5 LANDSLIDES

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5.1 INTRODUCTION

Landslides, permanent movements or catastrophic events can be defined according to the types of phenomena as well as by their intensity and probability of occurrence. According to a generally admitted classification the generic term *Landslides* includes all gravity-induced movements of a soil or rock mass along a slope (WP/WLI 1990), which may be composed of five major mechanisms (1) *fall*, (2) *topple*, (3) *slide*, (4) *flow*, or (5) *spread*. Both first quoted mechanisms are already dealt with in the preceding chapter on rockfall, whereas spread is a peculiar phenomenon hardly related with slopes, but more to large scale settlement of underlying soft layers, for which no global resilient infrastructure can be imagined, except rigid structures for buildings. Therefore this chapter mainly deals with ***slides*** (translational, rotational, complex phenomena of various sizes — from 1 ha to several km^2) and with mud and debris *flows* which often extend over smaller areas than slides, but are more dangerous in terms of damage.

The first major characteristic to mention for these two types of phenomena is their non-repetitivity : unlike snow avalanches they induce either a slow permanent movement or a sudden violent displacement of soil masses with a variable percentage of water, but the conditions of such events will never be reproducible, so that, for their analysis, statistics is not an adequate tool and experiencs of past events is not always significant. However, a detailed observation of their characteristics and behaviour often allows a proper determination of the hazard they imply, by the adequate identification of warning signs and analysis of preparatory and triggering causes.

When focusing on the relation between the dangerous naturai phenomenon and the man-made structure to be protected (buildings, roads, lifelines), it is worth noting that in the case of debris flows the disnstcr resilient infrastructures have to be designed mainly in the *transition zone*, as no relevant action can be taken in the source area, except reforestation, and as the cost of structures resisting by themselves to the pressure of the flow is too high. In the case of slides, the notions of zone of origin, transition and impact are irrelevant, as most of the man-made structures are located on the moving mass itself; therefore either the planned infrastructures tend to block or slow down the sliding mass, which is the most frequent case (eg. by drainage, fill or anchors), or the structures themselves are designed so as to tolerate or impede movements of their basement (DUTI 1985). The foundations of bridge piles laid on bedrock can also be protected from the sliding mass above by a concrete shaft surrounding them and ensuring a sufficient gap to allow an independent movement.

5.2 MAIN FACTORS FOR LANDSLIDE RESILIENT INFRASTRUCTURE

As far as *slides* are concerned, four main factors condition the feasibility of stabilization projects. First the *depth* of the active sliding mass imposes limits to any type of resilient infrastructure arid is one of the major criteria to select the appropriate system (for instance length of anchors, depth of drainage boreholes or trenches, etc.). Thus many landslide zones in Switzerland as well as in the world cannot be stabilized due to the large depth of the sliding niass, exceeding *100* m.

Then the *velocity* of the slide, considering mainly its average permanent movement, determines the possibility of application of some construction techniques, specially when the major displacements are concentrated at a unique slip surface. For example, vertical drainage boreholes are only applicable when the movement is slow enough (approx. 1 cm/year) to allow a stabilizing effect to occur before they are sheared.

A third important point is the occurrence of *differential movements* in some lateral zones of a slide or at the limits of a secondary slip surface which induce unhomogeneous conditions in terms of depth, velocity, movement pattern, so that the buildings and lifelines in these zones can be severely affected. These first three factors are somehow related to the general notion of intensity in a hazard analysis.

The last factor rather deals with the concept of probability which has to be also considered in a hazard and risk analysis. It includes the *potential* for progressive or ***sudden** accelerations* which often cause distress to supposedly resilient infrastructure. Such accelerations depend mainly on the variations of climatic conditions, either at a short-term scale (high intensity rainfall during some days to some months) or at a long-term scale (periods of several wet years, global climate change). The effects of an increase of precipitations can be either direct, raising the groundwater level and inducing higher driving forces in the sliding mass, or indirect, for example through more significant erosion rate at the toe of the slide. Such a relation is quite often complex and needs long-term monitoring to assess this parameter.

