Landslide Control: Tool of the Chain of Functional Structures in Systematic Debris Flow Control

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Abstract

In Systematic Debris-Flow Control (SDFC) you have two principles, active and passive countermeasures. The passive measures are mainly land-use planning keeping the endangered areas free of settlements and infrastructure to prevent economic damages. Active countermeasures start at the debris flow source area and are continued through the debris flow course down to the apex and the debris flow cone. These countermeasures cover various functions and their belonging structures. From top to bottom, from the debris flow source to the debris flow cone, the countermeasures are like a chain of functional structures and countermeasures. That means that each part respectively each reach of the debris flow can be dealt by a specific control function and therefore by a specific functional structure. The first functional countermeasures to prevent the development of debris flow are afforestation and revegetation to fix the debris source. The functions are drainage, retaining, consolidating, stabilizing, sorting (sizing), dosing and energy dissipation and sedimentation. The related functional structures are drainage, retention dams, consolidation dams, bars, sorting (sizing) structures, dosing dams and Energy dissippators (debris flow breaker). The functional chain ends at the debris flow cone with trapping the debris flow mass and its sedimentation. There the finally levelling down of the energy line of the debris flow takes place. All these functional structures correspond with specific functions, the chain of functional debris flow control countermeasures.

The Chain of Functions carries out the sequence of functions to influence the energy balance of debris flow and leads to the Chain of Functional Structures and the Systematic Debris Flow Control (Fiebiger 1992). The single functions and their interlockings and their belonging structures are defined and discussed. Summarizing the importance of the chain of functions and their belonging structures to develop a functional landslide control leading to a functional systematic debris flow control is shown up.

Keywords: Landslide Control; Debris Flow Control; Chain of Functions; Functional Structures;

Introduction

In the last decenniums of the past century the Austrian Service for Torrent and Avalanche Control Engineering developed new techniques in Torrent-, Debris Flow-, Landslide- and Flood Control. All these techniques are based on an Environmental Analysis of the belonging watershed and catchment. Depending on the state of the catchment and the conditions of the watershed you have to develop the aim of the control system respectively management and as the next step the basic idea of the systematic control and management. In debris flow control we distinguish active control and passive control. Debris flow management can be subdivided into debris flow prevention and debris flow control Passive controls are Landscape Management, Forest Management and Hazard & Risk Mapping. Active controls are measures like Structural (Technical) Measures.

The master planning of structural countermeasures against debris flow is developed on the base of debris flow management. Runoff Control, Discharge Control and last but not least Watershed Management are corresponding debris flow prevention. The master planning procedure should always be in a systematical way. The master planning of structures of debris flow countermeasures is the same step to step development like the planning procedure in torrent control (Fiebiger 1992). Step 1 the Environmental Analysis of the debris flowing watershed ecosystem leads to step 2 Debris Flow Management. At step 3 our decision will be Debris Flow Control. Step 4 let us develop the countermeasures as the basic idea of the system. The master planning of structures of debris flow countermeasures are in general the planning of energy dissipator (structures of energy disappearance), dam systems (debris flow training) and single training structures for local control. Energy dissipators are debris flow breaker, debris flow screens rakes grids and grills, debris flow traps, woody debris

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traps, woody debris filters, deposit settling and sedimentation basins and structures with a combination of functions. Dam Systems are known as systems of debris flow structures, functional dams (retention and other functions), steel-grid dams and stabilizing systems. Training systems are dykes and channels and alignment dykes.

The aim of this paper is to show clearly the connections between the analysing and planning procedure by the chain of functions in watershed management, landslide control and disaster prevention

The Chain of Functions in Systematic Control

The functions which have to be discussed as structures of the chain of functions and base for the deduced control measures are shortly discussed on the principles of bedload management (Fiebiger 1988).

If we follow them from top to bottom we are talking of the chain of functions, which is necessary to equalize the natural processes and if we put these functions in a systematic control to reach the desired effects we are speaking of the chain of effects or stronger of the chain of impacts.

