Long-term studies of joint technical and biological measures

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Abstract
Systems used to stabilise steep slopes and gullies usually consist of technical and biological measures. While the lifespan of engineering structures principally depends on the mechanical properties of the building materials, the long-term behaviour of vegetated structures and biological measures is influenced by additional factors and interactions.

Based on previous studies, the mechanical strength of 60-year-old wooden check dams was found to still average within the values defined by the now relevant Swiss timber design code.
The two steep scree slopes Schwandrübi and Valzalära-Gazi have been documented and investigated since their stabilisation in the early nineteen eighties. They were stabilised by combinations of gabion walls, timber log crib walls and biological measures. As such combinations are quite often used in modern eco-engineering, the two investigation areas may be considered as fairly representative. Not unexpectedly, the gabions were still fully functional after about 25 years. The timber of the log crib walls, on the other hand, had considerably deteriorated and the future stability of the structures is assumed to depend on the surrounding vegetation and/or on the plants growing in the interstices.

The actual gradients of slopes successfully stabilised by biological measures were compared with the decisive angle of internal friction of the soil and with the angle of internal friction of planted soil (laboratory samples). It could be shown that the laboratory results, which rated the increase in the angle of internal friction by vegetation effects at about 5°, corresponded well with the actual slope gradients.

Whether it is possible to draw conclusions about the long-term behaviour of eco-engineering measures on the basis of investigations carried out 25 years after installation is open to question. Generally it depends on the specific measures included, but vegetated log crib walls and steep slopes stabilised by biological measures are likely to undergo further change in the future.

Keywords: eco-engineering, plants, soil, shallow landslides, erosion, torrent control, slope and gully stabilisation

1 Introduction

Shallow landslides, surface and gully erosion do not figure among the most dangerous natural hazards as far as built-up areas are concerned. Since shallow slides quite often occur spontaneously, however, they may well become a threat to single buildings and, particularly, to traffic routes (Münchner Rück 2002; SCHMID et al. 2002; Swiss Re 2005). As erosion and landslides often become dangerous in conjunction with torrents or rivers, they have to be considered as important sources of sediment transport and debris flow (MATHYS et al. 2003; ICE et al. 2004; BEZZOLA and HEGG 2008; Fig. 1). Protective measures against these processes, therefore, very often depend on torrent control methods – usually based on check dams – providing a safe base to prevent foot erosion of unstable slopes and subsequent progressive failure (BÖLL 1997).
The long-term and areal protection of affected sites, however, depend on the well coor-
dinated application of both technical and biological measures and, particularly, on the successful
and persistent re-colonisation process by plants after eco-engineering interventions
(SCHIECHTL 1973; GRAY and LEISER 1982; MORGAN and RICKSON 1995; GRAY and SOTIR
1996).

Eco-engineering protects soil from erosion and prevents and stabilises shallow landslides
by means of plants, cuttings of plants and engineering structures (VSS 2009). Eco-engineering
methods are considered to be environmentally compatible. The long-term effects of eco-
engineering stabilisation methods depend on site characteristics, slope failure processes and
the technical and biological measures employed (STOKES et al. 2007).

Since 1980 eco-engineering – or soil bioengineering as it was then called – has been a
research topic at WSL (EAFV until 1988). In 1981/82 joint technical and biological methods
were chosen to stabilise Schwandrübi, an ancient scree slope in Central Switzerland. The
work was carried out by the forestry service of Nidwalden, and WSL was called in for con-
sultation. BÖLL (1983) summarised the first results and found eco-engineering measures to
be most useful methods for combating erosion and slope failures, provided that the surface
of sliding runs reasonably close and approximately parallel to the ground surface.

Based on these first experiences, WSL has been investigating a number of sliding areas
and gullies stabilised by eco-engineering methods, assessing the suitability of arrangement
(BÖLL 1986, 1990), root growth and plant development (BÖLL and GERBER 1986; GRAF and
GERBER 1997), succession of plants (ROMER 2007), stability of slopes (FREI et al. 2002;
2003), engineering structures and the long-term effects (BÖLL 2003; BÖLL et al. 2008). The
sites examined are situated in mountainous regions and the lower Alps of Switzerland. The
slopes are usually larger than about 80 m (length) by 20 m (width). The gradients of the
slopes depend on the shear strength of the soil, which is usually characterised by the angle of
internal friction $\Phi'$ (LANG et al. 1996). Generally, the original surfaces were not covered by
vegetation and the soil had been exposed to weathering until the eco-engineering measures
were applied. Since the angle of internal friction depends on the degree of interlock between
the soil particles (TERZAGHI and PECK 1967), loosening processes like surface erosion and
weathering can lead to a time-dependent loss in shear strength.

It is generally acknowledged that engineering structures have to be replaced after a certain
period of time, whereas biological measures are assumed to be sustainable (SCHIECHTL
1973; COPPIN and RICHARD 1990; FLORINETH 2004). Biological measures in gullies and on
steep slopes, however, are part of a rather complicated system that is influenced by time-
dependent factors like the weathering of soils, seepage flow, erosion and secondary slides. In
due course, such factors may well become critical. Long-term studies that take the relevant
site conditions into account are, therefore, necessary to assess the long-term behaviour of
eco-engineering measures. Such investigations, however, are rare although an increasing
demand is emphasised (PASTOROK et al. 1997; ANAND and DESROCHERS 2004).

For this review, two particularly well-documented sites with comparable soil characteristics
were chosen. Both sites were stabilised about 25 years ago by joint technical and biological
measures representing state-of-the-art eco-engineering. Since the number of comparable
and well-documented sites is still fairly small, the analyses have to be considered as case
studies. Subsequently, we will focus on the long-term efficiency of eco-engineering measures
in connexion with surface erosion, shallow landslides and gully erosion. Not considered are
small road embankments, man-made earth dams and river embankments subjected to
tractive forces. The main focus of this paper is on the technical and biological measures used
to stabilise gullies and steep slopes, as well as on wooden check dams used in torrent control
as protection measures against the foot erosion of unstable slopes.
The concept of joint technical and biological measures

Slope stability analyses are necessary to successfully determine stabilising methods. One of the most important questions concerns the depth of the sliding surface and the measures have to be chosen accordingly. Shallow slides may be stabilised by ordinary retaining walls (concrete, gabions, timber) in combination with biological measures (Fig. 2). If the gradient of the slope meets certain requirements defined by the angle of internal friction $\Phi'$ of the soil (LANG et al. 1996; FREI et al. 2003; POWRIE 2004), the supporting structures may be omitted.