As far as *debris flows* are concerned, the last factor mentioned above is certainly prevailing, as high intensity *storms* are the main cause of disaster. In this case the major difficulty lies in the determination of local precipitation distribution as intense rainfall occurring on a limited drainage area may not be recorded at the nearby raingauge station.

A second factor for assessing the intensity of the event is the *slope* of the stream in which it occurs, as it will directly condition the velocity of the debris flow, and thus the potential for increasing the sediment mass by erosion.

A final factor is the availability of *loose materials* in the upper part of the drainage area either at the surface and liable to direct erosion, or along the torrent channel which may be mobilized by local lateral slides, inducing the phenomenon of retention and consecutive violent outflow.

5.3 SLIDE RESILIENT INFRASTRUCTURE

In order to reduce or to stop permanently the movements of slides and thus limit their disasterous impact, foiir main classes of remedial measures can be used. Indeed they also apply to the stabilisation of rockfall source zones. This presentation corresponds to an internationally approved list (WP/WLI 1990, Popescu 1996).

5.3.1 Modification of slope geometry

As the driving and resisting forces within a sliding mass are mainly related to the geometrical Characteristics of the slope, the basic way to reach a definitive and sure stabilisation of a slide, provided it is of fairly limited dimensions, can include the following earthworks :

- Removal of material from the upper area, with a possible substitution by lightweight fill.
- Construction of a buttress berm or fill at the toe (Sève and Pouget 1998).
- Reduction of the general slope angle and trimming of loose surface material.

However these earthworks often require a lot of surrounding space to organize construction activities and affect a large part if not the whole surface of the unstable zone, so that in many cases it is not econoinically and socially applicable.

5.3.2 Retaining structures

A similar action, but inducing a localized increase of resisting forces by the application of structural means, at the surface or at shallow depth, can include the following types of retaining structures :

- Gravity retaining walls and reinforced concrete walls.
- Crib block walls, which are more flexible than retaining walls.
- Gabion walls, also useful against toe erosion (Federico 1985).
- Passive piles and caissons, sheet piles.
- Reinforced earth retaining structures (with strip/sheet polymer/metallic elements).
- Buttressed counterforts of coarse-grained material, providing an increase of shear resistance (Sève and Pouget 1998).

Several quoted solutions combine also the advantages provided by drainage action and the reliability offered by mass movements. However their action at shallow depth may impede providing a reliable protection against deeper instability phenomena that can be induced by long-term erosion at the toe of the slide.

5.3.3 Internal slope reinforcement

A series of improvements in drilling and grouting techniques as well as in the design of soil/rock inclusions have allowed an impressive development of stabilization means by internal reinforcement, leading to applications even at large depth and insuring long-term stability. The main advantage of most of the following techniques consists in applying effective resisting forces at the level of the slip surface :

- Rock bolts and soil nailing.
- Anchors (prestressed or not).
- Micro-piles and anchored piles (see Fig.5.1) (Wichter and Meiniger 1985).
- Grouting and jetting.

