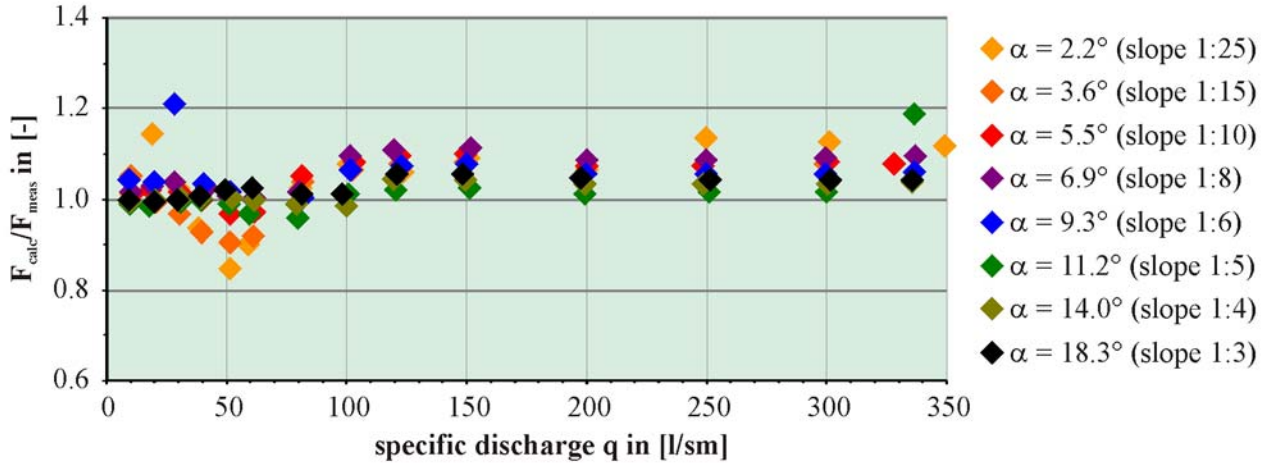
The experiments have shown that the hydrodynamic forces F_{dyn} basing on high fluctuating hydrodynamic pressures can be neglected on riprap protection layers. The reason for that is on the one hand, the lower flow velocity due to the higher roughness compared to the placed stones and on the other hand, the fact that negative and positive hydrodynamic pressures compensate as a sum of all the stones of the protection layer. Fig. 5 shows a comparison of the calculated and the measured values of the forces parallel to the slope, whereas for the calculation of F_{calc}, the forces G_{sx}, G_{wox} and G_{wplx} have been considered. For the discharge through the protection layer q_{pl} the measured data was used as calculative approaches (Martins 1990, Abt et al. 1991) generated values which strongly differed from the measured values. For the calculation of the flow depth y and the air content parameter σ, approaches from Scheuerlein (1968) were used, which showed a good agreement to the measurement. The values of F_{calc} for discharges $q > 0.1$ m²/s are mostly slightly higher than those of F_{meas}. For the dimensioning this means an extra safety. Depending on the slope, the range up to 0.12 m²/s is the one where only a flow through the protection layer occurs ($q_o = 0$). For the practical use, where the protection layers are designed for the maximum possible specific discharge q, usually this range is not interesting.

Thus, the safety against sliding can finally be calculated as follows:

$$\eta_{slide} = \frac{F_f}{G_{sx} + G_{wx} + G_{wplx}} = \frac{\dfrac{\tan\varphi'}{\tan\alpha}}{1 + \dfrac{\gamma_w}{\gamma_s - \gamma_w}\left(1 + \dfrac{y}{d_{pl}}\right)} \geq 1,3 \qquad (10)$$

For an arrangement of the protection layer on a filter layer the friction angle φ' can be estimated between $\varphi' = 30°-35°$. However, this should be verified in every single case.

INVESTIGATIONS ON DISRUPTION OF THE PROTECTION LAYER

Disruption of the protection layer made of placed stones (not possible on riprap protection layers) is caused by high shear forces F_s combined with high lifting forces F_l directly upstream of a retaining structure. This process can occur with two or more stones depending on a large variety of geometric values (e.g. ratio of the length of the stone to the thickness of the stone).

The investigations on that failure scenario are in a very early stage. They base on a stability analysis on strongly idealised stones for different possible rotation angles, using forces which were calculated according to Rathgeb (2001). Those rotation angles depend on the dimensions of the stones and some average geometric discontinuities which is defined as degree of a deviation of a rectangular stone form. The calculation leads to a length of the protection layer on which the retaining gravity forces and the forces which cause the disruption result in an equilibrium. The first calculations on an disruption process of two stones showed realistic results. More investigations on disruption of more than two stones will be performed soon.

CONCLUSION

For protection layers on overtoppable earth dams with slopes between 1:3 and 1:25, comprehensive approaches for the practical design have been generated for the failure scenarios erosion of single stones and sliding of the protection layer up to $q < 0.35$ m³/s.m. Considering that the present investigations corresponded to model tests with a geometric scale of 1:2, the design approach should be valid for prototype specific discharges up to about $q = 1.0$ m³/s.m. This is roughly the highest specific discharge which occurs in reality on the small dams for flood protection purposes described in the introduction.

For the failure scenario "erosion of single stones" a dimensioning equation to determine the required minimum diameter of stones $d_{50,req}$ was developed covering a wide spread of slopes. Experiments on "sliding of the protection layer" have shown that hydrodynamic forces F_{dyn} are negligible on riprap protection layers. However some more experiments with an elaborated measuring programme will be performed to determine the hydraulic parameters in highly turbulent flows, such as flow depth y, flow velocity v and the air content parameter σ. The more theoretical investigations on the failure scenario "disruption of the protection layer" are at a very early stage and could only be roughly described.

LIST OF SYMBOLS

d_{50} Diameter of stones at 50% in stone size distribution curve in [m]

d_{pl} Thickness of the protection layer in [m]

d_s Diameter of stones in [m]

$d_{s,er}$	Averaged diameter of eroded stones in [m]
F_b	Buoyancy force in [N/m²]
F_{calc}	Calculated force in [N/m²]
F_{dyn}	Hydrodynamic force due to turbulent flow in [N/m²]
F_f	Friction force between protection layer and filter layer in [N/m²]
F_l	Lifting forces on the protection layer in [N/m²]
F_s	Shear force parallel to the slope in [N/m²]
F_{meas}	Measured force in [N/m²]
$Fr_{s,er}$	Erosion-critical stone-referred Froude number in [-]
g	Gravitational constant in [m/s²]
G_s	Gravity force of the protection layer in [N/m²]
G_{wo}	Weight of the water – overtopping portion in [N/m²]
G_{wpl}	Weight of the water – portion flowing through protection layer in [N/m²]
S_0	Slope on uniform flow conditions in [-]
L	Length of the protection layer in [m]
m_E	Specific eroded masses in [kg/m²]
m_s	Mass of the stones in [kg]
n	Void ratio in [-]
N_{res}	Resulting normal force rectangular to the slope in [N/m²]
q	Specific discharge in [m³/sm]
q_E	Specific discharge at the beginning of the erosion process in [m³/sm]
q_o	Specific discharge – overtopping portion in [m³/sm]
q_{pl}	Specific discharge – portion flowing through protection layer in [m³/sm]
v	Flow velocity in [m/s]
y	Flow depth in [m]
α	Angle of the slope of the protection layer in [°]
γ_s, γ_w	Bulk density of stones in [N/m³]
η	Safety factor in [-]
φ'	Friction angle in [°]
ρ_s, ρ_w	Density of stones/water in [kg/m³]
σ	air content parameter in [-]

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