Type-Testing of Rockfall Barriers — Comparative Results

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Abstract

Since the introduction of the Swiss Guideline in 2001, flexible rockfall barriers consisting of wire nettings and steel posts have been systematically tested. For the first time comparative results concerning mechanical properties of individual structures can be presented. In accordance with the Guideline, the barriers were dynamically tested by free-falling test bodies and characterized by energy absorption classes ranging from 250 kJ to 3000 kJ. For each test a number of different data were gathered before, during and after the actual impact. The forces acting on the supporting ropes are of prime interest but the wire netting deformations are also of great importance. The braking times and braking distances of the test bodies in the wire nettings are necessary basics to establish new and important results. Apart from the most important results obtained from type-testing of rockfall barriers, measuring procedures and data analyses will be discussed, and observations concerning the first governmental guideline worldwide for the approval of rockfall barriers will be presented.

Keywords: rockfall, protection barriers, testing procedures, impact, loads

Introduction

In the Alpine region many roads and highways are exposed to a considerable risk of natural hazards, which can only continue to rise as traffic increases. One of these natural hazards is rockfall. To protect traffic against this phenomenon many protective measures have long been applied. Widely used measures are flexible protective net barriers that are capable of interrupting and breaking the fall of stones and rocks. In recent years, various types of wire nettings of various constructions have been developed in Switzerland. In order to enable a quantitative assessment of their respective characteristics and qualities, the Swiss Federal Office for the Environment, BAFU, which subsidizes these protective measures, has issued guidelines for the testing of wire nettings that protect against rockfall (Gerber 2001). So far thirteen different types of wire nettings have been submitted for tests, eleven of which succeeded in complying with the norms set by the guidelines. In this report we present individual test results that may answer various theoretical and practical questions. It will be shown that a relationship exists between the kinetic energy of the impacting stone and the deformation of the protective net, varying with the length of the trajectory and the moment the falling body was first braked. These data enable us to evaluate the degree of stiffness or softness of the braking process (abrupt- / gentle braking processes). During the last Interpraevent in Japan, Gerber and Boell (2002) introduced new methods to assess the braking process. In the present report the authors will present, among other features, the forces measured during the braking process of the body falling into the net.

Method

In order to test the capacity of wire net barriers to protect against rockfall under realistic conditions, a test facility that meets certain requirements is needed. The basic problem is how to dynamically load a net with stones or other projectiles in a way that corresponds as closely as possible with the way this happens in natural circumstances. Stones falling from slopes mostly move in a bouncing motion. Maximum velocity of the stones occurs at the end of the trajectory, shortly before they hit ground. The author’s analyses of many rockfall trajectories in the field show that the impact angle of the trajectory is often about 15° greater than the angle of the slope. Zinggeler (1990) obtained similar results. When these premises are applied to various slope angles, the relevant test conditions may be derived from them.

In the past eighteen years, protective nets have been submitted for testing under the aforementioned conditions (Fig. 1) at six different test sites in Switzerland. The experience resulting from these tests has proven

pp. 189–198 ©2006 by Universal Academy Press, Inc. / Tokyo, Japan
that a vertical test installation also enables test circumstances 'approaching nature', provided the correlations between the slopes remain the same. This means that the protective nets in a vertical test setting have to be mounted at an angle of 30° to the horizontal. This measurement is reached when the first three settings in Fig. 1 are rotated at 60°, 45° and 30° respectively. In the vertical test setting, all possible settings for tests with slanting trajectories may be simulated. Therefore, the tests described in this report have been carried out on a vertically-orientated test installation.

**Installation**

In the Walenstadt test facility the protective nets to be tested were mounted on an almost vertical slope. Four supports were attached on foundation bases at distances of ten metres from each other and the head of each support was fixed by means of retaining ropes to the mountain slope. Subsequently, the lower and upper ropes holding the nets were attached to the supports. Depending on net type, the supporting ropes usually contained incorporated braking elements in order to keep the impact forces at a predetermined level, or to slow down any further increase of these forces. Measuring cells were also incorporated in the ropes in order to register these forces (Fig. 2).

