The SafeLand Compendium of Landslide Risk Mitigation Measures

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Abstract

A compendium of structural and non-structural mitigation measures for different landslide types has been developed as part of the EC sponsored SafeLand project, to be used both as a basis for a web-based "toolbox" also developed as part of the project and more generally as a resource for a wide variety of users. Emphasis has been placed on providing a rational framework applicable to all the measures listed in the compendium, classifying them in relation to the terms of the "risk equation" (hazard, vulnerability, elements at risk) addressed by the specific mitigation measure. Hazard mitigation measures are subdivided in relation to the physical processes involved. The compendium is supplemented by fact sheets that provide specific guidance on hazard mitigation measures, including a brief description, guidance on design, schematic details, practical examples and references, as well as subjective (provisional) ratings of their applicability in relation to the descriptors used for classifying landslides. More details of the various mitigation measures considered may be found in Deliverable 5.1 of the SafeLand project.

Keywords

Mitigation • Stabilization • Control • Avoidance • Tolerance

Introduction

SafeLand is a large-scale integrating collaborative research project funded by the Seventh Framework Programme for research and technological development (FP7) of the European Commission. Thematically the project belongs to Cooperation Theme 6 Environment (including climate change), Sub-Activity 6.1.3 Natural Hazards. The project team composed of 27 institutions from 13 European countries is coordinated by Norwegian Geotechnical Institute (NGI).

SafeLand will develop generic quantitative risk assessment procedures as well as tools and strategies for landslides management at local, regional, European and societal scales.

Within the general framework of the Project, the objectives of Work Package 5.1 are to provide:

- A Compendium of tested and innovative structural and non-structural (including risk-transfer) mitigation measures for different landslide types (Deliverable 5.1);
- A web-based "toolbox" of risk mitigation strategies and guidelines for choosing the most appropriate risk management strategy, based on technology, experience and expert judgment in Europe and abroad (Deliverable 5.2).

Besides feeding into the web-based toolbox, the Compendium is intended also as a stand-alone resource providing technical guidance on mitigation measures to a wide variety of end users. It has been compiled by the author and colleagues at Studio Geotecnico Italiano, with contributions from ICG of Norway, also responsible for quality assurance, AMRA and the University of Salerno from Italy, Aristotle's University of Thessaloniki, Greece, Zurich Technical University and the University of Lausanne, Switzerland and the Geological Institutes of Slovenia and Romania.

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It is currently under validation and will be made available in 2012.

Continuous technological progress and innovation make it impossible to provide an exhaustive and detailed list of mitigation measures. Each of the techniques or approaches described in the compendium could have many variations, reflecting differences resulting for example from specific conditions which vary form place to place; technological development; commercial interests to differentiate products to overcome patents and copyright; different or changing legislation. Apparent variations may result also from the use of different terminology to describe substantially the same measure.

While every effort has been made to provide a comprehensive and balanced compendium, inevitably readers will note omissions and, possibly, apparent repetition.

In drafting the compendium, particular emphasis has been placed on providing a rational framework applicable to all the measures listed in the compendium and to any other specific measure that may be developed in the future. In the context of the SafeLand Project and in light of the general consensus on a risk based approach to landslide management, the classification of mitigation measures has been related to the term of the "risk equation" which is specifically addressed by each mitigation measure.

Classification of Mitigation Measures

It is widely accepted and is the backbone of the SafeLand Project that the management of landslides and engineered slopes involve some form of risk assessment and risk management (Ambrozic et al. 2009).

Figure 1 summarizes the framework for landslide risk management; it is widely used internationally and has been adopted as the reference framework in the "Guidelines for landslide susceptibility, hazard and risk zoning for land use planning" published by Fell et al. (2008).

The evaluation, implementation and control of mitigation measures fall within this framework and in fact complete and complement the risk analysis and risk assessment stages of the process. It is therefore useful to relate the classification of mitigation measures to the same principles and criteria used in the rest of the process, using the internationally accepted definitions (Fell et al. 2008), which have also been adopted for the SafeLand Project and are repeated here for the avoidance of doubt: *Hazard* (H_i); *Vulnerability* (V_i) and *Elements at risk (E)* and *Total Risk* (R_{ti}).

