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LOADS ON ROPE NET CONSTRUCTIONS FOR WOODY DEBRIS ENTRAPMENT IN TORRENTS

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ABSTRACT

Further results of a large research project with regard to rope net barriers for woody debris entrapment in torrents are introduced. A model test using different steepness and roughness of banks and sites in straight and curved sections of torrents was carried out. Low inclined banks and rough surface significantly reduce loads on the net. One-sided loads on the net and one- sided accumulation of wood coming along with high current-loads on the banks are the consequence of nets in curves. Furthermore a full-scale nature test on rope net barriers was realized. Dynamic loads in the beginning of the woody debris entrapment process were determined. They are not significant if no debris flows occur. The static loads on the rope net were compared between nature and model. Loads and backwater in nature are about 20 to 30 % higher due to a greater volume of fine material with less dimension and sagging ropes respectively nets. The function of the net barriers was proved.

KEYWORDS: rope net, woody debris, entrapment, loads

INTRODUCTION

For the last few years more and more rope nets are used to entrap woody debris in torrents. The main advantage is that simple building equipment can be used; only a few lightweight materials have to be transported. It is possible to use commercial components and techniques which have been proven in avalanche control for years. Moreover, rope nets are inconspicuous and almost do not impair the landscape.

The main structure to bear the forces consists of ropes which are spanned over the torrent at right angles with flow direction. The ropes usually have a diameter between 18 and 28 mm. The nets have a distance of about 0,50 to 1,0 m to the torrent bed, so bedload and smaller floods without woody debris can pass unhindered.

Until now there was little practical experience available regarding this kind of construction. Therefore a research project (see Fig. 1) is carried out at the Institute for Hydraulic and Water Resources Engineering at Technische Universität München, to study how rope nets for woody debris entrapment work and how to dimension them. It is sponsored by Bayerisches Landesamt für

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Wasserwirtschaft, Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen and Deutsche Bundesstiftung Umwelt. The main topics are the following questions:

- How is the process of the entrapment in rope dams proceeding?
- Which forces occur and what are the main parameters of influence?
- Which recommendations for the construction of net-dams can be given?

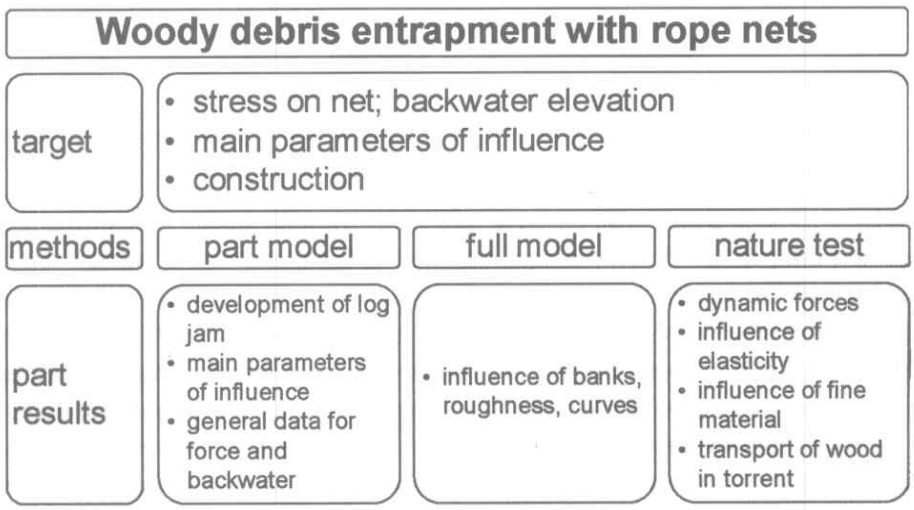

Fig. 1 programme of the research project

MODEL TESTS

Many different parameters of influence were investigated in the model tests (comp. Fig. 2). The main results of the first stage of the research project are (comp. also Loipersberger et al. (2000)):

Before the entrapment process starts, single wood parts can pass the net. A single ramified wood piece can trigger the development of a log jam. Substantial for how dense respectively compact the log jam shapes up is the composition of wood entrapped: the larger the rate of small and fine particles, the more dense is the log jam and the higher is the backwater and the force on the net. The second important aspect therefore is the discharge, since the force on the net rises nearly linearly with discharge. Also very significant is the gradient and the quantity of wood.