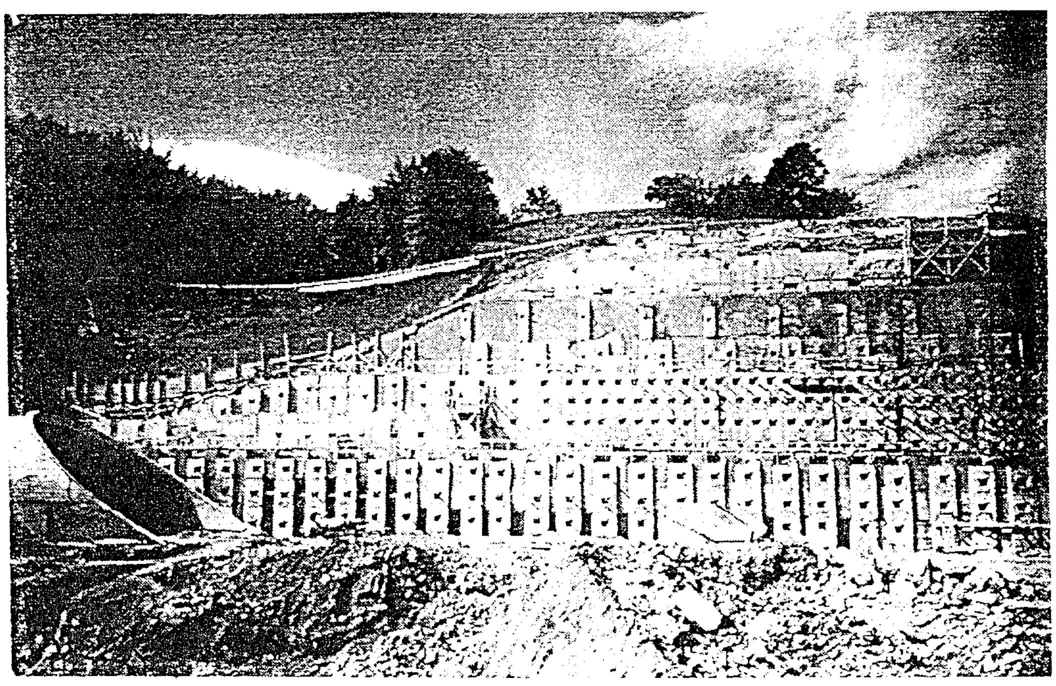

Fig.5.1 La Criblette landslide stabilized **by** prestressed anchors along A9 motorway near Lausanne.

In the same category of stabilization means it is possible to add heat treatment and elecírosmosis as well as freezing, although their applicability is really reduced to very specific situations. Finally much has been said about biotechnical slope stabilization, which induces an internal reinforcement at very shallow depth through man-made wooden structures and the roots of some specific plants. But although it appears a sustainable means, its long-term effect **is** often not guaranteed as the vegetation may decay due to drought and **as** deeper slip surfaces may cause the destruction of such structures.

5.3.4 Drainage

Finally, giving due consideration to the fact that *groundwater* is the main destabilizing factor of unstable slopes, the different types of drainage, superficial or underground, constitute one of the most efficient means to control or at least reduce slide movements, especially for large landslides. Several systems have been developed and applied in various sites of Switzerland (as well as in the world), in a whole range of situations, implying sliding volumes from some thousands of m^3 to 1 billion m^3. The main drainage systems include :

- *Surface drains* to divert run-off water from flowing onto the slide area, by collecting ditches or by wooden, mortar or steel channels.
- Shallow or deep *trench drains* (max. depth 15 m) with pipes, filled with free-draining geomateriaís, i.e. coarse granular fills protected by geosynthetics (Cancelli 1985).
- *Buttress counterforts*, localized trenches, masks or gabion structures providing a draining and a mechanical effect.
- Vertical small diameter *boreholes* with pumping or vacuum dewatering, siphoning or self draining into a gallery or an underlying pervious rock layer (Noverraz and Bonnard 1993).
- Vertical large diameter *wells* filled with coarse material, with gravity draining at the toe by a horizontal borehole or a gallery.
- *Subhorizontal boreholes* from the surface or from a shaft.
- *Drainage tunnels*, galleries or adits.

Additionally vegetative planting which induces a higher evapotranspiration can also be considered as a drainage means.