The Total Risk R_{ti} due to a particular (ith) phenomenon within a specified period of time and within a given area can be expressed as:

$$R_{ti} = (E) \cdot (H_i \cdot V_i)$$

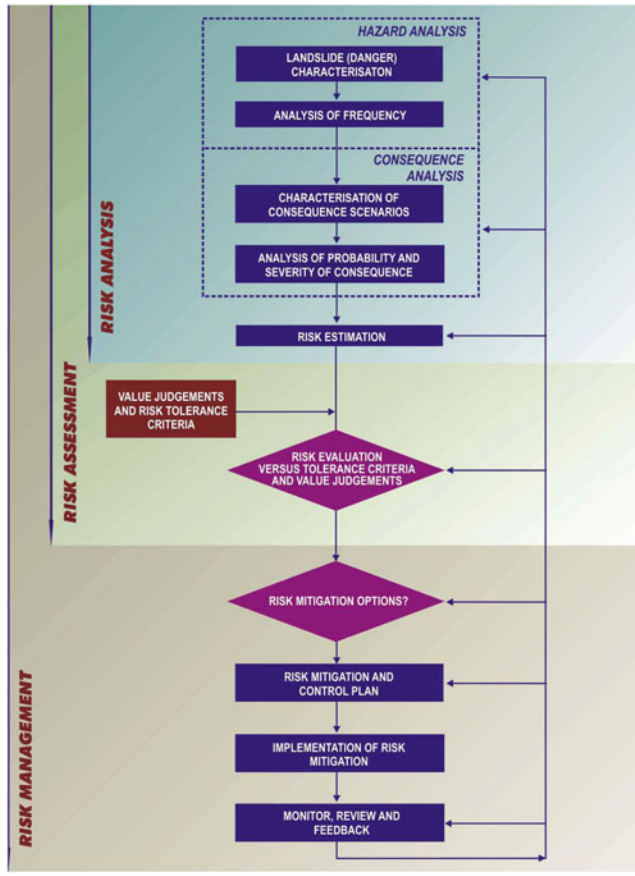


Fig. 1 Framework for landslide risk management (After Fell et al. 2008)

The Total Risk R_t from all (N) possible landslide phenomena within a specified period of time and within a given area is the sum of the risk posed by all the specific (ith) phenomena that impinge on the area of interest, subject to considerations of conditional probabilities of occurrence and to "domino chains", i.e. the progressive triggering of distinct phenomena in a linked sequence of cause and effect (e.g. large landslide → natural dam → overtopping → debris flow etc.).

$$R_t = \sum_{i=0}^{N} (E_i) \cdot (H_i \cdot V_i)$$

It is evident that the Total Risk can be mitigated by reducing (see for example Canuti and Casagli 1994):

- The Hazard (i.e. the probability of occurrence of one or more phenomena);
- The Vulnerability (i.e. the the degree of loss to the elements at risk for a given hazard);
- The Elements at risk (i.e. their number and/or specific value).

This represents a useful basis for classifying mitigation measures, because it provides a direct link with quantitative risk assessment and it highlights where the benefits of the mitigation measure being considered are accrued.

Other classifications of mitigation measures have been proposed, based on similar concepts but expressed in different terms. For example, Evangelista et al. (2008) distinguish between:

- *Stabilization*: measures which increase the "margin of safety" of the slope or that intercept the run out (structural measures);
- *Restrictions on the use of the element at risk*: permanently or temporarily;
- *Restrictions on land usage:* through land-use planning tools, to limit the presence of elements at risk in the area threatened by the landslide (non-structural measures);
- *Actions by the Civil Protection authorities:* which allow to remove from the area threatened by the landslide within a suitably short reaction time most valuable elements at risk, including as a minimum human life (emergency plans).