Deep running slides usually require structures tied back by anchors and resting on piles, but such systems are not considered here.

Slope stability and the efficiency of stabilising measures are usually influenced not only by soil mechanics but also by hydrological factors and hydraulics. The combined effects are rather complex and are often responsible for failure (BÖLL 1997). Surface erosion and landslides are usually long-term processes (over some decades and more) and stabilising measures are required to have a correspondingly long lifespan. The bearing capacity and functionality of supporting structures are likely to become critical in the course of time, and biological measures may fail to prosper. Periodical site inspections are therefore necessary to properly plan maintenance and/or replacements. Knowledge about the development and long-term behaviour of joint technical and biological methods (eco-engineering systems) is indispensable (PASTORAK et al. 1997; ANAND and DESROCHERS 2004).
Eco-engineering methods have a long tradition in slope stabilising practice (DUILE 1826; DEMONTZEAU 1887). In the 20th century, however, their use became rather restricted. This was partly due to the fact that it became possible to set up engineering structures (concrete) even in remote and hitherto inaccessible regions. Furthermore, such structures were (and quite often still are) considered superior because their stabilising effects can readily be quantified through calculations, which is an important requirement for modern risk analyses (YONG et al. 1977; EL-RAML Y et al. 2002; FREI et al. 2002). During the last thirty years, however, eco-engineering has enjoyed a revival and the old techniques have been adapted to meet modern practical requirements (SCHIECHTL 1973; MORGAN and RICKSON 1995; SCHIECHTL and STERN 1996; LEWIS 2000). Ways of considering the methods in stability calculations are, however, still rather limited (WU and WATSON 1998; BÖLL and GRAF 2001; SPRINGMAN 2004; WU 2007; GRAF et al. this issue).

Complete eco-engineering systems (Fig. 2) to stabilise steep slopes and gullies consist of the following elements (BÖLL 1983):

- Stabilisation measures along the foot of the slope, e.g. check dams to prevent the encroachment of a torrent onto the slope or the gully;
- Technical measures (supporting structures like retaining walls) to ensure the stability of the slope as defined by the allowable slope gradient (“new slope” as opposed to “original slope” in Fig. 2). Such structures, of course, can be omitted if the two gradients coincide;
- Biological measures like seeding, brush and hedge layers to protect the slope from surface erosion and local slides;
- Auxiliary measures like drains, rounding off of crests (slope scaling), and protection of foundations.

Fig. 2. Retaining walls and biological measures stabilise a slope against surface erosion and shallow landslides. If the foot of the slope connects with a torrent, check dams in the latter are a prerequisite. The supporting structures (gabions in this example) are each protected against rockfall by a log grid on top of them.
The long-term efficiency of a stabilising system depends on the site conditions, the natural processes involved, the individual eco-engineering elements and on their interactions. Some general aspects can be summarised as follows:

Due to their mainly linear design, engineering structures like retaining walls cannot protect a slope against surface erosion. The combined effect of technical and biological measures is what finally allows the development of the sustainable vegetation cover necessary for the stability of the top-soil layers (BÖLL 1997).

As engineering structures are liable to deteriorate in the course of time, the question arises whether the vegetation cover will eventually be able to replace individual structures. Timber structures, particularly log crib walls, are often furnished with live cut branches of willows, which are expected to take over when the timber can no longer carry the load. According to BÖLL et al. (1999), a log crib wall needs a backward inclination of, at least, 5 in 1 to become successfully vegetated. A soil and vegetation cover may improve the life-span of a log crib wall, but whether it can actually replace the wall depends mainly on the latter’s height. KUONEN (1983) recommends a maximum height of 3 m for vegetated log crib walls. He does not imply, however, that such heights can be safely maintained by vegetation alone. LEWIS (2000) suggests heights of about 1.5 m to 1.8 m (5 to 6 ft), and claims that vegetation can gradually take over the structural functions of the wood members, which more-or-less confirms observations we have made at WSL.

Vegetated timber walls are possible only on slopes and in gullies where the channel flow is negligible. The long-term efficiency of timber structures that cannot be vegetated and/or be covered by soil, particularly check dams in torrents, depends on the behaviour of the wooden components, the presence and dynamics of decay fungi, the exposition, and on certain design characteristics (ZELLER and RÖTHLISBERGER 1987; BÖLL et al. 1999; NOETZLI 2002; NOETZLI et al. 2008).

Initial conditions for eco-engineering measures are usually rather unfavourable. The area to be stabilised is still barren, partly unstable and erosive processes abound (GRAF and GERBER 1997; GRAF et al. 2003). The installation of technical measures to ensure the stability of the slope and to generally improve conditions for plant growth quite often causes further problems (BÖLL 1997): Excavation leaves erodible scars and excavated material, carelessly dumped, may be the source of future landslides. Supporting structures are likely to disturb the surface flow, resulting in water infiltration and secondary gully erosion. Insufficiently drained walls may deform or even fail under the combined effects of earth and water pressure. Footings and lateral abutments of retaining walls, as well as lateral ridges, are particularly susceptible to secondary erosion.

3 Assessment criteria and testing methods

3.1 Technical measures

3.1.1 Wooden check dams

This part deals with the long-term mechanical strength in bending of structural members of wooden check dams. One-walled log dams in torrents may be designed to withstand hydraulic pressure, with each individual log treated as a beam in bending (BÖLL 1997; BÖLL et al. 1999).

In autumn/winter 2000/2001 three 60-year-old one-walled log dams, destined for demolition, were investigated under real in situ conditions (Fig. 3). The check dams were situated in a westerly orientated torrent at about 650 m a.s.l. in Hirzel, Canton Zurich (Fig. 4). Fourteen logs were subjected to bending tests and the bending moments at failure $M_a$ were
compared with the calculated values of ultimate bending resistance $M_R$ according to the Swiss timber design code (SIA 164, 1992). Of the 14 logs tested, seven came from the first check dam, four from the second and three from the third.

The bending tests carried out in 2000/2001 were part of an extensive study considering the influence of decay fungi, construction characteristics, and environmental conditions on the quality of wooden check dams (NOETZLI 2002; NOETZLI et al. 2008). The bending tests are described in detail in NOETZLI et al. (2002). The results concerning the long-term bending strength of individual structural members were based on the then relevant Swiss timber design code (SIA 164, 1992). For this study the new Swiss timber design code (SIA 265, 2003) was applied.

