PROTECTIVE BARRIERS AGAINST ROCKFALL

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ABSTRACT: Barriers (protective embankment dams) in rockfall-endangered zones are gaining more and more importance due to increasing settlement and building activities. Villages and infrastructure in mountainous areas often require protection by passive measures, such as steel nets, rock sheds or - most effective - earth fill dams. Small-scale model tests disclosed, that geosynthetic reinforced earth-fill dams are able to resist much higher dynamic loads than not reinforced structures due to a more efficient load distribution. Furthermore, advantages of different geosynthetic arrangements, anchoring and degree of compaction were systematically investigated and compared in an economic study.

1 INTRODUCTION

In Alpine regions large-scale rockfalls became an essential factor for regional planning during the last years. Not only single, well-known disasters like the rockfall “Eiblschrofen” in Schwaz/Tyrol drew the attention of the public and the authorities to extensive measures for protecting such areas. Terms of investment often comprise several questions concerning risk-analysis, like the probability of a severe event and particularly its amount of damage. Taking into account economical matters leads to a limited risk reduction in many cases of rockfall protection as well as in geotechnics in general.

During the past years the prediction of rockfall underwent a great advancement concerning the trajectories of the falling blocks by highly developed computer modelling, that provides consideration of mass, geometry, damping, vegetation etc. and yields the blocks´ kinetic energy at any position. Nevertheless, in most cases the prediction of the behaviour of an unstable block itself involves uncertainties and therefore often requires a wide parameter-variation in the calculation and design.

Relevant cause for comprehensive research work concerning rockfall protection in Austria was the above mentioned disaster in Tyrol, where a wide part of the town Schwaz had to be evacuated due to a threatening rockfall:

On July 10th, 1999 a rockfall of several thousand cubicmeters occurred on the Eiblschrofen massif, fortunately not causing any damage to persons or buildings. About 300 persons had to be evacuated for safety reasons due to expected further rockfalls. This fact led to an intensive planning and designing of possible protection measures, whereby the rockfall´s main trajectories were widely known from the topography. Rockmechanical considerations resulted in the construction of two protective earthfill barriers (embankment dams) where the expected rock mass justified and required respectively such measures.

The geotechnical design of the main barrier was rather complicated due to the unfavourable subsoil conditions and the steep slope. Mining wastes had been filled in the 14th century – of course without compacting – in the best suitable area for erecting the earthfill-barrier. Due to time pressure, subsoil explorations and sampling were not possible in a quantity and quality that a construction of such dimensions would have deserved. Based primarily on sounding results, a soil replacement of about 3 meters had to be carried out before the construction of the barrier could be started.

Figure 1 Protective barrier (geosynthetics-reinforced earthfill dam) Schwaz/Tyrol; view from the restraining area to the valley

As the construction site was directly exposed to the rockfall´s main trajectories, the detachment area had to be permanently surveyed in order to release an alarm signal. All people at risk had to leave the endangered site within 45 seconds.

The main barrier provided a restraining capacity of more than 200 000 m³ at a height of 25 m and a crest length of 170 m. The overall fill volume of the barrier was 130 000 m³, where 30 000 m³ were excavated from uphill to increase the catch volume.

The barrier had slope inclinations of 4:5 on the uphill (mountain facing) side and 2:3 on the downhill side. As shown in Figures 1 and 2 the upper slope was reinforced with geosynthetics to increase the slope stability on the one side and to improve the load distibution of the expected dynamic impact on the other side. The top layers (about 5 m under the crest) were designed as a 60° inclined reinforced earth wall using a lost formwork of steel mesh and a geocomposite consisting of a polypropylen continuous filament needlepunched nonwoven with high strength PET yarns. Beneath this section, the reinforcement was parallel-placed.

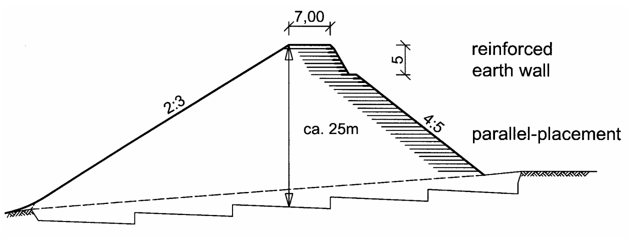

Figure 2 Cross section of the main barrier against rockfall (partial view).