**Testing**

The procedures for the individual subtests and the demands made on the protective nets have already been described in the guidelines (Gerber 2001) and summarised in Gerber and Boell (2000). Therefore in this report we will limit ourselves to the procedural basics and concentrate on the methods of interpretation and analysis. In the first three subtests of type-testing, the protective nets are dynamically loaded with test bodies. In a subsequent subtest the specific characteristics of the construction itself are tested. A type-testing procedure consists therefore of the following subtests:
Fig. 3. Force diagrams for the upper supporting ropes, lower supporting ropes and retaining ropes according to Fig. 2.

a) Small energy tests (test bodies with a lateral length of 10 cm, 20 cm, and 50 cm); to test the deformations of the laid-on mesh
b) 50% energy tests (test bodies with 50 % mass); to establish the required repair effort
c) 100% energy tests (test bodies with 100 % mass); to test bearing capacity and deformability
d) Tests according to special criteria; to test the practical suitability

In this report we will limit ourselves to the methods and results of the tests under b) and c) as these produce the most significant data, i.e. especially those regarding the forces acting on the supporting ropes and the resulting deformation of the wire netting. In the 50% energy testing, the test body is dropped from a height of 32 metres into the net, reaching an impact velocity of 25 m/s. Coupled with the weight of the falling body, this produces the required energy with which the net is dynamically loaded. During and after the impact, the measurements presented below are carried out, after which the net is repaired. The procedure for the 100% energy-test is basically the same, except for the dropped object being correspondingly larger.

**Force measurement**

The force applied is measured with measuring cells incorporated in the ropes. These are situated in such a way so as to ensure measurement of the maximum forces effected in the upper and lower ropes supporting the sides of the net, and in the holding rope in the centre field. These cells send 2000 measurements per second to a circular buffer, in which the data are continuously overwritten every 3–6 seconds. If any measurement of the master cell should be greater than the pre-determined measurement, a signal is triggered which causes the registration of all data within the range of 0.5 seconds before the signal, to 2.5–5.5 seconds after the signal. During the evaluation and presentation of the measurements, the time axes of the force measurements and the video registrations are synchronised, the zero point being the first contact of the falling body with the net. The test report shows the course of the individual measurements from about 10 measuring cells within a time interval of 3–6 seconds. Of special interest is the first half-second in which the falling body is braked and the forces on the ropes reach their maximum (Fig. 3). Forces on the various rope types (upper supporting ropes, lower supporting ropes and retaining ropes) are registered and the maximum forces determined. If multiple dynamometers have been installed, individual measurements are added up and from these sums the maximum measurements identified. In this way the maximum forces, or the combined forces, of impacts of varying energies may be compared.

**Video measurement**

The movements of the bodies falling into the net as well as the resulting deformation of the net were filmed with two high-speed cameras (250 frames / s). The cameras were activated by the same signal that triggered force measurement. With the capacity to continue shooting for approximately 2 seconds, 20% of all potential images were usually shot before the trigger signal and 80% of them afterwards. Measuring rods were included within the frame of the stills so that the scale of the image and the height of the falling body could be calculated when the images were interpreted and analysed. To this end the images were projected on the screen in AVI-format (480 * 420 pixels) and the separate measuring points measured in pixels on the vertical measuring rod. Two measurements result in two series of data defining the real measurements in metres of the
measuring points and their corresponding pixel values. The scale of the image on the measuring rod can be derived from these data by means of a linear regression calculation.

Subsequently, the deviations of the separate manually-measured points on the measuring rod with respect to the theoretically linear progression measurement may be calculated. The differences between the two measurements and the calculations are shown in a diagram (Fig. 4). This quality control is a demonstration that position determination with ‘sub pixel exactness’ as claimed by Frischholz (1997) can indeed be reached. With a real image size of about 14 m * 12 m and a 480 * 420 pixels format, each pixel represents a real size of about 3 cm * 3 cm (Fig. 5).

Knowing the distance between camera and measuring rod and the distance to the trajectory of the falling body allows the calculation of the scale of the body’s plane. In this way real measurements may be assigned to the subsequent positions of the falling body. These assessments, however, refer only to the system of coordinates that starts from the lower border of the image. Significant positions and timelines of the falling...
Fig. 6. Positions and velocities of 2 falling bodies (1600 kg and 3200 kg) with respect to first contact with net.

body for further analysis of the images taken by the camera are listed as follows:

- Position and timing of the falling body at the upper border of the image (Fig. 5a)
- Position and timing of the falling body on the net (Fig. 5b)
- Time of the trigger signal (Fig. 5c)
- Position and timing of the falling body at the lowest point (Fig. 5d)
- Position and timing (if any) of the falling body at its highest point (Fig. 5f)

From these data the following relevant results can be derived:

- Velocity of the falling body at the upper border of the image
- Velocity of the falling body on the net (start of the braking process)
- Time difference between the measurement by the camera and the measurement of force
- Braking distance and braking time of the falling body in the net
- Elastic component of the energy deforming the net
- Height of the falling body in position coordinates with respect to each timing

The graphical representation of the height of the falling bodies refers to their position at the moment of the first contact with the net. The time axis also refers to the time of the first contact with the net. This allows for an immediate calculation of both the braking path and the braking time of the falling body. The position/time data pair allows the calculation of the velocities every 0.008 seconds (2 image intervals). These velocity results enable an evaluation of the quality of the position measurements, as the results calculated in this way are strongly dependent on the precision of the measurement of the falling body’s position. Irregularities in the course of the position measurements result in a peak on the graphic representation of the velocity values (Fig. 6).