These functions are

Stabilizing:	Fixation of debris flow channels in a wanted level to stop and/or prevent depth erosion. The main goal of landslide control is stabilization of the gliding mass to prevent further landslides.
Consolidating:	Elevating of debris flow bed to support and/or prevent landslides and gliding/creeping slopes and lateral erosion. Bank Stabilisation
Retaining:	Storage and deposition of bedload transport or a debris flow until it's aggradation to the retention capacity.
Sorting & Sizing	Filtrations and/or storage of undesirable bedload components during bedload transport or a debris flow.
Bedload sizing:	Filtration and storage the large pieces of bedload during bedload transport or a debris flow.
Wood grading:	Filtration of undesirable wood during woody debris transport or a debris flow.
Breaking of debris flow:	Decrease the high energy level of a debris flow to a lower level under particular energy change.
Dosing:	Parting of a large mass of bedload transport or of a debris flow in small amounts. (Kettl 1984)
Bedload Dosing:	Quantitatively dosing and discharging of intermediate stored debris flow and bedload by declining floods and mean waters. (Ueblagger 1972)
Flood (Water) dosing	Quantitative change of the water discharge by qualitative change of the flood hydrograph at a specific site. (Kettl 1972)

The dosing of bedload disasters and debris flows depends on the water bedload ratio of debris flow and related disasters and their grading. Therefore needs the constructions of debris flow-dosing dams and of bedload-dosing dams a well founded planning and research and should the occasion arise model experiments

Water dosing dams allow us to control the medium of origin and transport of debris flow. Therefore the requirement is the existence of enough voluminous reservoirs in front of the erosion track. These types of construction are the quintessence of debris flow management, because by making the medium of transport and it's dosing to a harmless bulk the transport medium (debris flow and bedload) goes secondary importance.

Functions and their related Measures

The usual functional dam-types like sills, bed-sills, consolidation-, retention-dams and deposit-dams, which are defined also as bedload-strengthening structures as well as bedload storages structures (Leys 1973) will be exchanged of the discussion. These dams are no new development and the state of the art can be granted. Only some new types of functional dams will be discussed without demand for completeness (Fiebiger 1984).

DOSING-DAMS: the function (dosing) described previously can be filled only under following prerequisites. The bed-forming mean discharge must be able to flow through the dam as unhindered as possible.

During a flood the bedload mass must be reduced and an intermediate storage must be possible. Theoretically, the entire grain-distribution is handed over again by mean discharge and small floods into the lower course after temporary bedload storage and temporary deposition.

The main condition for this structure is the exist of enough storage capacity to store the difference between incoming flood and reduced outgoing discharge. This demand is the reason that flood doing-dams cannot be planned and constructed very often. The existing storage capacities are usually to small and are not able to store the necessary flood charge.

The desirable sorting effect will be only reached under the condition of enough storage capacity and enough amount of discharge for spilling after the disaster event, flood or debris flow or bedload disaster (Stauder 1972a, Stauder 1972b).

The large disastrous components of the bedload must be sedimented in the backwater of the storage basins root and the sorting-openings should not be locked by woody debris. The storage capacity of the sorting(sizing)-dam should be equal to the torrents disaster potency.

Woody Debris Rakes (Gratings, Grills, Filter): These dams have to fulfil the function of grading the woody debris out of the discharge The bedload transport should continue however preferably unhindered. In function-combined dams in torrents with a large amount of woody debris to prevent the locking of the opening a woody debris grill must be constructed to protect the function of the openings. As appears from the experience, inclined gratings and grills are preferred to the vertical beam-fields. Newer developments showed that crestfallen grills promote the rolling up of woody debris during the starting event.

Debris Flow Breakers: The desirable function, energy dissipation during a debris flow, can be reached on two ways. The first is to carry out a massive construction The second is the combination with a sorting-dam considering decreasing the impact-energy at the structure. The regular structure used for a debris flow breaker is the second way.