2 MEASURES AGAINST ROCKFALL

The development of structures against rockfall received an enormous boost during the last 15 years in the field of nettings, where the cost-benefit ratio could be perceptibly improved by a highly absorbing deformation energy. These results were facilitated also by full-scale fall-tests, where not only further developed types of nettings but also new forms of evaluating the absorbed forces were applied.

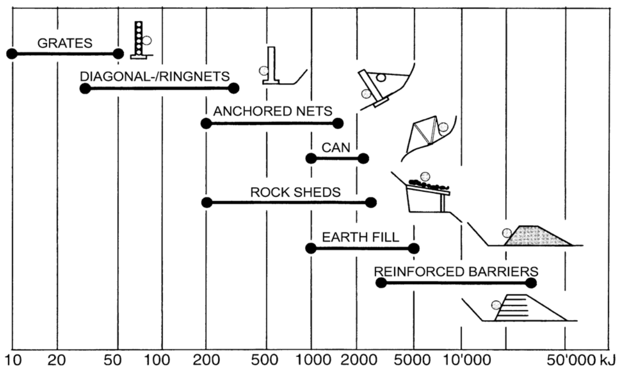

Figure 3 Structures against rockfall according to their deformation energy, DESCOEUDRES (1997)

DESCOEUDRES (1997) cites various structures against rockfall rated according to their deformation energy (Figure 3). Among these passive measures against rockfall earthfill barriers and especially reinforced embankment dams (barriers) take up the utmost position. In contrast to flexible nettings, the energy-absorbing effect of protective barriers is mainly given by their mass. Enough space and a topography, that makes the rockfall´s so called “transit-area” sufficiently known are prerequisites for the choice of an embankment barrier. Furthermore, the risk and the quantity of the expected rockfall have to justify the costly variation of building an earth-fill barrier instead of nettings.

As different trajectories of the falling blocks and their rotational behavior can be predicted to a high degree by computer modelling, it seems appropriate to take this into account not only when positioning the barrier but also in the design of its upper (mountain facing) slope. Obviously, geosynthetic-reinforced slopes offer more possibilities in “shaping” the embankment properly to prevent the blocks from running over the barrier. Additionally, the catch basin can be enlarged by steeply sloped barriers. Questions on the comparability of barriers with regard to their overall-resistance against dynamic impact seemed hitherto unanswered as well as economical aspects of such structures.

As a rule, full-scale tests require big effort when comparing various kinds of earth-fill barriers under the same conditions. Therefore qualitative and semi-quantitative model tests seem to be a reasonable possibility to study the interacting factors of the geosynthetic arrangement, anchoring lenghts or the degree of compaction.

3 QUALITATIVE MODEL TESTS

WALZ (1982) describes qualitative model tests in soil mechanics primarily as a method to recognize the failure mechanism of stability problems. Starting from this “philosophy” a series of 20 dynamic 1g-model tests were carried out on protective barriers against rockfall scaled 1:50. In the soil mechanics laboratory at the Technical University of Vienna special attention was directed on the measurement of forces, acceleration and deformation in order to gain comparable results and to enable systematic parametric studies.

3.1 *Measuring devices*

To exactly record the dynamic impact, the rockfall was simulated by a rigid pendulum, that contained dynamic force- and acceleration transducers. For exact measurements it was necessary to leave the six degrees of freedom, that a single falling block has. Interpretation of the measured data was supported by deformation-gauges in the embankment and optical recording by two digital video cameras. Figure 4 shows the pendulum with its hemisperical penetration surface, dynamic force and acceleration transducers and a threadpole for additional weight.

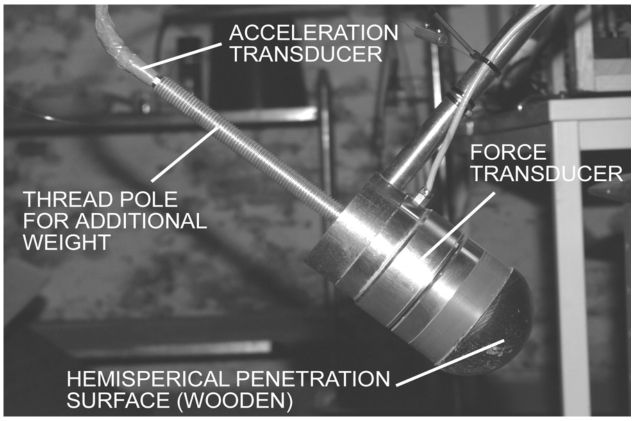

Figure 4 Pendulum simulating the rockfall

3.2 *Construction of the models*

The models were constructed in a steelframe structure with formboards. As templates for the cross sections of the barriers served chipboards. To grant a uniform density the model soil (sand with low degree of uniformity) was compacted in thin laterally boarded layers in such a way that the required soil mass could be weighed and controlled (Figure 5). Without the formwork for the embankment the conditions in the impact area would not have been reproducible.