Deformation measurements

This report only describes the principles for determining the height of the net before testing and the remaining effective net height after the testing. To this end, the distance $a$ between the lower and the upper supporting rope in the centrefield, and the distance $c$ from the lower supporting rope to the centre of the foundation base were measured before and after the impact. Fig. 7 shows the following individual measurements:
Fig. 7. Required measurement values for the determination of the net heights.

- Distances $a_v$ and $a_n$ between upper and lower supporting rope (oblique)
- Slopes $\gamma_v$ and $\gamma_n$ between the ropes
- Distances $c_v$ and $c_n$ of the lower supporting rope (horizontal)
- Height position $e_v$ and $e_n$ of the upper supporting rope (vertical)

From these measurements the required measurements for the effective height $h_v$ and the remaining effective height $h_n$ may be calculated. A pre-determined reference line of $\Psi = 75^\circ$ (Fig. 7) lies at the base of these calculations. The equations necessary for the calculation of the net heights are as follows:

$$
\begin{align*}
    h_v &= (av \cdot \cos \gamma_v + cv + ev \cdot \tan(90^\circ - \varepsilon) \cdot \cos(90^\circ - \varepsilon)) \\
    h_n &= (an \cdot \cos \gamma_n + cn - en \cdot \tan(90^\circ - \varepsilon)) \cdot \cos(90^\circ - \varepsilon)
\end{align*}
$$

Results

So far, out of 13 type tests, 11 net types have turned out to comply with the guidelines and so are eligible for subsidy by the Federal Office for the Environment. The most important test results from the published data in the relevant certificates (http://www.umwelt-schweiz.ch/typenpruefung) will be summarised as follows (SAEFL 2006). They are the results concerning the following issues:

- The braking process of the falling bodies (braking distance and braking time)
- Maximum forces on the upper and lower supporting ropes and the retaining ropes
- Net height and remaining effective height of the net’s centrefield (field 2)
- Labor required for repairs, in working hours after a 50%-test

The braking process

All falling bodies reached the protective net at velocities of between 24.9–25.2 m/s, loading the net with an energy corresponding to their mass. As the same energy levels may be produced by either a 50% load or a 100% load, the results of the 50% tests have been entered slightly below the energy axis and those of the 100% tests slightly above the energy axis (Fig. 8). This distinction facilitates the assignment of the 0.2–0.5 second braking times to the corresponding braking distances between 2.8 and 7.0 metres (Fig. 8).
Force measurements

The maximum forces, or the maximum of the combined forces, of all the forces measured are registered graphically. The combined forces measurements were obtained from types of wire nettings that incorporated multiple ropes of the same type. All protective nets have lower and upper supporting ropes and retaining ropes, and these elements are also presented in the results. This allows us to compare these maximum levels over an overall range of energy of between 250 and 3000 kJ and to arrive at some general statements with regard to these. The largest sums of 100–550 kN occurred in the upper supporting ropes. These measurements are generally higher than the maximum measurements of 60–500 kN from the lower supporting ropes. In the retaining ropes maximum forces of 35–350 kN were measured.

Net heights

The effective heights of the nets depend on the length of the supports used. As the supporting ropes extend as a result of the weight of the net they are supporting, the effective heights $h_v$ are in all cases smaller than the lengths of the supports. After mounting, the net heights $h_v$ were between 2.1 and 5.0 m. After the 100% tests the remaining effective heights $h_n$ reached measurements of between 1.4 and 3.2 m. (Fig. 10).
Repair costs and labor

After the 50% test of the eleven net types, repairs were carried out to damaged or strained supporting elements. Most were limited to exchanging some braking elements in the ropes and retightening the supporting ropes. During these repair operations materials used as well as the number of hours worked were registered (Fig. 11). These figures depended on the amount of energy with which the respective nets were charged. The duration of the repair operations varied between some hours and some days. Figure 11 enables the prospective buyer to compare the repair efforts for different net types of a given energy level.

Conclusions

The results presented in this report show both the many differences between the individual net types and the wide range of energies deployed in the tests. The differences between net types are mainly caused by differences of construction by the various manufacturer. The nets diverge principally in the net type, the way they are fixed, the number of supporting ropes and their arrangement. Furthermore, differences in the number and arrangement of the braking elements decisively influence the results.