The set-up for the bending tests is depicted in Figure 3. The individual beams were assumed to be simply supported at the ends. The force $Q$ applied in the middle of the beam was continuously increased until failure occurred at the ultimate load $Q_u$. After the test the beam was removed, and the diameter $d$ of the circular cross-section and the nominal span $L$, to be used to calculate the bending moment $M_u$ at failure, were measured. The magnitude of $M_u$ is $M_u = Q_u L/4$. The $M_u$ (thus determined) does not depend on the design code so that the actual values of $M_u$ in the 14 individual tests could be taken from NOETZLI et al. (2002).

The ultimate bending resistance $M_R$ depends on the cross-section of the beam and the mechanical properties of the wood. These are listed in design codes. $M_R$ equals

$$M_R = W_Y \cdot \eta_w \cdot f_{m,k},$$

where:

- $W_Y = \pi \cdot d^3/32$ (Section modulus for a circular cross-section of diameter $d$)
- $\eta_w = 0.6$ factor to account for the water content of the wood (SIA 265, 2003)
- $f_{m,k} = 20$ Nmm$^{-2}$ bending strength (characteristic value for coniferous wood C20 according to SIA 265, 2003).

Fig. 3. Bending/failure test on a one-walled log dam. The force $Q$ was applied in the middle of the beam by a steel wire rope and a winch powered by a tractor (Picture: Martin Frei).
The factor $r = M_u/M_R$ denotes whether failure occurred at a bending moment greater ($r > 1.0$) or smaller ($r < 1.0$) than the ultimate bending resistance given by the design code. In other words, $r \geq 1.0$ means that, from a purely mechanical point of view, the corresponding 60-year-old beam was still in working order.

### 3.1.2 Technical measures to stabilise gullies and steep slopes

The general set-up of the joint technical and biological measures studied in this paper is outlined in Figure 2. According to the mechanics of surface erosion and shallow slides, the technical supporting structures were retaining walls consisting of either gabions or timber and stones (log crib walls). As far as possible, the technical structures and the biological measures were treated separately (BÖLL et al. 2008). Technical measures have to stabilise a slope or part of a slope by reducing the gradient so that biological measures can be employed and a sustainable vegetation cover may develop. To characterise this quality, the aspects listed below were analysed. These aspects and the general requirements are independent of the building materials employed. Consequently, gabion walls and log crib walls were treated in the same way.

- **History**: Reasons for the original project; age of the structures; extreme events and their effects on the stabilising measures.
- **Arrangement of the structures**: Are the dimensions of the retaining walls (particularly their heights) and the distances between the structures in accordance with the admissible slope angle (defined by the angle of internal friction of the soil) and the general aspects of soil loss? Are any defects either recognisable or to be expected due to faulty arrangement (e.g. erosion at footings or lateral abutments)? What kinds of auxiliary measures have been taken to avoid or repair such defects? Were such measures successful and how will they perform in future?
- **Bearing capacity**: Is the stability of the individual structures and the stability of the complete system still given, and will it be given in the future? The bearing capacity was estimated by visual inspection (BÖLL 2003).
- **Functionality**: How did the structures perform in view of the natural processes acting on the slope or in the gully? Could erosion and soil loss be stopped? How have the structures affected surface flow and infiltration? What will happen in future?
- **Efficiency regarding the requirements of biological measures**: Could soil movements be inhibited to permit plant growth? Are the gradients compatible with the long-term requirements of the biological measures? Are there still instable parts (particularly scarps) that could endanger the vegetation cover (e.g. rockfall)?
- **Future development**: Although this is not a major topic of this paper, there are several questions that might be of interest. Apart from the ones listed above, assumptions were made about whether the vegetation could eventually replace deteriorated structures.

### 3.2 Biological measures

The stabilising effects of biological measures were characterised by vegetation and soil parameters (BÖLL et al. 2008):

- **Vegetation cover and plant diversity**: The vegetation cover represents the plants’ ability to protect the ground against surface erosion. It furthermore characterises the development of plants, which is often retarded by difficult site conditions. Registration of plant species and their diversity serves to assess the succession phase, naturalness and stability of the ecosystem.
– **Root growth**: Intensive root growth and deep rooting plants improve the mechanical stability and the hydrological regime. The root length per volume of soil was established for the top 20 cm. Individual bushes and some soil profiles were excavated to assess the depth of root growth (EGGENBERGER et al. 2005). To estimate the strength of root anchorage some plants were torn out.

– **Soil structure and slope stability**: The structure of the soil was characterised by its grain size distribution and aggregate stability. The grain size distribution affects the slope stability and describes the stage of soil formation. Barren soils contain a high percentage of coarse particles. The soil aggregate stability characterises the stability against mechanical influences and erosion. According to FREI et al. (2003), root length per volume of soil, aggregate stability and the angle of internal friction are positively correlated.

### 4 Study sites

#### 4.1 Hirzel

The seven wooden check dams were built during the Second World War in a westerly orientated torrent about 650 m a.s.l. in Hirzel, Canton Zurich. The ground consists of marl and its weathering products. Since the structures were shaded by the surrounding forest (mainly *Fagus sylvatica*) and the torrent is not liable to debris flows, the general conditions for the timber structures were quite favourable (BÖLL et al. 1999). The one-walled log dams consisted of individual trunks of Norway spruce (*Picea abies*) and Silver fir (*Abies alba*). They varied in height between about 0.8 m and 1.6 m (Fig. 4). Originally, the check dams were topped by wooden wing walls. In the course of time, the wing walls suffered from decay, ground and water pressure. By 2000, practically all the wing walls were missing rendering the system highly vulnerable to uncontrolled water discharge (overflow) and lateral erosion. Accordingly, it was decided that the check dams should be replaced, which offered us an ideal opportunity to study the mechanical behaviour of individual logs (Fig. 3).

![Fig. 4. One-walled wooden check dams in Hirzel. The dry stone wall with the culvert (top) supports a forest road (Picture taken in 2000 by Martin Frei).](image-url)
4.2 Schwandrübi

Schwandrübi near Dallenwil, Canton Nidwalden, is a steep scree slope in moraine containing two gullies separated by distinct lateral ridges. Except for a few bushes of *Salix appendiculata* growing on some of the ridges, the area was completely barren until about 1980. As a consequence, surface and gully erosion prevailed, rendering Schwandrübi a dreaded source of sediment transport and debris flows of the torrent (Flüeligraben) flowing along its foot. Furthermore, a pylon of the cableway Dallenwil-Wirzweli stands quite close to the unstable scarp forming the upper boundary of Schwandrübi (Fig. 5). The adjacent climax forest site is dominated by *Fagus sylvatica* and *Picea abies*.