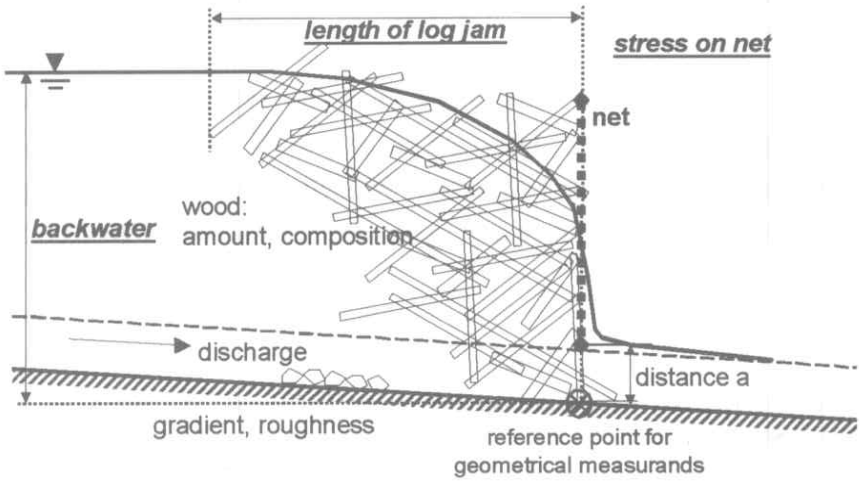

Fig. 2 parameters of influence and *measurands* in model tests

In the second stage of the research project some spatial influences on the entrapment of woody debris were studied in a full model. The arrangement of nets in straight and curved torrents were compared as well as different roughness and steepness of banks (see Table 1). All following values are given as specific values, referring to b_s = 1,0 m width of channel.

Table 1 situations in model tests

symbol in diagramms	*steepness of banks*	*roughness (k_{st} in [$m^{1/3}/s$])*	*Froude number [-] (discharge 3,0 m^3/sm)*	*net position*
	vertical	36	4,06	straight, curve
	1:1	36	4,06	straight
	1:1	70	2,15	straight
	1:2	70	2,15	straight
in all cases:	gradient: 5,0 %	m 1 b_s=10 m	5,0 m	

If a net barrier is built in a curve, the loads are concentrated at the exterior bank. In the beginning of the entrapment process the woody debris accumulates in the area of the main current. As a consequence of this one-sided concentration, the current gets diverted towards the inner curve. This can cause relocation of the woody debris and even circulation currents (comp. Fig. 3). The flow parallel to the plane of the net generates additional tensile forces to the anchors in the undercut slope. In general the banks get very high loads due to the changing currents.

Thus rope net barriers shouldn't be built in curves with a radius smaller than about 10 times the width of the channel. Additionally the distance of the net from a curve should be at least 5 times the channel width in direction of the flow.