Due to the fact, that maximum slope inclinations of 3:1 should be achieved in the model, the soil had to be compacted at proctor water content, thus gaining a certain kind of apparent cohesion, which of course would not exist in a non-reinforced prototype for a long time. These steep slopes were carried out for reasons of comparison to reinforced barriers (see 3.4).

Figure 5 Construction of the “Standard” model

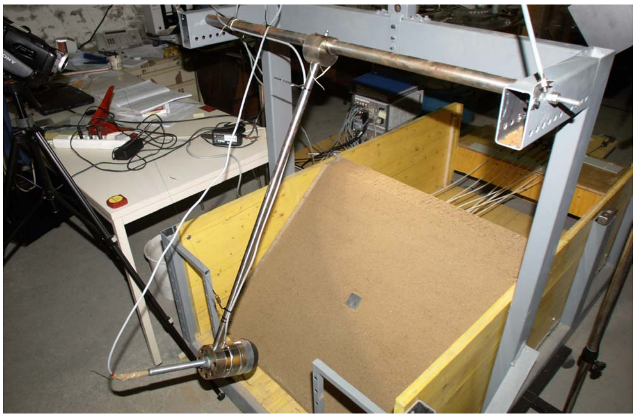

Figure 6 Test arrangement of the “Standard” model

3.3 *Dynamic Impact*

As mentioned above, the dynamic impact was simulated by a rigid pendulum for reasons of an exact placement of the transducers. The pendulum was orientated horizontally in half of the barrier height at the moment of impact. To gain information about the behaviour of the barriers under that kind of load, each test contained several strokes beginning with little impulse and increasing to a maximum impulse to destroy the model. The “loading history” of each test had to be exactly the same, to grant comparability. To control the increasing impulse, additional weight and/or the release height were varied (Figure 6). The release of the pendulum from its certain height was conducted by a steel wire and a special clamp, that provided releasing almost without jerk. This method was essential, since triggering of the measurement was executed via the acceleration signal of the pendulum in order to gain sufficient data from the whole period of impact at a maximum measuring rate. Optimising these parameters led to a possible measuring time of max. 2.5 seconds at 2400 Hz dynamic rate.

3.4 *Tested Variations*

The main goal of the qualitative model tests was to compare influences of geometry and compaction on the one hand, and effectiveness of geosynthetic reinforcement on the other hand. Therefore, 20 model tests were performed, where the first three tests were conducted under exactly the same conditions on a so called “Standard”-model to verify reproducible results. Then single parameters like geometry, compaction and the arrangement of geosynthetic reinforcement were varied. Combinations of changed parameters were not subject of this first series of model tests.

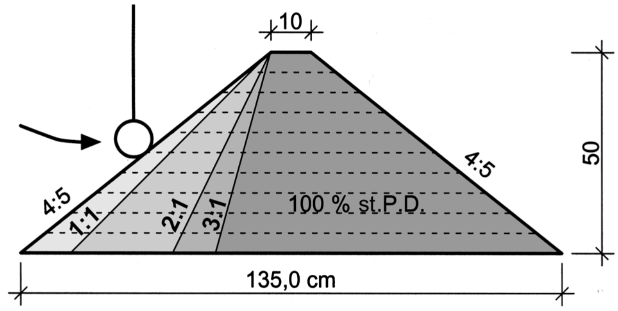

Figure 7 Variation of the uphill slope inclination for non-reinforced models

First the g e o m e t r y of non-reinforced barriers was varied starting from the “Standard” test with 4:5 inclined slopes on both sides in a range up to 3:1 for the uphill (mountain facing) slope (Figure 7). The same inclinations were used when constructing the reinforced models (Figure 8), whereby a wrapped soft facing was created. The anchoring length was 35 cm (70 % of the barrier´s height).