Combined Bi(Multi)functional dams: In accordance with the possibilities of the combination of functions bifunctional or multifunctional structures are developed. The most frequent types are the combination of consolidation & sizing-dam, consolidation & dosing-dam, sizing-dam with woody debris filter, sizing-dam & debris flow breaker. The constructions of bi(multi)functional dams are in future certainly increasing. The increase is promoted by high economic value.

Landslide Control in the Chain of Functions

Landslide control stands in the chain of functions of torrent control on the top of the systematic control together with afforestation reforestation and runoff control. On the other side there is landslide control for itself independent (Marui 1988) and not influenced by torrent or streams. Such landslide can influence torrents and torrential streams seriously. In Systematic landslide control (SLC) you have two principles, active and passive measures. The passive measures are mainly land-use planning keeping the endangered areas free of settlements and infrastructure to prevent economic damages. Active measures start at the landslide main scarp and are continued through the zone of depletion down to the toe at the end of the zone of accumulation. The measures cover various functions and their belonging structures. The functions are like in systematic torrent and/or avalanche control chained. That means that each part respectively each reach of the landslide can be dealt by a specific control function and therefore by a specific functional structure. Before starting the considerations an environmental analysis with the emphasis to geology and geomorphology and slope hydrology including runoff behaviour is essential. A combination of mechanical prevention and stabilization measures should be implemented after consideration of the mechanism and dimension of a landslide. A suitable combination of mechanical measures depends on the importance and value of protected objects. Mechanical measures can be classified into two categories, control and preventive. Control works stop or reduce the landslide movement by changing the natural conditions such as topography, distribution of groundwater etc.

Preventive works partially or completely stops landslides movement using structures. The first functional countermeasures to prevent the gliding of a landslide are afforestation and revegetation to fix the landslide and drainage the upsides above the main scarp and the displacing and displaced material to control, to check and to take away the transporting medium water from and out of the landslide. In the landslide neutral zone, between the depleting zone and the accumulating zone could be the best possibility to build up some structures to stop the landslide and to consolidate the flanks of the landslide to prevent bank erosion. The functional chain ends at the landslide toe with supporting walls to level down the energy line to stop the gliding mass and force its deposit. All these functional structures correspond with specific functions, the chain of functional landslide control measures.

The Chain of Functions carries out the sequence of functions to influence the energy balance of landslides and leads to the Chain of Functional Structures and the Systematic Landslide Control (SLC).

In principal, if the mass movement continues, preventive measures are not effective and installation is difficult. Control measures such as drainage and the removal of soil mass should be implemented beforehand. After the reduction of the landslides movement preventive measures and structures could start.

Experience with the chain of functions

In the last two decades of the past century in Austria systematic torrent control increased The countermeasures directly changed from protection to prevention, from object control to catchments management and watershed management.

The system of the chain of functions will be explained partially by the example of the Russbach watershed and its tributaries The catchment between 800 and 1800 m.a.s.l. in the district Hallein south of the city of Salzburg in the limestone prealps. The tributaries Randobach and Rinnbach damaged frequently the village of Russbach by debris flow and bedload disasters.

A master planning in systematic control starts always with an environmental analysis. The environment analysis documents the links between vegetation, forestry, geomorphology, anthropogeneous influences and the torrentiality of the catchment (figure 1). The case study shows areas with high runoff, landslides, soil creeping, debris input and bedload agglomeration. Depending on the environmental analysis necessary functions were derived. These functions are, to level down high runoff — afforestation, reforestation and runoff control and so one. To minimize or to stop landslides, soil creeping — landslide control, drainage, consolidation and revegetation by others are used. To control reaches of bedload agglomeration and development and debris input from slopes it is necessary to stabilize and to consolidate at least to control the banks.