The village of Dallenwil is situated on the alluvial fan of the Steinibach, the receiving stream of Flüeligraben, and had suffered for centuries from natural hazards originating in Steinibach and its tributaries. In the 1970s, several projects were initiated to improve matters, including the Schwandrübi Stabilisation Project, which is the focus of this section. The project was planned between 1978 and 1981, and principally realised in 1981 and 1982.

Schwandrübi is not the only source of sediment transport and debris flow in the catchment area of Flüeligraben. The most important one is the larger, north-facing Hexenrübi (about 4 ha), which forms the upper end of Flüeligraben (1090 to 1220 m a.s.l.) and has similar soil characteristics. The Schwandrübi project was the first to be carried out, with the intention not only to stabilise Schwandrübi but also to gain experience in solving the problems and to apply it to Hexenrübi and to other steep scree slopes. The Hexenrübi project is still under construction.

The north-east orientated Schwandrübi leads into the upper reaches of Flüeligraben at 1030 m a.s.l. It ends at 1140 m a.s.l. and covers an area of about 0.5 ha (GERBER and BÖLL 1996). In 1978, the Forestry Service of Nidwalden, responsible for the stabilisation measures in gullies and on slopes, issued a first draught of the Schwandrübi Project. To stabilise Schwandrübi (and Hexenrübi), it was necessary first to build check dams in Flüeligraben

![Fig. 5. Schwandrübi scree slope. Left: in 1978 prior to the application of joint technical (gabions) and biological (*Alnus incana, Salix purpurea*, hydro-seeding) measures conducted during 1981 and 1982 and right: in 2005 after the heavy rainstorm event in August. (Pictures: left Forestry Service of Nidwalden; right WSL).](image-url)
along the foot of the scree slopes. A group of such dams (reinforced concrete) was duly built in 1980/81 by the Stream and River Service of Nidwalden.

In order to establish the allowable slope gradient between the prospective supporting structures ("new slope" in Fig. 2), the Forestry Service of Nidwalden consulted with the Research Institute EAFV now known as WSL. In close collaboration with the Institute of Soil Mechanics and Ground-Engineering at the Federal Institute of Technology in Zurich (IGB-ETH-Z now IGT-ETH-Z), detailed soil analyses were made in 1980. The soil was classified according to the USCS-system as GC-CL (VSS 1966). The triaxial tests carried out at the laboratory of IGB-ETH-Z yielded the angle of internal friction ($\phi'$) related to the soil density; expressed by the dry unit weight ($\gamma_d$). A positive correlation between the soil density and the angle of internal friction could be established. Cohesion was zero. As the angle of internal friction ($\phi'$) is decisive for the stability of a slope (TERZAGHI and PECK 1967), the allowable slope gradient was defined as the angle of internal friction $\phi' = 33^\circ$ of the disturbed (loose) soil (BÖLL 1985). The laboratory results corresponded quite well with the conditions encountered in Schwandrübi.

The original stability was mainly given by the high density of the subglacially precompressed soil, and the steep parts of exposed ground ("original slope" and "crest" in Fig. 2) were assumed to be temporarily stable, and under favourable conditions, even for some decades. But due to weathering, initiated by surface and gully erosion, the original strength deteriorates and the gradients gradually decrease until they reach the critical value of about $\phi' = 33^\circ$ (BÖLL 1983). This gradient could actually be measured in the lower part of Schwandrübi, where eroded soil from the upper parts had accumulated. The theoretical factor of safety for an extended slope inclined at $\phi' (= 33^\circ)$ depends on the seepage pressure in the ground and is 1.0 or less. In ground engineering, a factor of safety of about 1.3 or more is usually required (LANG et al. 1996). For the stabilisation project it was assumed that the biological measures installed between the supporting structures would eventually raise the theoretical factor of safety to an acceptable level (BÖLL 1983).

Most of the stabilising measures were carried out during 1981 and 1982. Retaining walls, consisting of gabions, were built to reduce the gradients according to Figure 2, with the aim to change the slope angle to 33°. The heights of the walls varied between 2 m and 4 m (Fig. 6). The areas between the retaining walls were then covered by hydro seeding and planted with *Alnus incana*. Stakes of *Salix purpurea* were also used but to a considerably lesser extent.

It soon became clear that two major practical problems might cause difficulties, namely the gradients between the walls and the stability of lateral abutments. Although the spatial arrangement of the walls to reduce the gradient to 33° was fairly easy to achieve, it was nearly impossible to obtain a uniform gradient between the walls. A temporary cable crane, running above each gully from its bottom in Flüeligraben to its top on Wirzweli, gave access to the building site. The walls, therefore, had to be erected consecutively upwards in the gullies. Apart from the soil excavated to set up the walls, there was practically no soil available to backfill them and to build up a uniform gradient as well. As a consequence, the lower parts of the new slopes were often too gentle and the upper parts too steep (Fig. 6). As the steep parts more or less coincided with the footings of the neighbouring upper walls, some of the footings soon became endangered by secondary erosion. To safeguard such footings, additional log crib walls, consisting of timber and stones, were installed in 1984 and 1985 (Fig. 6).

The stability of the lateral abutments depends on the behaviour of the lateral ridges. It was planned to set the walls well into the ridges, but this could not be achieved without disturbing the ground. As a result, some of the extremely steep ridges failed locally, leaving the lateral abutments exposed. Since the gabion walls were designed as gravity structures, their mechanical stability does not depend on the lateral abutments. Their functionality,
However, became seriously restricted and it was not long before secondary gully erosion and rockfall, originating from instable ridges, could be observed. To mitigate such processes, the most affected walls were laterally elongated by adding log crib walls in 1984 and 1985 (Fig. 6), even though that log crib walls were not considered ideal in view of their long-term behaviour under the given conditions. They had to be used, however, because the cable crane used for installing the gabion walls was no longer available. Furthermore, the biological measures were already beginning to show some effects, and it was hoped that they could eventually take over the structural functions of the log crib walls. The walls varied in height between about 1.0 m and 1.5 m. Rockfall originating from steep ridges and also from excavation work was a general problem. To protect the potentially vulnerable gabions, a log grid was installed on the top of each single wall (Fig. 2).