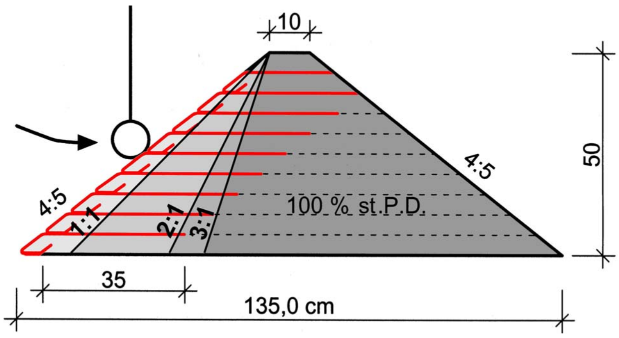

Figure 8 Variation of the uphill slope inclination for reinforced models (reinforcement schematically for inclination of 4:5)

Another parameter, which frequently causes discussions is the effect of c o m p a c t i o n of the fill regarding the single dynamic impact by a falling block. Consequently, some alternatives were examined besides the “Standard” test of 100% standard Proctor Density:

First a generally low compacted model with 90% of the standard Proctor Density (st.P.D.) was considered, secondly a so called “compation in zones” barrier was built up, whereby a “loose” cushion (90% st.P.D.) was situated in front of a well-compacted core (Figure 9). All those variations were constructed as reinforced as well as not reinforced systems.

Two more variations considered the c o n f i g u r a t i o n o f r e i n f o r c e m e n t: First a barrier with half of the standard anchoring length and secondly a parallel-placed reinforcement was chosen instead of a wrapped facing. The latter variation has to be evaluated with respect to economic efficiency, due to the absence of any formwork.

Finally two “s p e c i a l s o l u t i o n s” in terms of maximum resistance against dynamic impact were tested: First a “Sandwich-type” model was raised wrapping each layer completely with geosynthetic (Figure 10). Secondly a “Compound-type” barrier was built up, whereby each layer of reinforcement was bonded together wit the upper one (illustrated by dashes in Figure 11).

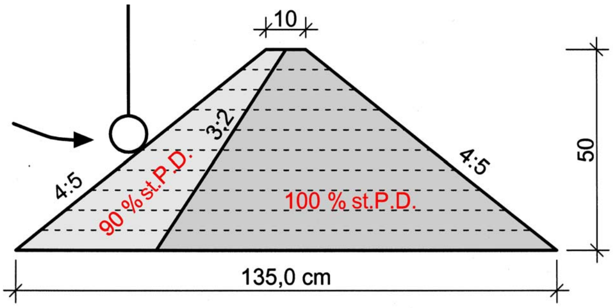

Figure 9 Variation of “compaction in zones” (exemplarily for non-reinforced models)

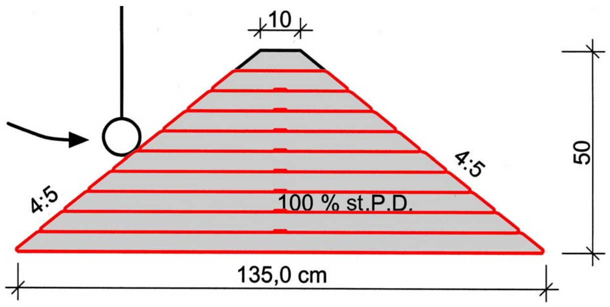

Figure 10 “Sandwich-type”

3.5 *Analyses and Results*

The measured data were analysed first by a detailed comparison of each registered signal (i.e. force and acceleration during impact) for the first three strokes of each test and secondly by an overall comparison, regarding every stroke until failure of the model.

3.5.1 *Detailed Comparison*

The detailed comparison facilitated to define a useful term or characteristic parameter for evaluating the resistance of earth-fill barriers: Single values like peak values of force or acceleration showed certain dependencies on the condition (local compaction) of the impact area - especially for the first “soft” impacts of each test. Therefore a combined term like impulse or energy seemed more reasonable in this manner. Figure 12 gives an example of the force-time relation for both reinforced and not reinforced standard barrier. While the long impact periods for strokes on a not reinforced barrier caused just low peak values in the force signal, the reinforced tests showed the opposite behaviour. Therefore, the area beyond the signal (the impulse) could be used to reasonably describe the resistance of the barriers.