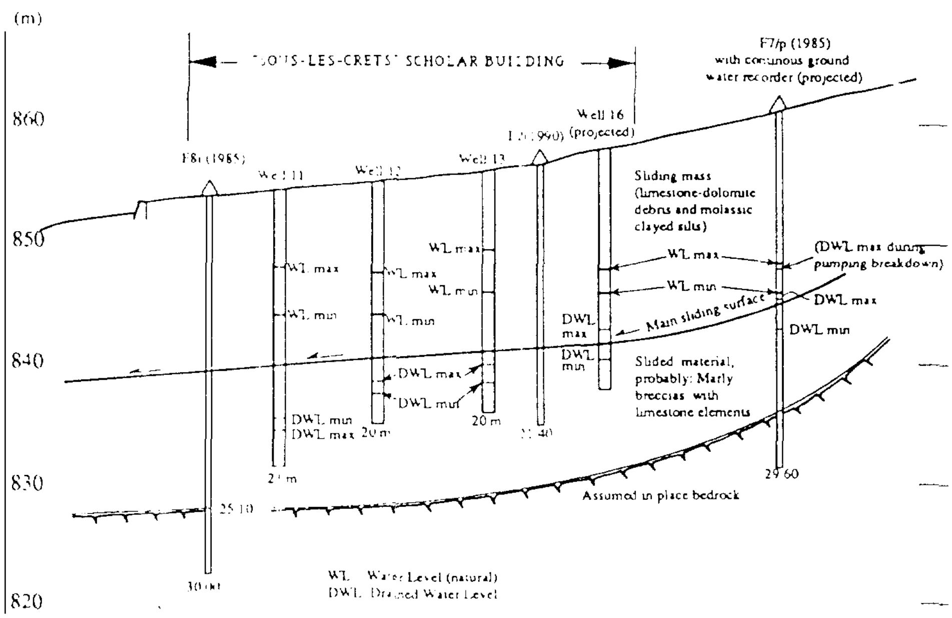

Fig.5.2 Cross-section of St-Imier landslide **with** location **of** investigation boreholes and drainage wells.

Two major problems arise however in the use of drainage. First the future *efficiency* of a drainage system of any kind is difficult to predict, as the localized effect of drainage works will not fully extend to the whole slip surface and thus only increase locally the resisting forces (Sève & Pouget, 1998). Then the actual groundwater conditions are difficult to assess and can be modified substantially by extreme climatic conditions. Drainage works need also regular monitoring and maintenance works in order to check that their long-term operational capability corresponds to the original design. Despite of these limitations inducing often a partial stabilization, ***drainage works*** often appear as the most adequate **and economical** counter-measure to insure the safety of structures and lifelines located on *a* slide (Fig.5.2) (Noverraz and Bonnard 1993, Gabus et al. 1988).

Some major drainage works have been carried out these last 20 years in Switzerland in order to provide a complete or improved stabilization of large landslides. Although being certainly not exhaustive, a list of some interesting cases (including only drainage works) may be given :

- Arveyes Landslide (canton of Vaud) where 16 deep boreholes equipped with pumps reduced to 1 mm/year the velocity of a $25 \cdot 10^6$ m^3 slide (1983-1986) (Gabus et al. 1988).
- La Frasse Landslide (canton of Vaud) where 28 boreholes equipped with pumps tried to reduce the velocity of the lower part of a $60 \cdot 10^6$ m^3 slide; but several were rapidly sheared (1995). Surface drainage channels had also been carried out (Noverraz et al. 1998).
- Ballaigues Landslide (canton of Vaud) where hundreds of vertical boreholes (spacing at 2 m) discharge drained water in the underlying pervious rock 40 m below the surface and significantly reduced the movements of a slide (1983-84) (Noverraz et al. 1998).
- St-Imier Landslide (canton of Berne) where 16 boreholes equipped with pumps limited the velocity (to 5 mm/year) of a slide on which **a** college was built (1981), despite of some very wet years (Noverraz and Bonnard 1993).
- Braunwald Landslide (canton of Glarus) where a drainage trench carried out by a diaphragm wall equipment was built with a jacked tunnei beiow it, in order to protect **a** hotel at the edge of a very large slide zone (1983).
- Campo Vallemaggia slide (canton of Ticino) where a 2 km long gallery with radial boreholes below a huge landslide ($1 \cdot 10^9$ m^3) was built in order to control the movements which showed sometimes high accelerations (1996) (Noverraz et al. 1998).