The site was periodically inspected from 1985 until 2007 and the plants were coppiced. Particular care was taken to prevent alder (*Alnus incana*) from growing to large. This has resulted in a considerable diversity and a species composition close to the natural succession stages. Consequently, stability has been further improved from an ecological point of view, resisting several natural hazard events.

The persistent heavy rainfall events from 20 to 22 August 2005 resulted in the loss of human lives and tremendous damage to infrastructure all over Switzerland (BEZZOLA and HEGG 2007). Many of the measures intended to provide protection against such natural hazards were stressed to their limits or even beyond due to soils becoming water saturated and extreme discharges occurring in torrents. This particular configuration made it possible, and essential, to investigate the reliability of some eco-engineering measures. Schwandrübi was one of the study sites chosen (BÖLL *et al.* 2008). Although many superficial landslides were registered in the neighbourhood (RAETZO and RICKLI 2007), the technical and bio-

![Fig. 6. Retaining walls and slope gradients in Schwandrübi 1985: The gradients between individual gabion walls are partly too gentle and partly too steep. In the upper left, a log crib wall was added to protect the footing of the gabion wall immediately above it. In the bottom left a gabion wall was elongated by adding a log crib wall to stabilise the lateral ridge. The two independent log crib walls (lower middle and upper right) were built to prevent erosion in the part of Schwandrübi that had not been stabilised by gabion walls. Note that all the log crib walls were built as non-vegetated structures.](image-url)
logical measures in Schwandrübi turned out to have coped well and Schwandrübi remained stable (Fig. 5, right). The findings about the behaviour of the eco-engineering measures used in Schwandrübi are summarised in this paper.

4.3 Valzalära-Gazi

Valzalära-Gazi near Passugg-Churwalden, Canton Grisons, is a recent, trough-shaped slide in a stratum of moraine which overlies partially outcropping Bündner schist. The steep south-east orientated slope borders on the Landwasser River at about 900 m a.s.l. and on a forest road at about 980 m a.s.l. The slide area of about 0.2 ha is surrounded by woodland consisting of *Abies alba*, *Picea abies* and, to a lesser extent, *Pinus sylvatica*. Originally, it was also tree covered. The forest road was built by Polish war internees in the early 1940s and contains a water supply line of regional importance.

The slide, which endangered both the road and the supply line, was triggered off by extreme rain fall events in the late 1970s. In 1980 it was decided to undertake a stabilisation project. The original project contained a prefabricated concrete crib wall to restore the road (Fig. 7), a retaining wall consisting of gabions at the foot of the slope and a number of biological measures. The concrete crib wall will not be discussed further in this article.

The project was realised between 1981 and 1988. The gabion wall elevated the foot of the slope by about 3 metres. This, however, was not enough to decisively reduce the gradient, which still averaged about 40°. The project was based mostly on experience rather than on soil mechanics, and an allowable slope gradient was never defined. Based on field classification, carried out by WSL, it may be assumed that the mechanical properties of the moraine are quite similar to those in Schwandrübi. The partially outcropping Bündner schist, which is highly susceptible to disturbance and weathering, makes conditions rather more difficult (HUDER 1976). In comparison with Schwandrübi, therefore, an allowable slope gradient of 33° seems possibly too optimistic, but will be used as a reference in what follows.

In some places log crib walls were set up to locally reduce the gradients, to prevent secondary slides and surface erosion and to successfully apply biological measures (Fig. 7).

![Fig. 7. Valzalära-Gazi slide and stabilising measures in 1987. Brush layers are still visible below the concrete crib wall and between the vegetated log crib walls. Secondary slides and erosion produced the scar on the left and laterally endangered the topmost log crib wall.](image-url)
The log crib walls built of timber (*Picea abies*), stones and excavated soil were vegetated by *Salix purpurea* stakes and *Alnus incana* plants. The height of the walls varied between about 1.2 m and 2.0 m. The backward inclinations varied between a fairly gentle 2.5 in 1 and a rather steep 4 in 1. The biological measures consisted of brush layers with *Salix purpurea* stakes, hedge layers containing *Salix purpurea* stakes, *Alnus incana* plantlets, as well as individual *Alnus incana* plants.

The success of the eco-engineering measures was rather varied. It soon became clear that most parts of the slide could be successfully stabilised with either joint technical and biological measures or with biological measures alone. A section on the left and some lateral scarps, however, remained unstable (Fig. 7), i.e. they failed soon after re-vegetation.

The site was periodically inspected from 1988 until 2007 but practically no maintenance was carried out. Due to the rainfall events of August 2005, some landslides occurred in the neighbourhood of Valzalära-Gazi (RAETZO and RICKLI 2007). The region, however, was not as severely affected as Central Switzerland (Schwandrübi). On the whole, the technical and biological measures in Valzalära-Gazi performed well, and the parts that had looked stable in 1987 remained more or less stable (Fig. 8).

The investigations carried out in 2007 concentrated mainly on the behaviour of the (timber) log crib walls.
5 Results

5.1 Technical measures

5.1.1 Wooden check dams

Fourteen logs were tested under bending. The diameters $d$ of the circular cross-sections varied between 142 mm and 220 mm, and the nominal spans $L$ between 4.10 m and 5.99 m (NOETZLI et al. 2002). There was no correlation between the diameter and the nominal span.

In the study of NOETZLI et al. (2002), which was based on the then relevant Swiss timber design code (SIA 164, 1992), the median of the factors $r = M_u/M_R$ equalled 1.18 $\cong$ 1.2 and was significantly greater than 1 (Wilcoxon-Test $p < 0.05$). Four logs failed at bending moments $M_u$ smaller than the calculated ultimate bending resistance $M_R$, and one log collapsed at the very low level of $r = M_u/M_R = 0.50$ (tabulated results in NOETZLI et al. 2002).

In this study, the new Swiss timber design code (SIA 265, 2003) was consulted to determine the ultimate bending resistance $M_R$ for each log, with practically the same results. For the comparable timber quality C20, the ultimate bending resistances $M_R$ were slightly more conservative than the values obtained by NOETZLI et al. (2002), which resulted in slightly greater factors $r = M_u/M_R$. For practical purposes, the differences are negligible. The median of the factors $r$ equalled 1.23 $\cong$ 1.2, which was significantly greater than 1.0 (Wilcoxon-Test $p < 0.05$). Four logs failed at bending moments $M_u$ smaller than the calculated ultimate bending resistance $M_R$ ($r = 0.82; 0.83; 0.95; 0.95$, respectively). One log, mentioned above, collapsed at the conspicuously low level of $r = M_u/M_R = 0.52$.