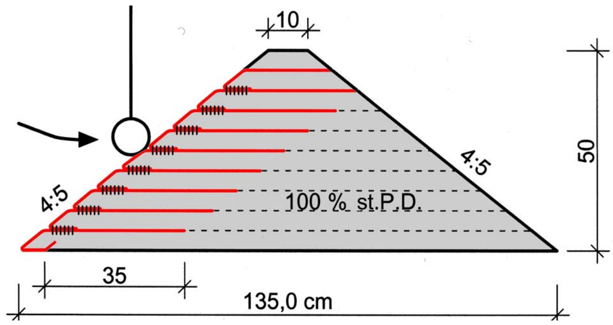

Figure 11 “Compound-type”

The evaluation disclosed, that in this example the transmitted impulse of impacts on reinforced barriers reached higher values than on not reinforced ones. This result was also obtained when comparing other data from reinforcement tests. Analysing compaction-tests in detail showed, that compacting a barrier sufficiently led to a better shear resistance and therefore a higher impulse at impact.

3.5.2 *Overall comparison*

The results of the detailed comparison were similar when evaluating not only the first three strokes but also their number, that was necessary to completely destroy the model. First, the number of strokes differed for each of the tested variations, and secondly the measured and calculated data for each impact yielded different values. Figure 15 shows summarizingly the overall sum of impulse for each tested model, whereby the value of the not reinforced standard barrier was assumed to be 100%.

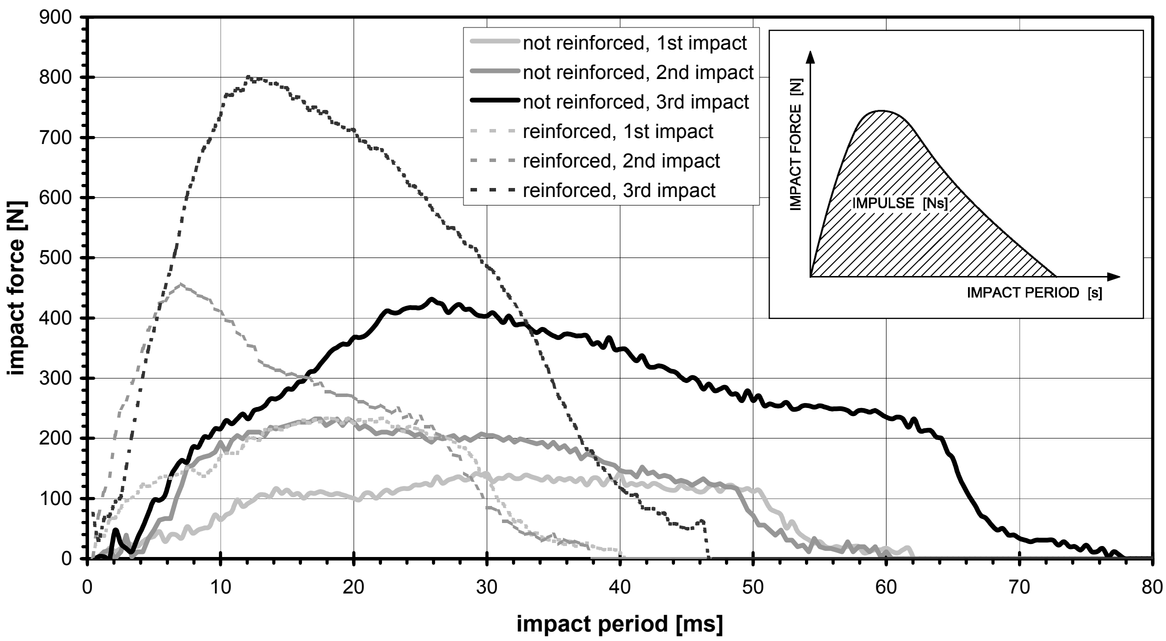

Figure 12 Force-time relation for the first three impacts (reinforced/not-reinforced), exemplarily.

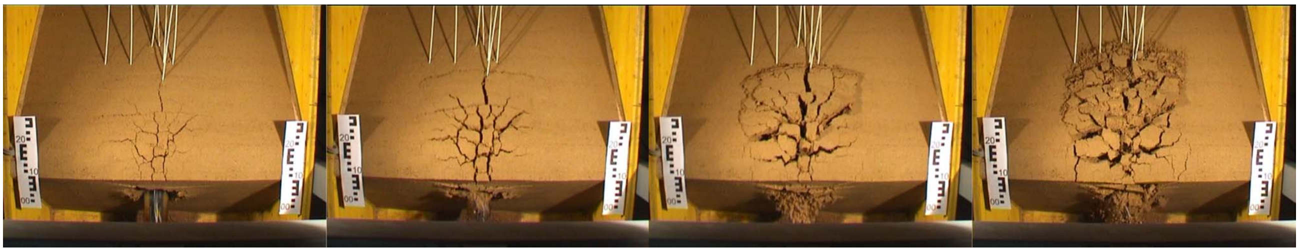

Figure 13 Effects of a dynamic impact (5th stroke) on a non-reinforced model-barrier