5.4 DEBRIS FLOW RESILIENT INFRASTRUCTURE

The high energy developed by debris and mud flows (showing velocities in excess of 10 m/s) and the Iarge volume of transported material (reaching sometimes 50000 m3) impedes most of the time the safe design of containment structures with concrete walls or earthfill dams (an interesting exception may be quoted at Les Crétaux Landslide (canton of Wallis) where two reservoirs were operated alternately and then emptied to store frequent small debris flows). Therefore four main classes of remedial measures can be used to control these events before they hit structures or lifelines which are essentially not able to resist to such thrust.

5.4.1 Escalonated river protection scheme

The first possible action is to build a series of concrete or wooden **dams** of limited height, in the stream beds with a debris flow potential, so as *to* reduce the flow velocity, impede regressive erosion and retain a part of the debris flow mass before it reaches the lower alluvial **fan where** structures have to be protected. *Check dams* have been carried out quite often in Alpine regions for more than a century, providing even a partial stabilization of a whole slide slope at the Swiss largest landslide at Heinzenberg/GR (Noverraz et al., 1998).

5.4.2 Lateral protection dams and dikes

The second possible action irequently carried out consists in the construction of lateral dams or ***dikes*** along the stream bed in the expansion zone (alluvial fan), so as to avoid that the debris flow may overtop the natural banks and destroy nearby structures. Debris flow mass control is then often shifted downward, for instance into the riverbed where the stream merges with the main river, but such situations may be solved by an adequate junction angle allowing the river flow to erode the deposited material. This type of work is frequent in the Swiss Alps.

5.4.3 Emergency spillway structure

When the capacity of the stream bed or artificial channel near the impact zone may be exceeded in case of very important debris flow, it is possible to foresee a concrete emergency ***spillway*** structure that will divert a part of the debris flow towards a safe zone where no major damage is liable to occur. Such work has been constructed at the Pissot stream bed (canton of Vaud), downstream of a first retaining structure of limited capacity and before the channelized stream passes above **A9** motorway.

5.4.4 Structure separating bed load from water (Japanese trap)

The last control system of debris flows consists in a large open reinforced concrete structure built below the riverbed and covered by a *steel ruck* with large spacings between the bars. This type of sieve allows the draining of the debris flow mass, as the water will fall into the structure and be evacuated downstream in the stream bed, whereas the large size bed load rolling on the subhorizontal gate will loose their transport means, i.e. the muddy water, and thus stop on the gate or just downstream. Such type of work developed in Japan has been built on the Dorfbach near Randa (canton of Wallis) and has proved quite successful.

5.5 GUIDELINES TO IMPROVE THE SAFETY OF DISASTER RESILIENT INFRASTRUCTURE

Despite of the development of new stabilization techniques and the improvement of landslide modelling, the long-term reliability of disaster resilient infrastructure tends to decrease with time, due to maintenance problems, whereas the safety requirement and induced risks increase, following the construction of more and more buildings and lifelines in exposed zones. Therefore any type of slope stability improvement works has to be completed by a comprehensive *monitoring system* allowing for early detection of a critical behaviour, based on adequate warning signals. But until the alarm criteria corresponding to such systems are duly established and tested, which may take time, it is necessary to complement resilient infrastructure with *passive management measures* relying on limited use of endangered land, whatever are the economic pressures towards its development.

The major *research needs* deal with the relation between drainage efficiency and the hydrogeological conditions, especially their evolution with time during crisis events, for which continuous pore water pressure monitoring is one of the most important information. The role of unsaturated layers in the slope stabilization represents also a major research challenge *to* master the long term behaviour of landslides. **All** the monitoring data should provide a basis for an adequate risk analysis in which direct and indirect economical factors as well as *safety criteria* can be duly included, which will certainly lead to the necessity of more landslide resilient infrastructure.

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