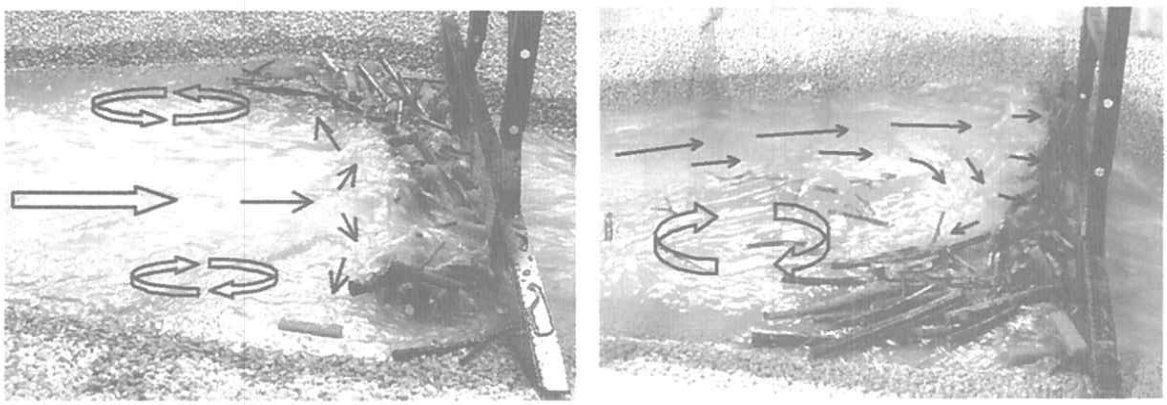

Fig. 3 comparison: net position straight (left) and curve (right); 3,0 m^3/m of wood; 3,0 m^3/sm discharge

The backwater and the loads on the net rise with the steepness of the banks (comp. Fig. 4). The less steep the banks are, the wider the water surface becomes and the woody debris can spread more easily. Then the log jam is less dense and therefore the water level rises less. With vertical banks it can happen that logs stick to the bank while the water level rises during entrapment process and they are not lifted up by the buoyant force. Then large friction forces can reduce the loads on the net, so they even can get less than with 1:1 sloped banks (see Fig. 4 left).

The loads on the net are significantly reduced by rough bottom and rough banks. Then the wood can deflect much force into the banks and bottom. Furthermore the density of the log jam is reduced due to lower impact forces and lower flow velocity in the beginning of entrapment process. It has to be considered, that the reduction of loads due to roughness can suddenly disappear: wood pieces shore up on single rocks in the bank so loads are transferred to the bank; due to erosion these rocks can get exposed and relocated, which suspends the friction forces.