Figure 14 Effects of a dynamic impact (5th stroke) on a reinforced model-barrier

The effects of absorbed impulse can be clearly visualised by comparing for example a reinforced model with its non-reinforced pendant from the upper camera position, as shown in Figure 13, 14.

Most remarkable was the general difference between reinforced and not reinforced barriers. A clear relation to the mass (geometry) could also be obtained: The higher the slope inclination (the lower the mass), the lower impulses were registered. Lower compaction always caused lower resistance of the barrier, whereby the difference to the standard values was more significant in the case of not-reinforced models.

Two variations were clearly ahead of all others, namely the compound-type and the sandwich-type. Those models were primarily designed to take up highest loads in two different ways: The sandwich-type required a lot of geosynthetic reinforcement to cover each layer completely, the compound-type used a relatively small area at the facing, where upper and lower end of the geosynthetics were bonded.

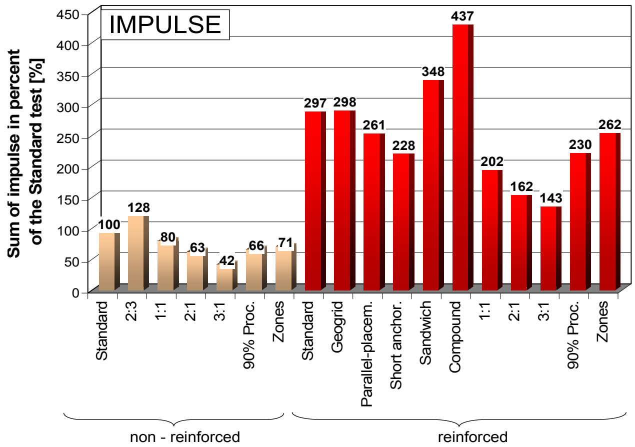

Figure 15 Sum of impulse for all tested models related to the non-reinforced standard test as 100%

4 ECONOMICAL EFFICIENCY

To include economic matters, cost calculations for the corresponding prototypes of the model barriers were carried out. The following assumptions were taken:

- barrier lenght of 200 m, constructed in 0.5 m thick layers,
- fictive construction time of 7 months,
- 0.3 m overlapping of the geosynthetic reinforcement,
- 2 km transport distance for the fill material,
- no direct passing over the reinforcement by skip lorries,
- wedge of humus for a vegetated facing of the reinforced walls.

In the case of reinforced structures, obstructions between filling and reinforcing working teams on the site were taken into account: Due to the barrier´s geometry, filling with constant efficiency yields increasing headway of the filling-crew. To maintain sufficient utilisation of the expensive filling machinery, the reinforcement-crew was accordingly resized. Even so, a certain loss of efficiency had to be considered when filling the top (narrow) layers.

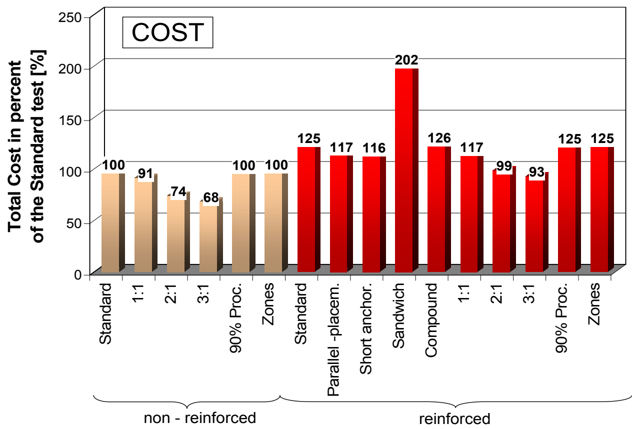

Figure 16 Calculated total construction cost

Figure 16 shows clear relations between volume and cost as well as an about 40% higher cost level for reinforced barriers compared to not reinforced ones. Filling without high quality compaction does not yield significant lower cost, due to the fact that the vibrating roller is neither an expensive equipment nor on the critical path regarding efficiency. The remarkable higher level of the sandwich-type barrier results from the higher amount of reinforcement products.