The functions derived from the environmental analysis leads to functional structures and therefore to the chain of functions (Fiebiger 1992) (Figure 2). The case study Russbach explains for the tributary Randobach: flood dosing dam with integrated woody debris filter grill (bi-functional dam) — landslide control — debris flow breaker (energy dissipator) — bedload trap (sedimentation basin) with dosing facility. The second tributary Rinnbach shows another chain of function: reforestation — landslide control — sorting (sizing) dam — bedload dosing facility with two consolidation dams as inlet, two sedimentation basins with two dosing dams as outlet and a third dosing and consolidation dam (bi-functional dam) downstream.

The difference between these two chains of functions lays in the difference of the subcatchment geology. The bedrock of the eastern tributary Randobach are the "Gosau formation" with layers of marl and cretaceous shists. In contrary the western catchment is build up by dolomites of the Trias period.

The systematic control of the torrential watershed Russbach and its tributaries was very effective. In spite of some disastrous precipitations since the finish of the implementation of the master plan 1992 no torrential disaster damaged the village of Russbach.

The Functional Structures of Systematic Landslide Control

The links of the chain of functions in the systematic landslide control are drainage, retaining structures, piles, anchors, slope reformation and erosion prevention. Revegetation and Reforestation is the rehabilitation of the landslide surface after technical treatment. The vegetation cover prevents the production of unstable debris on hillsides and slopes. The drainage systems deal with surface drainage and subsurface and groundwater drainage.

Surface drainage (runoff control) will be done to prevent infiltration from rainfall, springs, ponds, channels and other surface waters. If the landslide movement is related to short-term rainfall surface water should