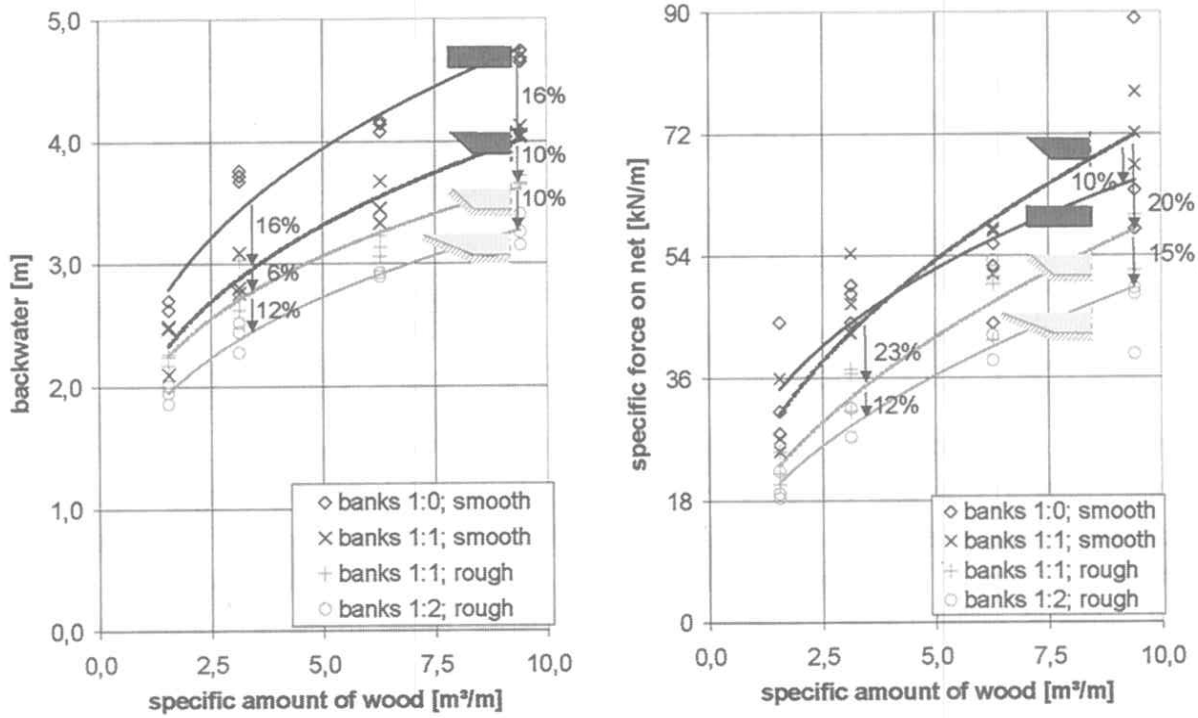

Fig. 4 comparison between different roughness and different banks

THE FULL-SCALE NATURE TEST

Introduction

A very important part of the research project is the full scale nature test of a prototype net construction. A detailed documentation on the full-scale test can be found in Rimböck (2002 a). The main objectives of this investigation are:

- Specify the dynamic forces on the net barrier
- Comparison of the final static loads between nature and model
- Define the influence of fine material and of the elasticity of steel and wood
- Observe the mobilisation and transport process of wood in the torrent

The site is located in Lobentalbach near Füssen, Bavaria. About 400 m upstream a small reservoir provides the required water for the artificial floods (comp. Fig. 5). The planned hydrograph can be created by controlling the bottom outlet of the reservoir. The whole testing area is easily accessible by unpaved roads. The woody debris was placed in the torrent either by an excavator or dumped off

of a truck. After the experiment the excavator removed the logs from the rope net and the truck transported it upstream again for the next test.

The testing net barrier consists of 3 ropes and a ring-net. The distance from the bottom is 0,50 m and the distance between the ropes is 1,5 m .

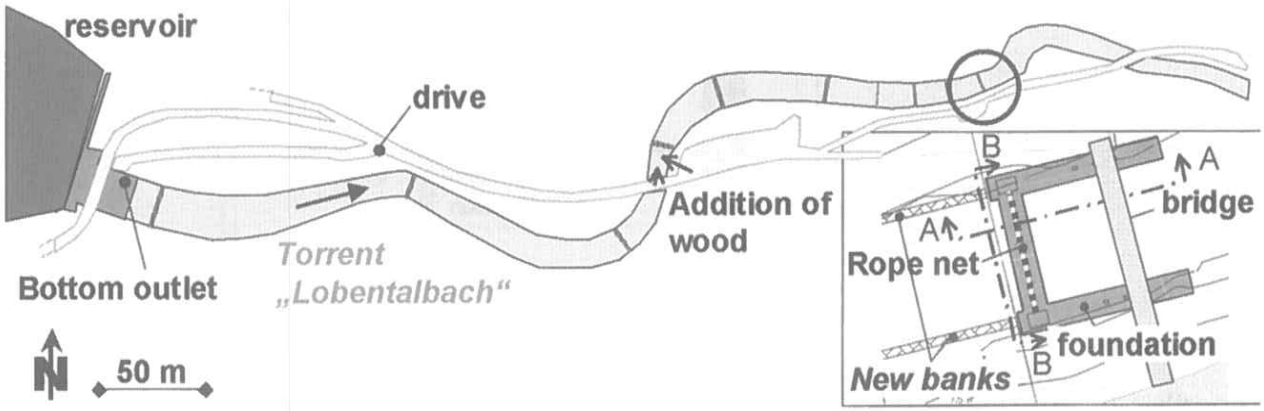

Fig. 5 layout of the testing area

The material in the adjacent banks is not suitable for anchoring. Therefore it was decided to build up a frame system where the forces in the plane of the net are distributed into a bottom and an upper strut (see Fig. 6). The forces in direction of the flow are delivered into a hinge column, the foundation and finally by friction into the ground. This special static system causes a very massive and expensive construction, which is not recommended for normal use. In any case anchoring should be the first choice.

To avoid current passing around the net and loads on the columns where they cannot be measured, new artificial banks are built which direct the woody debris into the net (see Fig. 5 and Fig. 6).