5.1.2 Technical measures in Schwandrübi

The technical and biological measures have been influenced since the 1980s by earth and water pressure, seepage flow, surface flow and erosion. In August 2005 these influences became extreme. The resulting damage to the complete system was, however, almost negligible. Some individual retaining walls suffered slightly from erosion (MORDINI 2007).

Arrangement of the structures:
Not all of the structures complied with the criteria defined by the allowable slope angle (33°). In some cases gradients of about 40° were measured between consecutive gabion walls (Fig. 6). As mentioned above, some auxiliary log crib walls had been installed in 1984/1985. Except for some minor lateral erosion scars, no damage (due to faulty arrangement) could be registered. The protective log grids on top of the gabions had decayed, but showed no signs of rockfall impact.

Bearing capacity:
The stability of the individual gabion walls, as well as that of the complete system, was still adequate, and is likely to remain so in future. The log crib walls had badly decayed and their bearing capacity had become critical. As their overall height is less than about 1.5 m, it was assumed that their stability was maintained by plants (Fig. 9).

Functionality:
The complete system was still functional and is likely to remain so in future. Erosion and soil loss could be stopped. One gabion wall showed defects due to the erosion of one of its lateral abutments (MORDINI 2007). Maintenance is needed to prevent secondary erosion. One gabion wall had started to bulge slightly, probably due to earth pressure.
Efficiency regarding the requirements of biological measures:
Erosion and soil movements could be stopped and plant growth was quite impressive. On the whole, the steep ridges seemed stable. One such ridge showed signs of erosion with a single rock dropping into the gully. Fortunately it did not hit any structures. The forecast for long-term stability is fair, but the steep ridges will probably always remain a source of local hazards.

Fig. 9. Part of a log crib wall in Schwandrübi in 2007: height about 1.5 m. This wall was built in 1984 as a non-vegetated structure to stabilise the lateral ridge of a gabion wall (Fig. 6). The few alder (*Alnus incana*) in the actual wall grew naturally. It may be assumed that the plants growing on top and immediately behind the wall will be responsible for its continued stability.

5.1.3 Technical measures in Valzalära-Gazi

Since the 1980s, the technical and biological measures have been influenced by earth and water pressure, seepage flow, surface flow and erosion. In August 2005 these influences became pronounced. As parts of the stabilising system had already suffered before the events of 2005 (Fig. 7), it was not possible to unambiguously decide what damage was due to single events. According to the findings from former inspections by the authors, it can be assumed, however, that the general behaviour of the eco-engineering measures was influenced by continuous processes rather than single extreme events.

Arrangement of the structures:
The retaining wall (gabions) along the foot of the slope serves to locally reduce the gradient to about 34°, which more-or-less corresponds with the assumed allowable slope angle of 33°.
At a (horizontally measured) distance of about 16 m from the wall, the ground rises sharply to about 40° until, after an additional distance of about 30 m, it meets the concrete crib wall. The width of the slope fans out from about 6 m at the foot to about 24 m (about 12 m from the foot), and then remains practically constant at about 20 m. In order to locally reduce the
gradient, four consecutive log crib walls were built on the right-hand side of the slope (Fig. 7), and two walls were set up in the middle of the slope. The gradients behind the crib walls vary between about 23° and 35°, and correspond fair to well with the assumed allowable slope angle of 33°. As the crib walls act only locally, the gradient of about 40° is still representative for the greater part of the slope (Fig. 7). All these facts considered, the log crib walls performed well. Some lateral erosion occurred soon after installation (Fig. 7) but did not decisively progress in the course of time. Otherwise, the areas covered by log crib walls seemed quite stable in 2007 (BLUM 2007).

Bearing capacity:
The gabion wall along the foot of the slope was still stable in 2007, and is likely to remain so in future (BLUM 2007). The timber elements of the vegetated log crib walls, on the other hand, began to show distinct signs of decay as early as 1996 and were in an advanced stage of dilapidation in 2007. The interstitial Salix stakes and Alnus plants, however, developed well over the years (Fig. 10). Since 1996 they have grown quite considerably. As they are expected to compensate for the loss in mechanical strength and structural stability of the timber elements, their long-term behaviour is of great importance. BLUM (2007) found that they had reached dimensions which might well become critical for the stability of the crib walls. Large and heavy plants are highly undesirable as they act like cantilever beams on the walls. They should, therefore, be periodically pruned. The backward inclinations of the walls corresponded well with the requirements of plant growth (BÖLL et al. 1999). The highest wall (about 2.0 m), which originally was considered to be critical, is inclined at 3 in 1. If the plants are properly cared for, the system might well remain stable.

Functionality:
The log crib walls were still functional (BLUM 2007). The lateral erosion scars had remained more-or-less constant since 1987 (Fig. 7). The future functionality was assumed to depend on the long-term behaviour of the vegetated walls (Fig. 10) and on the stability of the potentially critical erosion scars. Periodic inspection and maintenance would be highly recommended.

Efficiency regarding the requirements of biological measures:
Erosion and soil loss could be stopped to a considerable extent. Plant growth, on the whole was quite good (Fig. 8). Secondary slides and erosion scars, however, will remain a source of severe hazards and may eventually endanger the footing of the concrete crib wall (Fig. 7).

5.2 Biological measures

5.2.1 Biological measures in Schwandrübi

Vegetation cover and plant diversity:
The development of the biological measures, which consisted of rooted plants of Alnus incana and, to a considerably lesser extent, cuttings of Salix purpurea combined with a conventional seed mixture (hydro-seeding), was most satisfactory (Fig. 5, right). Shrubs covered about 60–100 % of the ground (MORDINI 2007). The dominant shrub species were Alnus incana and Salix appendiculata. This latter species had never been previously used artificially due to its low vegetative reproduction. It shows a high stabilising potential, thriving particularly well on steep parts. In some scantily revegetated lateral glades it was still possible to see the original gullies (Fig. 5). Plant association analysis showed that the vegetation was of considerable diversity, with a species composition close to natural succession stages (BURRI 2006).
Root growth:
Root excavations in the field and laboratory experiments confirmed a high degree of rooting. In the top soil layer (0 to 10 cm), the average rooting degree was 1.5 cm/cm³. This value corresponded with the rooting degree measured in the neighbouring Hornwald. Hornwald, a forest characterised by *Abies alba* and *Fagus sylvatica*, represents the climax phase of the stand and was used as a reference site (BURRI 2006). Between soil depths of 10 and 20 cm, the rooting degree was considerably lower than in the top soil layer and also than at the corresponding depth in the Hornwald. Root excavation showed the high rooting potential of *Alnus incana* (Fig. 11).