The braking distances and braking times increase with rising energy levels (Fig. 8). Analysis of each energy class shows a considerable scattering of the results. For example, at a energy of 1000 kJ (100%), braking distances varying between 4.6 and 7.0 m were measured. In order to be able to make more detailed statements about the braking process of the falling bodies on the net, braking distances and braking times must...
be presented independently of the energy deployed. With the help of these data pairs, it can be established whether the falling body has had a stiff or a soft landing. The theoretical basis of this evaluation was published by Gerber and Boell (2002). The evaluation of a braking process is based on the calculation of the so-called force factor $f_k$. A low factor means a soft landing, whereas a higher factor indicates a proportional increase in the stiffness of the braking process. In Gerber and Boell (2002) we began with force factors between 1.5 and 3.5. The results presented in this report, however, show the force factors to be relatively near to each other, approaching measurements of between 1.1 and 2.0 (Fig. 12). This means that the differences between the net types with regard to the braking processes are not as large as was originally assumed. Furthermore no clear difference is visible between the effects of 50% and 100% energy tests.

The result of the force measurements shows large differences between the various rope types, as well as within the same energy category. The highest and lowest force measurements within one energy category may diverge by a factor of two. In a scientific paper it is, of course, not feasible to list the pros and cons of specific industrial products. The considerable differences in the force measurements are caused by the different constructions of the protective wire nettings. The highest force measurements, or combined forces measurements, were made, with a few exceptions, in the upper supporting ropes; in the lower supporting ropes somewhat lower forces were observed. On average, measurements observed in the lower supporting ropes amounted to about 70–80% of the measurements of the upper ropes. A large part of this difference is accounted for by the redirection of the upper supporting ropes at the border supports. These redirections of the ropes require additional force in order to safeguard the stability of the supports. In the retaining ropes mean force measurements amounted to 35–55% of the maximum measurements in the upper supporting ropes. The maximum forces in the retaining ropes were observed at the centerfield supports. At these supports the ropes were redirected to compensate for the charge of the falling bodies on the centerfield.

Redirecting the ropes causes cross-pressure forces, and shifting of the ropes may cause additional friction at the redirection points. The way the dynamometers were applied in these tests did not allow for the measurement of these frictional forces. In the last few years two projects aiming at the examination of these frictional forces were carried out, the groundwork for these tests also took place in the Walenstadt testing facility. The results are reported in Grassl (2002) and Volkwein (2004).

Measurements of the net heights after mounting showed that here too there are differences between the various types of protective nets. The net heights proved to vary in proportion to the amount of tensioning force applied to the ropes to which the net was attached. Measurements of the remaining effective heights proved the soundness of the method indicated in the guidelines (Gerber 2002). However, the criteria required by the guidelines for the remaining effective height are rather high and some protective nets did not comply. A newly developed European guideline (EOTA 2006) contains somewhat milder requirements and the Swiss guidelines have consequently been scaled down (SAEFL 2006).

Repair costs and labour after a 50% test is dependent on the energy absorbing capacity of the net. On average, labour hours equal to 3–5% of the produced energy in Kilojoules must be allowed for.

Final conclusions and outlook

With the type testing of protective wire nettings against rockfall, a method has been developed that enables the comparison of various characteristics of the nets. Results show large differences between the various constructions. Nevertheless generally valid statements can be made regarding the deformation of the nets and the forces involved. The results will enable contractors and project developers to find the best solutions for their rockfall problems.

In 2000 the Working Group “Falling Rock Protection Kits” of the European Organisation for Technical Approvals started to develop a Guideline to test wire net structures against rockfall. As Switzerland does not belong to the European Union, the main author of this paper acted as a technical observer only. A draft of the Guideline was submitted for approval in the spring of 2006 (EOTA 2006). This draft can now be compared with the Swiss Guideline.

On principle, the EOTA Guideline also requests field tests wherein the structures are dynamically loaded by test bodies. According to the maximum load the barriers are characterised by energy classes. These latter are more or less compatible with the energy classes defined by the Swiss Guideline. The tests carried out at lower energy levels, however, are different. In Switzerland repair work on the barrier may be carried out after one test at 50% of the maximum load. For the European Union, EOTA stipulates two such preliminary tests, each one carried out at 30% of the maximum load.

Basically, however, the tests differ in the trajectory of the test bodies. While, in Switzerland, all structures are solely impacted by vertically free falling bodies, EOTA allows gradients of the trajectories between 0° and 90°. The direction of impact is, of course, decisive for the behaviour of the protective structure. In Switzerland, the installation of the barrier must be adapted to the trajectory of the tests bodies. This set up
guarantees the proper angle between the barrier and the test body. Figure 1 shows the solution of this problem for some examples of inclined trajectories and the corresponding barriers. In the European Union the barriers are installed according to the manufacturers' specifications and this will result in a wide variability of impact directions. In these circumstances it will be very difficult to compare the results of individual structures: the uniform Swiss testing procedures already show a wide range of results.

References