To outline the economical efficiency of the barrier variations, a value-cost ratio was determined finally by dividing the sum of impulse by the calculated cost. Figure 17 shows the results.

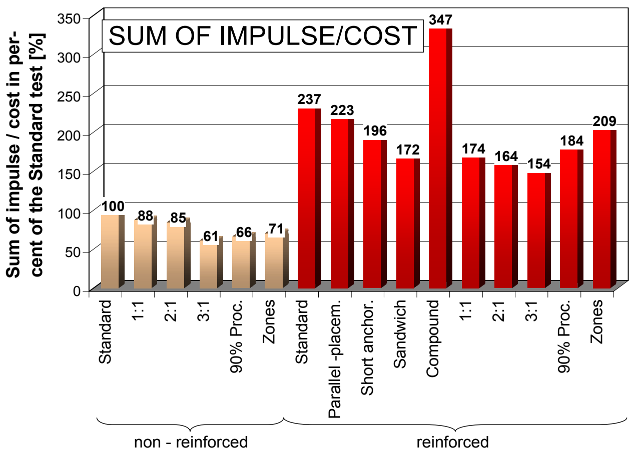

Figure 17 Value-Cost ratio in percent of the non-reinforced standard test

The generally higher impulse/cost level of reinforced structures underlines, that geosynthetic reinforcement provides more effectiveness than it causes additional expenses. Bonding layers for a “compound facing” provides a much higher resistance against dynamic impact at comparatively low cost. The effectiveness of sandwich-type barriers is relatively small due to the very high amount of reinforcement; its value ranges even behind the 1:1 inclined variation with a lower mass. The low-compacted barriers (“90% Proctor” and “Compaction in zones”) rank at last but two and last but one position. From the detailed comparison and video analyses it can be concluded that obviously a lack of shear resistance causes the poor results for these barrier types.

5 CONCLUSION

20 qualitative model tests on rockfall protection barriers provided detailed information about their deformation- and failure behaviour. The effects of reinforcement, compaction degree and geometry/mass could be clearly determined. From the applied measuring equipment, the exact high-dynamic registration of the impact-process provided most significant results - supported by single frame analyses of video recordings.

To evaluate the overall-resistance of such barriers, the sum of impulse proved to be a reasonable term. The test series on different structures showed a clear advantage of reinforced barriers that could be verified also by an economical comparative study.

Besides a wider load distribution reinforced barriers offer more possibilities for a proper design of the uphill slope and the protection against overrunning. The test pointed out that predominantly that layer was stretched, which was directly exposed to the impact. By means of a compound between the adjacent geosynthetic inclusions (sewing, welding, bonding, etc.) upper and lower fill-layers could be additionally activated as load distributors.

If no compound-type is used, both upper and lower anchoring lenght should be sufficiently dimensioned, otherwise heavy dynamic impacts would overextend the reinforcement.

Already a plain placement of geosynthetics without cover at the slope facing (“Parallel-placement”)) improves the resistance of the structure significantly. If a short construction time is required, this could be a reasonable alternative or compromise respectively.

Comparing just reinforced alternatives, it has to be stated, that filling volume/mass cannot be substituted by a special arrangement of the reinforcement (except compound-types). Nevertheless, reinforced barriers of lower mass showed a higher resistance than not reinforced barriers with a higher mass.

Regarding the orientation of the geosynthetic strips, static and dynamic effects have to be distinguished: The best orientation from a static view is transverse to the barrier (according to reinforced earth structures). Overlapping is not required then in the main direction of tension. The model tests pointed out, that the dynamic effect strains the reinforcement mainly in the longitudinal direction. For this reason a cross-orientation would be extremely counterproductive.

From this point of view an isotropic behaviour of the geosynthetics would be the optimum, which of course is not achievable for large areas due to the manufacturing process. To utilise the reinforcement in an optimal way, various kinds of connections instead of overlapping should be used.

Compacting the fill in form of zones did not show any positive effect for the tested structures. A kind of “crumple zone” would possibly cap the peaks of internal forces, but decrease the barrier´s resistance against snapping through. If barriers are designed extremely slender (space-saving), the risk of overturning could be reduced by such measures as well as the internal forces of possible retaining structures (ie. cantilever walls) supporting the barrier. The latter consideration offers a wide field of research and optimisation by further model tests.

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