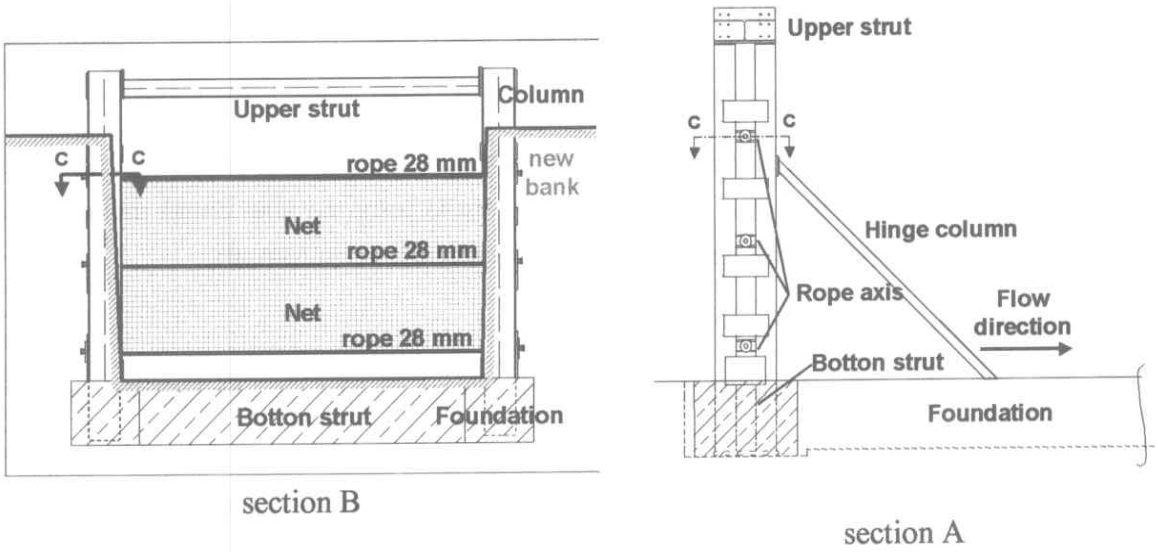

Fig. 6 system of the testing rope net construction

The measurands were: the longitudinal force in each rope, the horizontal deflection of each rope on each side (see Fig. 7), the water level upstream of the net barrier. Furthermore the whole process was documented by photographs and video-films.

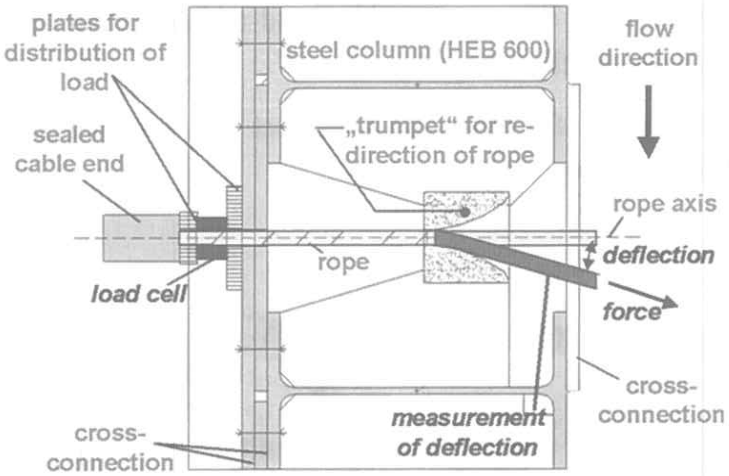

Fig. 7 detail of column and measurement system

Experiments

Altogether 18 experiments were carried out. Normally three single tests were performed with the same boundary conditions to average the results. Two different kinds of wood were used:

"Nutzholz / utility wood (NH)": straight logs, without branches; this should simulate material from lumberyards or woody debris, which was broken and lost branches during the process of transportation; its length reached up to 3,0 m, the diameter was between 15 and 70 cm

"Mischholz / mixed wood (MH)": a mixture of 60 % (per weight) "utility wood", 25 % "Wildholz / wild wood", containing root-stocks and logs with branches, and 15 % "Grünholz / green wood", including branches, sprigs, tussocks and other fine material. This should simulate the natural composition of woody debris as well as possible.