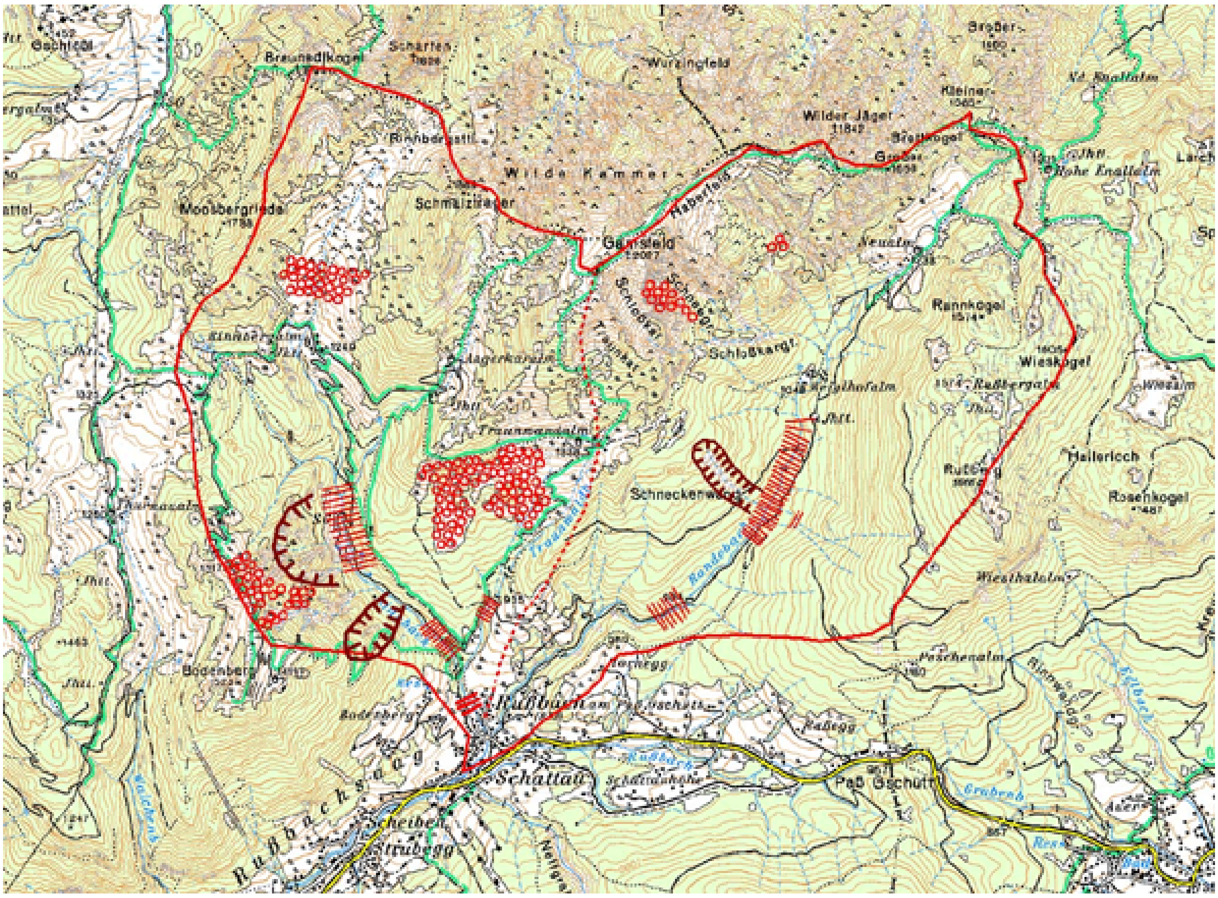

Figure 1: Necessary functions derived from the environment (hydrological and geomorphological) analysis.

	Environment Analysis	**Derived necessary functions**
	Area with high runoff	Afforestation, Reforestation, Runoff Control
	Landslide, soil creeping	Landslide control, Consolidation, Revegetation
	Reaches of bedload development and debris input from the slopes	Stabilization, Consolidation, Bank Control