Soil structure and slope stability:
To assess the effects of the vegetation cover on the soil structure, the grain size distribution and the aggregate stability of soil samples from Schwandrübi were compared with samples from two neighbouring areas. While the Hornwald represented the climax phase, the still mostly barren Hexenrübi had unstable initial conditions. Aggregate stability and percentage of fine particles were highest in Hornwald, slightly lower in Schwandrübi and significantly lower in Hexenrübi (BURRI 2006, BURRI et al. this issue).

The triaxial tests described in FREI et al. (2003) showed a positive correlation between root length per volume of soil, aggregate stability and the angle of internal friction. This laboratory-based result could be confirmed in Schwandrübi under in situ conditions. Before the application of eco-engineering measures, the steep and barren slopes had suffered from weathering, slope failure and permanent soil loss until their gradient was reduced to about 33°. This natural process could still be observed in the only partially stabilised Hexenrübi. The retaining walls built in Schwandrübi did not suffice to artificially reduce the gradients of all the slopes and ridges to 33° (allowable slope angle). As a consequence, the biological measures had to be applied on slopes as steep as about 40°. The investigations carried out after the rainfall events of 2005 (MORDINI 2007) showed that these slopes were still stable.
5.2.2 Biological measures in Valzalära-Gazi

Vegetation cover and plant diversity:
The development of the biological measures, which mainly consisted of brush layers (Salix purpurea stakes) and hedge layers (Salix purpurea stakes and Alnus incana plants), was rather inhomogeneous. While shrubs covered about 60% to 100% of the ground successfully stabilised by eco-engineering measures, the left-hand side of the slope (Fig. 7) was very poorly covered (≤ 20%). The dominant tree and shrub species were Alnus incana and Salix purpurea. Apart from these two artificially introduced species, individual plants from the surrounding forests established naturally, e.g. Fraxinus excelsior, Acer pseudoplatanus, Fagus sylvatica, Betula pendula, Picea abies, Pinus sylvestris, Lonicera xylosteum, and Viburnum lantana (BLUM 2007).

Root growth:
As the Valzalära-Gazi investigations concentrated mainly on the behaviour of the (timber) log crib walls, no root excavations were carried out. In the parts stabilised by eco-engineering measures, the soil and plant growth conditions were quite similar to Schwandrübi. It was assumed, therefore, that the root growth was comparable too.

Soil structure and slope stability:
As mentioned above, the allowable slope angle for this site had never been defined. In order to roughly characterise the initial stability conditions and their development over time, the allowable slope angle was assumed to equal about 33°. In the parts successfully stabilised by eco-engineering measures, the slope angles varied locally between about 23° and 44°. This corresponded quite well with the data gathered in Schwandrübi, so that similar correlations between the root length per volume of soil, aggregate stability and the angle of internal friction could be assumed (FREI et al. 2003). The scar on the left (Fig. 7), however, which
developed soon after revegetation on a slope averaging about 40° needs to be explained. The decisive local slope angle before failure was reconstructed on the basis of the longitudinal section recently measured (BLUM 2007), and was found to equal about 46°. Thus the scar is on the steepest part of Valzalära-Gazi. Furthermore, the locally outcropping Bündner schist might have been instable before eco-engineering measures were set up, so that slope failure could have occurred at depths not accessible to biological measures.

6 Discussion

6.1 Technical measures

6.1.1 Wooden check dams

The bending strength of the 60-year-old structural members of the wooden check dams was still surprisingly high. It could be shown that two-thirds of the 14 logs tested failed at a higher bending moment $M_u$ than the corresponding calculated value for the ultimate bending resistance, $M_R$. The median of the values $M_u$ was greater than that of $M_R$ by a factor of 1.2. This result is based on the Swiss timber design code applicable today (SIA 265, 2003). It is practically identical to the one obtained by NOETZLI et al. (2002), who used the now obsolete Swiss timber design code SIA 164 (1992).

From a purely mechanical point of view, design in accordance with the timber design code (SIA 265, 2003) seems adequate to ensure the safety of wooden structures in torrent control.

Design based on calculations is often not possible in eco-engineering, which makes this result quite important. In modern safety analyses, calculations are considered necessary. It is very clear, however, that the general behaviour, suitability and long-term efficiency of timber structures in eco-engineering depend on other important factors as well.

Thus the reason for replacing of the 60-year-old check dams was not that the mechanical strength of individual logs was questionable, but that complete dams had generally deteriorated. They were no longer able to fulfil their functions as the wings had failed and the water flow was no longer consistent with the stability requirements of the adjacent slopes.

6.1.2 Technical measures to stabilise gullies and steep slopes

In both Schwandrübi and Valzalära-Gazi, technical measures were necessary to ensure the stability of the slopes and to enable plant growth. For this purpose, retaining walls consisting of gabions or timber cribs were used. The most important differences between the two systems are their structural characteristics and their lifespans. In this particular case, the structural characteristics and the lifespan depended on each other. Twenty-five years after installation, the gabion walls with maximum heights of 4 m were still in perfect working order. The log crib walls, on the other hand, with maximum heights of about 2 m showed considerable wear after the same period of time. The retaining walls, arranged on steep slopes to decisively reduce the gradients (Figs. 2, 6 and 7), should be built for decades.

COPPIN and RICHARDS (1990) generally compared technical measures (inert structures) with biological methods (bioengineering works). They found that the initial costs were high for inert structures and medium for bioengineering works. The additional costs varied according to how often the inert structures had to be replaced or rehabilitated (considerable costs), while bioengineering works just had to be periodically maintained (usually low costs).
Gabion Walls:
Without touching the subject of costs, the gabion walls of Schwandrübi and Valzalära-Gazi must be considered as inert structures in the sense of COPPIN and RICHARDS (1990). They will have to be replaced or rehabilitated in the future. If proper care and maintenance can be guaranteed (FREEMAN and FISCHENICH 2000), they can be assumed to last for decades (BÖLL 1997).