The experiments were divided into two series. In the first series (part A) scientific experiments were carried out to compare the results with the model tests and to get basic results on the loads. Therefore a nearly constant discharge was used. As soon as the maximum discharge was reached the woody debris was dumped into the torrent.

In part B we wanted to simulate a preferably "natural" hydrograph. The wood was spread in the channel before the bottom outlet was opened. During these tests we also could make interesting observations about mobilization and transportation of woody debris in torrents.

Woody debris in torrent

The most important processes, which mobilize wood lying in the torrent bed are (comp. also Braudrick and Grant (2000)):

- Flotage: after reaching a certain flow depth, the logs float and drift away with the current
- Abutment: wood gets hit by floating or rolling logs and starts to move with the current
- Bank erosion: due to erosion of the banks, wood deposits can slide into the channel

Within the torrent the woody debris is transported rolling, floating or in suspension. If the flow depth is not enough for floating transport but the forces of the flow are strong, the woody debris rolls. With higher flow depth the wood rarely hits the banks or the bottom; it floats on the water

surface. Fresh branches or wood saturated with water have a quite high density and often are transported in suspension.

Long logs are turned parallel to flow during transportation. Logs with root-stock float with the root-stock ahead, if the flow depth is high. Otherwise the arms of the root-stock can hit the bottom and the log turns around.

The entrapment process starts, if

- One part of wood reaches the lower part of the net (above the lower rope)
- A large branched piece wedges between bottom an lower rope
- An accumulation of woody debris arrives, where a single piece cannot turn or move within the accumulation and the area between bottom and lower rope gets wedged

With each entrapped wood piece, the backwater upstream of the net rises, because the cross-sectional area of the flow is reduced. Then wood arrives above the wood already entrapped and accumulates there. The log jam develops from the bottom up. Gradually the flow velocity and therefore the kinetic energy of the woody debris decreases due to the rising backwater. The log jam gets less compacted then, the backwater rises only slowly and the woody debris accumulates upstream more and more (comp. Fig. 10: middle top). The direction of log jam development is from the net towards upstream. Pieces with a density near 1,0 kg/dm³ can easily accumulate in areas under the water surface, where strong current occur (comp. Fig. 10: right).

Dynamic forces

It has to be distinguished between the impact of one single log and a small pile. Furthermore the spot of impact within the net is very important, especially if the log hits a rope or the net. The most simple process to describe is the impact of one single piece of wood on a rope. Then the whole kinetic energy of the log is transferred into potential energy of the elastic strained rope:

log: kinetic energy $E_{kin} = 0{,}5 \cdot m \cdot v^2$; with m: mass [kg]; v: velocity [m/s]

rope: potential energy $E_{pot} = 0{,}5 \cdot c \cdot d\ell^2$;

with $c = EA/\ell$; E: elastic constant [N/mm²]; A: cross section area of rope [mm²];
ℓ : length of rope [mm]; $d\ell$ expansion of rope [mm]

The tensile force of the rope is then: $F_{rope} = c \cdot d\ell$

Figure 8 shows an example of two impacts of logs on the lower rope. The first log had a kinetic energy of about 700 kJ (v = 2,0 m/s; m = 350 kg). The measured tensile force in the rope was about 55 kN, which means a potential energy of 640 kJ. So about 90 % of the kinetic energy was transferred into potential energy of the strained rope. The difference was taken up by straining of the net.

If logs hit the net, up to more than 85 % of the energy is absorbed by the rings of the net and the ropes only receive the remaining energy. Additionally also a pile of wood respectively a log jam can absorb much energy and therefore the dynamic forces decrease immensely during the

entrapment process. Also the kinetic energy of the logs is diminished significantly due to the reduced flow velocity respectively rising backwater.

In all experiments the maximum measured dynamic force in the lower rope was 65 kN and the maximum static force at the end of the entrapment process was 300 kN. In one experiment the tensile force in the middle rope was even about 360 kN. So the dynamic forces are not decisive for the design of the rope net barrier, despite especially high flow velocities can occur or extremely large and heavy logs can impact. It is to mention that no debris flows were considered in our experiments. Their impact could cause much higher dynamic loads.