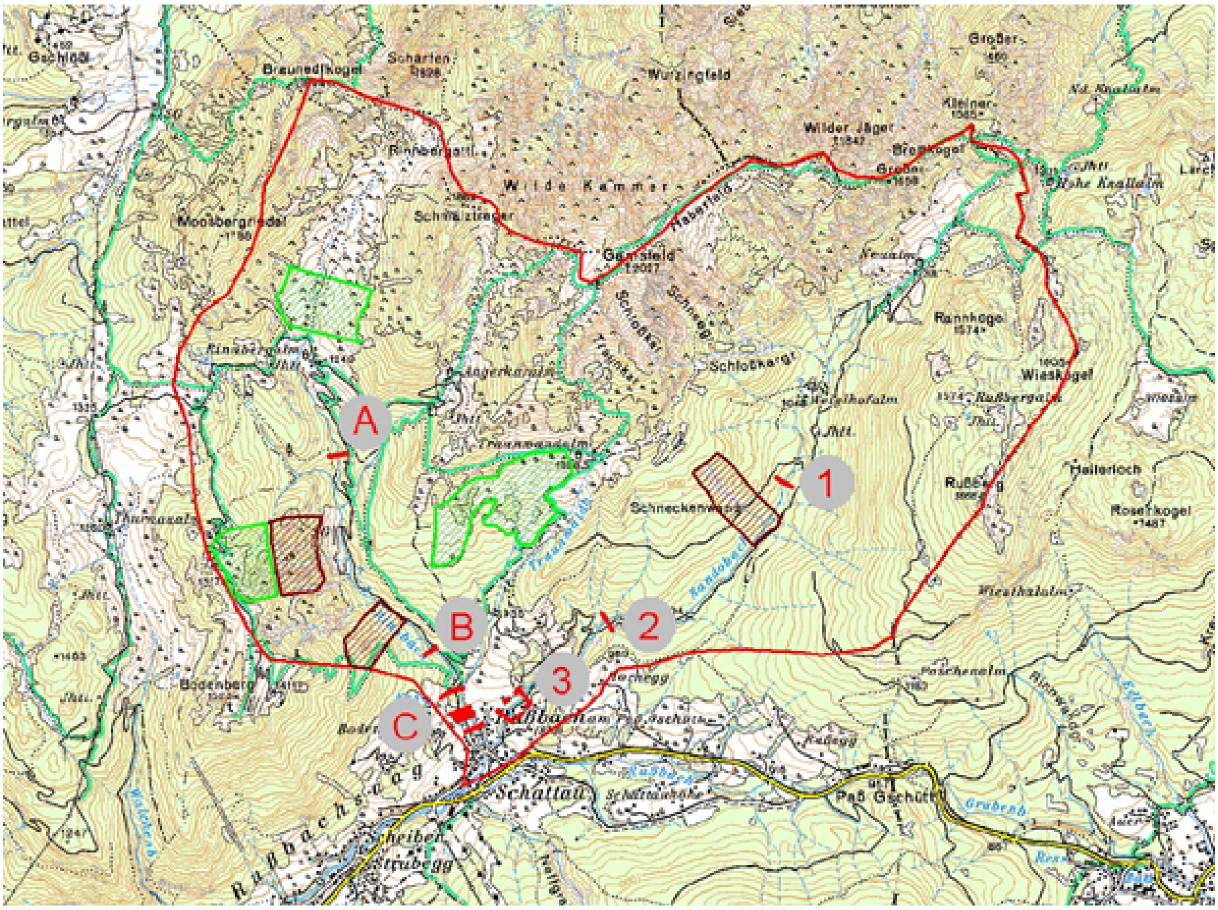

Figure 2: The chain of functional constructions derived from the environment analysis and the chain of functions. Reforestation, Landslide Control,
Randobach: 1 = Flood dosing dam with integrated woody debris filter grill, - 2 = Debris flow breaker, - 3 = Bedload trap with bedload dosing facility.
Rinnbach: A = Sorting (sizing) dam including an avalanche breaker, B = Sorting dam, C = bedload dosing facility: consolidation dam, 2 sedimentation basins with 2 dosing dams as outlet and a third dosing dam downstream.

be drained immediately. Also runoff control is necessary to guide the runoff out of crucial areas. Although the results cannot be calculated by slope stability analysis, this is generally effective as a countermeasure. Surface water drainage includes infiltration prevention and channelling.

Infiltration prevention knows two methods, filling of cracks and channel sealing. Many cracks and depressions are caused by landslide movements and surface water and runoff can easily infiltrate the sliding mass. Such openings should be filled with clay or cement or covered with vinyl cloth to prevent surface water infiltration. In many cases landslides are caused by infiltrated water from unsealed channels and ponds or from cracked ditches. Channel and pond bottoms should be sealed with impermeable material.

Channelling is installed to collect rainfall and storm runoff and divert it outside the landslide area To plan the channel net a detailed survey of the landslide area topography should be performed and a topographical map should be made. There are two types of channels, catchment and drainage channels.

The catchment channel is a type of a small channel which is attached to the drainage channel. It is wide and shallow and is made of asphalt, semi circle concrete or crockery pipes, etc. The drainage channel is installed to divert water outside the landslide area. This channel has a steep gradient. The discharge must be calculated Stabilizing sills should support the channel in the steep slope and at the end of the channel. The drainage channel is made from stone, concrete U-shaped pipes, crockery pipes etc.

Groundwater near the surface (subsurface) is drained by opening a vacant space to intercept and divert the water. We differentiate in shallow and deep groundwater drainage. Shallow groundwater drainage lies about 0.5–5.0 m below the surface and its velocity relatively slow. It drives from rainfall which is infiltrated near or at the concerned site. This type of groundwater usually causes a shallow landslide or the toe of a large-scale landslide. Deep groundwater drainage is closely related to long-term rainfall or snow melt and is able to cause extensive landslides. Deep groundwater generally has a relatively high velocity (up to 1000 m/day) and is distributed to aquifers. There are two types of deep groundwater, water flowing on the bedrock surface and water flowing along fracture zones or faults in the bedrock. In both cases are landslides large-scaled. The drainage will be done by Long Lateral Boring, Drainage Wells and Tunnel.