The upper catchment of the Eistlenbach Torrent near Brienz, Canton Berne, contains a most impressive gabion structure. The construction of this retaining wall, which is up to 10.5 m high and about 126 m long, started in the early 1950s when the first layers of gabions were built up to a height of 3 m. In accordance with the natural processes that continually back-filled the wall, it was gradually enlarged. By 1973, the wall had practically reached its final dimensions. Some supplementary gabions were added in 1989. By 2005 some parts of the wall had bulged slightly and some wires had corroded, but it was still functional (GRAF and RITLER 2005). Although this wall contains some of the oldest gabions found in Swiss eco-engineering, conclusions about its long-term behaviour do not generally apply to more recent structures. The older parts were made of gabion sacks, which are more liable to bulging than the basket gabions generally used today (FREEMAN and FISCHENICH 2000). The workmanship, on the other hand, was superb. All gabions were filled by hand with well sorted stones and minor defects were repaired in good time by the builders, who seldom missed a workseason in the catchments of the torrents near Brienz.

Log Crib Walls:
Should the log crib walls of Schwandrübi and Valzalära-Gazi be considered inert structures in the sense of COPPIN and RICHARDS (1990)? If so they will have to be replaced or rehabilitated in the near future. As structures strongly influenced by the surrounding vegetation (Schwandrübi) or vegetated structures (Valzalära-Gazi), their bearing capacity and general behaviour depend both on the mechanical strength of the timber components and the reinforcement by plants. The investigations in Schwandrübi (BURRI 2006; MORDINI 2007) and in Valzalära-Gazi (BLUM 2007) revealed a rather poor strength of the timber elements but a quite impressive growth of the plants. The pretty bad condition of the approximately 25 year old timber components compared rather unfavourably with the above described long-term behaviour of wooden check dams used in torrent control. This came not entirely as a surprise.

Buochserrübi near Buochs, Canton of Nidwalden is a scree slope quite similar to Schwandrübi. It was stabilised by eco-engineering measures between about 1930 and 1960. Apart from dry stone walls built in the early years of restoration it also contained a number of log crib walls set up in the 1950s. The walls were completely covered by soil and the resulting slopes were stabilised by Salix viminalis and Alnus incana. In August 1981 an extreme rainstorm event caused considerable damage in the region and affected Buochserrübi too. Many of the log crib walls failed and BÖLL (1990) described the poor mechanical strength of the timber components aged approximately thirty years. The log crib walls, by the way, were replaced by gabion walls in 1983 which are still in perfect working order.

6.2 Biological measures

The biological measures generally fulfilled our expectations. Their stabilising effects on steep slopes were quite impressive and corresponded well with the results obtained in laboratory tests. Triaxial tests carried out on pure soil and on planted samples yielded an increase in the angle of internal friction of about 5° in soil with plants (GRAF et al. this issue). In Schwandrübi, the allowable slope angle was defined as the angle of internal
friction of the disturbed (loose) soil, which equalled 33°. Slopes as steep as 40° there were successfully stabilised with biological measures, and similar results were obtained in Valzalära-Gazi.

In practice, biological measures are often applied to slopes that are too steep from a purely mechanical point of view, and the stabilising effects of plants are therefore rather difficult to quantify (GRAF et al. this issue). The combined results of laboratory tests and long-term field studies should yield more information.

The question arises whether investigations covering a period of about 25 years may really count as long-term studies. Over the past 10 years superficial landslides, in open country as well as in woodland, have become much more widespread and frequent in Switzerland (RICKLI et al. this issue). Only a few slopes stabilised by eco-engineering measures have, however, failed. As the total area of slopes covered by woodland is, of course, much larger than that stabilised by biological measures, this is not really surprising. The comparative studies of BURRI (2006), SCHWARZ (2006) and BURRI et al. (this issue) showed that the angle of internal friction increases on soil with vegetation both planted as a biological measure and grown naturally in woodland. Different strength and stability conditions may be the result of time dependent processes, like weathering, which affect the properties of the soils. Soils covered by woodland have usually developed over decades or even centuries, and, accordingly, destabilising processes have acted on them for considerable periods. Eco-engineering measures are usually applied after landslides, which means that the exposed soils forming the surfaces are initially fairly recent. Steep slopes then have, at least temporarily, a high soil density and are thus stable, and eco-engineering systems add further strength. Whether this added strength and the soil protecting plant cover can actually guarantee sustainable stability will depend on factors like soil properties, weathering processes, plant development as well as inspection and maintenance of the eco-engineering systems.

7 Conclusions

For timber check dams in torrents, a life-span of about sixty years can be assumed to be a realistic average (ZELLER and RÖTHLISBERGER 1987; BÖLL et al. 1999; NOETZLI 2002; NOETZLI et al. 2008). In practice, such structures are usually built by craftsmen who rely on their experience rather than mechanical calculations. This is by no means to a bad thing because the planning, arrangement and design of timber check dams have to take into account the natural processes at work in the catchment area and the torrents. Detailed knowledge of the local conditions will always be indispensable. For modern risk management and general safety, however, theoretical studies are necessary and should be carried out as well.

For gabion walls, the 25 years covered by this investigation represent a comparatively short period of time. The long-term behaviour of modern gabion walls in eco-engineering cannot yet be fully assessed. Further studies on their time-dependent stability and functionality are required.

For log crib walls, the 25 years investigated may be assumed to yield sufficient general information about their long-term behaviour. Their future functionality depends on the reinforcing and stabilising potential of plants. Considering their present overall condition, it seems rather unlikely that complete systems will fail. Some damage, however, has to be expected within the next five to fifteen years. Careful inspection and maintenance, e.g. pruning trees growing too tall in the interstices, are highly recommended.

NOETZLI (2002) studied the decomposition processes of wooden check dams in torrents and described methods to improve their long-term behaviour. Unfortunately, there are
no comparable studies of timber structures stabilising steep slopes and gullies. As such structures are widely used and are very important in modern natural hazards protection schemes, more detailed research is needed to decide on the best strategies to ensure that they can fulfil their protective functions for as long as possible.

The biological measures we studied had an average age of about 25 years. They have very promising slope stabilising characteristics. In terms of the time it takes for soil weathering, however, it follows that most well-documented eco-engineering systems in Switzerland are still relatively young. Detailed research is required to fully understand and quantify the relevant factors and the decisive interactions that govern the long-term effectiveness of biological measures for stabilising steep slopes.

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