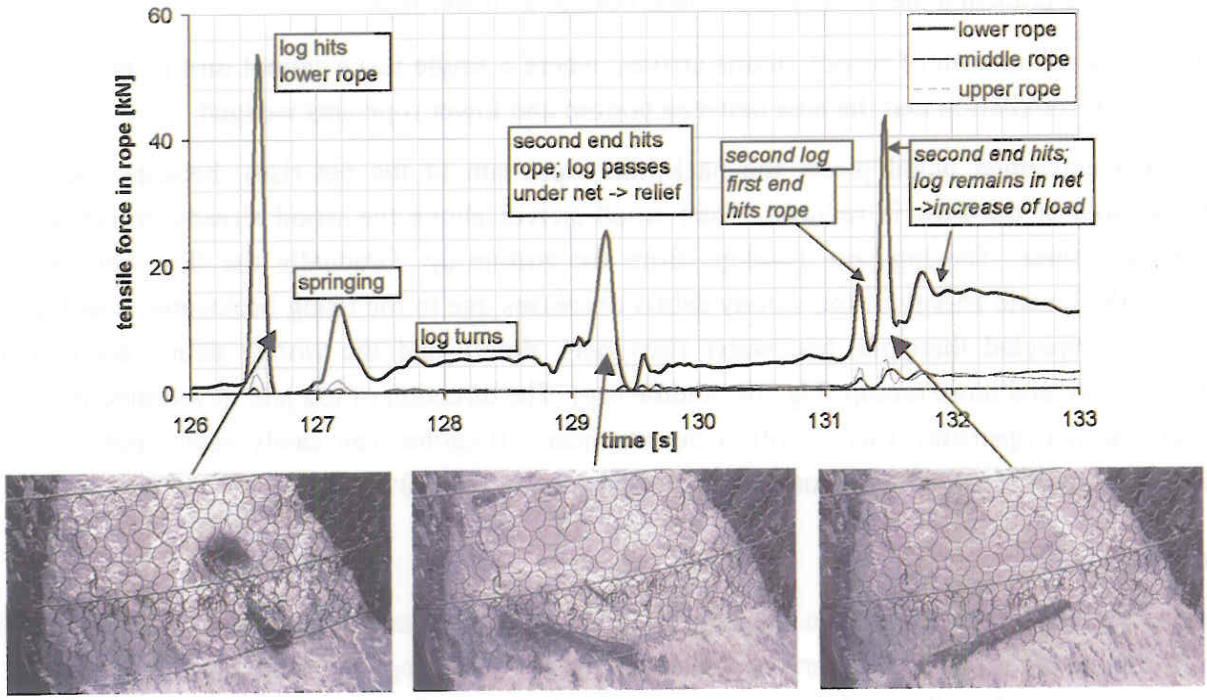

Fig. 8 impact of two logs; length 3,0 m

Comparison to the model tests and static loads

The form of the log jam in nature is very similar to that in the model tests (comp Fig. 9). The entrapment process including relocations reqires almost the same time. The length is reduced by a larger amount and smaller dimension of fine particles like grass and twigs in nature. They can reach smaller spacings between logs and rootstocks more easily which causes a higher density of the log jam. In the model they were simulated by blue sponges with larger dimension. After closing the bottom outlet the log jam gets dry. At the net many green fir twigs can be seen from downstream whereas from upstream only large logs are in sight.

In nature, more wood passes below the net than in model. The reason therefore is that due to a higher turbulence in nature, the wood gets relocated more often and can pass beyond the net even after a brief entrapment. Furthermore the lower rope always has a vertical sag, reducing the space between rope and bottom of torrent. After containing the first logs, the rope can move upwards, extending the distance to the torrent bed. Then even previously trapped wood can pass below the net. With the rigid mesh in model this effect can't occur.

	model	nature
backwater	3,47 to 3,62 m ***average 3,53 m***	3,83 to 3,93 m ***3,88 m (+ 10% comp. to model)***
force on net	262 to 300 kN ***283 kN***	275 to 315 kN ***300 kN (+ 6 %)***

Fig. 9 comparison between model test (left) and nature test (right); 15 m³ "mixed wood"; 20 m³/s discharge; bed slope 5,0 %; average out of 3 experiments

Fig. 10 some views of an experiment with 20 m³ "mixed wood"; 20 m³/s discharge; bed slope 5,0 %

The static loads represent the resultant loads in direction of the flow. They were calculated from the measured tensile force in each rope, the sag before the experiment and the length of the rope (comp. Palkowski (1990)).