Retaining structures are established to directly resist the thrust of sliding soil mass. This method is used to prevent small-scale landslides. It may also be applied to part of a landslide which has only small thrust, or the base of an embankment structure. It is usually used combined with other methods, because it is difficult to control a landslide with only a retaining structure. The movement of the groundwater is active in landslide areas therefore flexible structures such as cribs, cages (steel, concrete) or gabions should be used. The design of these retaining structures has to done adequate to the standards. The items like, stability to fail, stability to glide, stability to slide, bearing capacity of the ground (bottom pressing), and last not least the safety of internal stress must be considered During construction it is necessary to take care on excavating. Excavations at the toe of a landslide area increase he danger of activating the landslide. Special attention should be paid also to install a drainage system behind the retaining structures.

Piles are installed to stabilize a landslide through resistance. There are inserted in sliding soil mass and fixed in bedrock. Usually steel piles approximately 300 mm in diameter are inserted through bore- hole in the sliding areas. When the landslide moves, the piles resist the sliding force through bending moment and/or shear resistance. The pile is generally defined as bending pile since its length is long compared to its diameter.

An anchor is implemented to prevent landslide through the tensile strength of reinforcing steel which anchors the sliding mass to the bedrock. One end of the reinforcing steel is fixed to the bedrock and the other end is fastened to a bearing plate on the ground surface. The reinforcing steel is tightened and prestressed through the bearing plate. Important considerations for this method are the bearing capacity of the soil mass under the bearing plate and the bond strength between anchor grout and rock at the fixation part. Circumference friction and hole spreading friction are the two types of anchor fixation.

Slope reformation is done by soil mass removal. The sliding force can be reduced by partial or entire removal of the sliding soil mass. This is one of the most widely used stabilization measure because its effects are reliable and immediate. ¡it is therefore suitable as an emergency measure. However this method is not applicable in the stabilization of a large-scale landslide due to the quantity of the soil mass involved. Topography is also able to restrict the use of this method. Soil mass removal is done only at the head of the sliding area. Never at the toe! The volume of soil mass to be removed is determined by trial slope stability analysis taking the objective safety factor (F = 1,2) into consideration. Vegetation cover and surface drainage should be established on the surface of the slope after soil mass removal. The soil mass removal at the head of the landslide is often combined with an embankment. The embankment will be installed at the toe of the landslide to balance the sliding force with the additional loading.

Erosion prevention leads to the more technical part in the chain of functions. In many cases landslides are caused by the lowering of torrent bed or lateral erosion by meandering. In such cases erosion control by structures is important. The construction used are stabilizing and consolidating constructions like sills, bars, ground sills, consolidation dams or other lateral constructions like revetments, dikes, embankments, groynes and spurs,

Revegetation is rehabilitation with vegetation cover. The expected functions of vegetation are, to reduce surface erosion by runoff, to strengthen the surface and subsurface soils by the root system and to improve the hydrological conditions of landslides areas. Prevention and stabilization by revegetation is an important part of an integrated measure package. The effectivness of vegetation measures will not be overestimated. Revegetation is not the only way to prevent the production of debris on a hillside or slope surface. Other engineering facilities are also possible, but in general more expensive. In contrary vegetation covering of slopes is cheaper and has sometimes the advantage that the rehabilitated slope could be further used for agriculture. Generally failure surfaces and bare slopes are unsuitable for vegetation growth and the after landslide small debris movement, like slips and creeping is frequent. That means there is only a small possibility for successful revegetation a landslide surface without supporting measures. Basic engineering work should primarily stabilize the landslide afterwards the revegetation and soil bioengineering work can go on successfully. This preparation work before revegetation is made up of grading, soil retention, wattling, stone masonry, burying, brushwood piling, log piling, and channelling and surface drainage. The revegetation will be done either by seeding or by planting. The various methods for seeding are, full surface seeding, mixed seeding, spaying (hydro seeding),vegetation matting, linear seeding, vegetation blocking and vegetation bagging The planting mainly is done with seedling, piling sods, seedling after simple terracing, cover to protect the vegetation planted under, straw and brushwood and vegetation nets.