With all experiments the backwater and the loads are higher in nature than in model. The "mixed wood" leads to about 10 % higher backwater and about 6 % higher loads in nature. Possible reasons are:

- The woody debris arrives more slowly and can easily deposit in spacings of the log jam, leading to a denser log jam and therefore higher loads.
- In nature the fine material has less dimension, which results in a very clustered log jam.
- The flexible net in nature is strongly deformed; as a consequence the logs relocate and can close the spacings.
- The natural "wild wood" is less branched and the branches can break more easily. Therefore the wood can deposit more densely.

It was shown that the hydrostatic water pressure describes an upper level for the whole load on a rope net barrier, reduced due to friction forces at the torrent bed and the banks. The backwater is seen as the main criteria for dimensioning. At the moment it is still an empiric factor, because the entrapment process is very complex.

CONCLUSIONS

Finally we want to present some conclusions about construction and design, whereas the results of the former abstract are still valid (see Loipersberger et al. (2000)).

The site should be chosen carefully, whereas the height of the barrier respectively the adjacent banks and the width of the channel limit the range of use. A suitable site is situated in an almost straight section of the torrent, has low-inclined banks and has a rough torrent bed respectively banks. The gradient should be as low as possible and not exceed about 5 % to limit the backwater level and to avoid a too high construction and wood passing above the net. A specific discharge of about 3,0 m^3/sm is regarded as an upper limit, which can be risen with low-inclined banks.

The height of a rope net barrier depends on various parameters. A detailed design concept is given in Rimböck (2002 b). For example the height should be at least 4,5 (5,1) m to entrap 5,0 (10) m^3/m wood with a gradient of 1 % and a discharge of about 3,0 m^3/sm. For a larger bed slope of 3 respectively 5 % the height has to be at least 4,8 (5,7) respectively 4,9 (5,9) m. A supplement for higher discharge and larger percentage of fine material has to be considered. A reduction can be taken into account for low inclined banks. If necessary the height of sedimentation has to be added.

Choosing the distance between bottom and lower rope, a compromise has to be found between allowing smaller logs and fine material to pass in the beginning and a preferably complete entrapment of woody debris. Therefore the flow depth of a 10 years or 20 years flood can serve as a guide value, because it is concerned as the beginning of woody debris transportation. Moreover it can be reduced for high exposure downstream or risen for a torrent with low danger of log jams.

The channel bed and the banks have to be paved up- and downstream of the net at least on a length of about two times of the backwater level, avoiding local scours.

Decisive for the dimension of ropes is the load on the lower or middle rope. Each of them can transfer up to 60% of the whole load, depending on the structure of the log jam. If the site is placed in a curve, loads in the plane of the net from the exterior bank towards the inner bank have to be considered. Dynamic forces are not important, except when debris flows or very high flow velocities occur. Ring nets are recommended as they can transfer high dynamic loads and they easily can spread the loads to the neighbouring ropes. Also the whole net remains stable if one single ring fails.

Unfortunately it is almost impossible allowing the fine material to pass in the beginning of the flood by enlargement of the width of mesh. Moreover a wider mesh has no disadvantage, so concerning the other boundary conditions and based on our experience in the full-scale test it should range between 0,30 m and 0,60 m.

Altogether especially the full - scale test proved, that rope net barriers reliably can entrap woody debris during flood events. At the same time the construction allows to pass gravel and discharge during smaller floods without woody debris. This kind of uncomplex construction can make an important contribution to the reduction of danger due to woody debris in torrents, not disturbing the ecosystem torrent too much.

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