Reforestation as landslide prevention measure is performed about the sliding area in order to reduce the supply of infiltrated water into the sliding area. It is recognized that the surface soil of forests has larger water storage capacity than that of forest grassland or bare land. In forests the storage capacity for rainfall is large since the water content of the forest soil layer is low due to the transpiration of trees. To perform reforestation successfully it is necessary to understand the local environmental conditions and to know the natural phytosociety and natural forest of the target area. Appropriate tree species and methods for reforestation should be selected after due consideration of the conditions of the target area. The most important point in reforestation is to select suitable deep rooting trees based on the state of the slopes and on the estimation of the future state of the forest Due to the poor growth conditions on failure surfaces it is difficult to produce a forest right away. Slopes should first be covered with plants which are able to bear severe conditions. Primary trees are required, to grow in barren land, to bear dry conditions, to grow fastly, to have a root system which grows deeply and fixes soil and to have high budding potency.

Revegetation and reforestation management must be continuing after implementation by maintenance if it should be successful. There are two phases of management and maintenance the first leads from immediately after planting to covering with the pioneer plants, the second after covering with the pioneer plants to the stabilization of the target vegetation respectively the plant society.

Conclusion

After generally discussing the chain of functions in systematic torrent control and debris flow control the links to landslide control are shown up. Landslide control stands in the chain of functions of torrent control on the top of the systematic control together with afforestation reforestation and runoff control. On the other side there is landslide control for itself independent and not influenced by torrent or streams. Such landslide can influence torrents and torrential streams seriously The links of the chain of functions in systematic landslide control are drainage, retaining structures, piles, anchors, slope reformation and erosion prevention. Revegetation and reforestation is the rehabilitation of the landslide surface after technical treatment. The vegetation cover prevents the production of unstable debris on hillsides and slopes. At least the chain of functions in landslide control and their related structures and treatment systems are specified.

References

Kettl W. (1972): Sorting-dams in the Pongau: theories and experience *WLV 37 1*, 15–23 (German)

Leys E. (1973): Suggestions for a systematic view to dams and longitudinal structures used in torrent-control. WLV 37; 2; 43–60

Stauder S. (1972a): Different constructions of beam-dams in: colloquium on torrent-dams Mitt. D. FBV Vienna volume 102: 335–372; Agrarian-publishing house Vienna 1973 (German)

Stauder S. (1972b): Beam-dams in the Ziller-valley WLV 36, 1; 1–45 (German)

Ueblagger G. (1972): Retaining, dosing and sorting. In: colloquium on torrent-dams.

Mitt. D. FBVA Vienna volume 102; 335–372; Agrarian-publishing house Vienna 1973 (German)

Fiebiger G. (1984): Functional structures of torrent control on the base of bedload management. Proceedings

INTERPRAEVENT 1984, Vol.1 pp. 123–134; Research Society for Flood Prevention INTERPRAEVENT; Villach 1984 (German)

Fiebiger G. (1988): Bedload management in torrent control by functional check dams. In: Contributions to the research in erosion, torrent and avalanches. Mitt. D. FBVA Vienna volume 159; 325–331; Agrarian-publishing house Vienna 1988 (German)

Fiebiger G. (1992): The planning procedure in Torrent Control under special regard of the development of the basic ideas of their Master Plans. International Symposion *INTERPRAEVENT* 1992, Vol.6 pp 377– 406; Research Society for Flood Prevention INTERPRAEVENT; Villach 1992 (also in German and Japanese)

Marui H. (1988): Landslide prevention measures. FAO watershed management field manual. FAO conservation guide 13/4. Food and Agriculture Organisation of the United Nations, Rome 1988