Similarly, Ambrozic et al. (2009) identify the following possible strategies for risk management:

- *Avoidance*: can be implemented at the land-use planning stage for proposed development and/or to relocate existing facilities, if possible;
- *Tolerance:* can be implemented if the risk level is deemed to be sufficiently low such that direct or indirect costs associated with other strategies cannot be warranted. Possible actions include "do nothing" or risk reallocation through private insurance or public intervention such as declaration of a "state of emergency" and the awarding of special funding and compensation to victims;
- *Monitoring/warning*: can be implemented when landslide hazards affect large territories or when dealing with massive potential landslides. It provides additional information to enhance risk assessment and allows the implementation of warning systems for the temporary evacuation of the population at risk;
- *Stabilization*: requires the implementation of engineering works to reduce the probability of occurrence of landslides;
- *Control works*: requires the implementation of engineering works to protect/reinforce/isolate the elements at risk from the influence of landsliding.

Ambrozic et al. (2009) also refer more generally to:

- Measures to reduce the hazard (through reducing the probability of triggering through stabilization and/or by reducing subsequent ground movement through barriers or containment);
- Measures to reduce the vulnerability (i.e. reducing the consequences of failure).

This last statement exemplifies some of the difficulties that arise in classifying mitigation measures. In particular:

- Although it may be justified in some respects to classify barriers and containment as hazard reducing measures, in the context of area wide risk management they might be better classified as measures to reduce the exposure of the elements they protect;
- Avoidance may be as effective at reducing the consequences of failure as reductions in vulnerability, so inferring an exclusive association between reducing vulnerability and reducing the consequences of failure can be misleading.

Some of these difficulties derive from the definition of "vulnerability", which Ambrozic et al. (2009) extend to include not only the damage functions with respect to ground movement (vulnerability s.s.), but also the number of the vulnerable elements potentially affected by a landslide and the probability that they will intersect the landslide ground movement.

Warning/alarm systems associated with plans for emergency evacuation or safe sheltering are often classified as measures to reduce vulnerability. However, keeping to the distinct definitions of "vulnerability" and "elements at risk", these systems are best classified as measures to reduce (temporarily and selectively) the elements at risk, rather than their vulnerability.

Other somehow related, widely used, classifications of stabilization measures include distinctions between:

- "Active" and "passive" stabilization measures (Picarelli and Urcioli 2006; Evangelista et al. 2008), in relation to whether the mitigation measures "actively" pursue an improvement s.s. of the stability of slope, or they "passively" intercept the run out when movement actually occurs, protecting the elements at risk.
- "Hard" and "soft" stabilization measures (Parry et al. 2003a, b), where "hard" is normally used to describe structural techniques that are visually obvious, while "soft" is normally used to describe techniques that are visually less intrusive and which improve the strength or other properties of the ground, such as its drainage capability. The terms "hard" and "soft" can also be used in relation to the relative stiffness of the stabilization works and the surrounding soil, which results in the overall behaviour of the stabilized slope being modelled as an equivalent continuum or as distinct materials. "Hard" and "soft" can also be used in direct analogy with the terms "structural" and "non structural", with the same meaning of hardware and software, depending on whether the mitigation measure addresses tangible, material or intangible, "immaterial" aspects of the risk.

- “Preventive” and “remedial” stabilization measures (Parry et al. 2003a, b), relating to their relevance to different stages of movement (see Leroueil 2001).

Criteria for Selection

The selection of the most appropriate mitigation measures to be adopted in specific situations must take into account the following aspects:

- Factors which determine the hazard, in terms of the type, rate, depth and the probability of occurrence of the movement or landslide, such as, for example the physical characteristics of the geosystem which can determine the occurrence of movement or landslides, including:
  - The stratigraphy and the mechanical characteristics of the materials,
  - The hydrological (surface water) and the hydrogeological (groundwater) regime,
  - The morphology of the area, and
  - The actual or potential causative processes affecting the geosystem;
- Factors which affect the nature and quantification of risk for a given hazard, such as the presence and vulnerability of elements at risk, both in the potentially unstable area and in areas which may be affected by the run-out;
- Factors which affect the actual feasibility of specific mitigation measures, such as:
  - The phase and rate of movement at the time of implementation,
  - The morphology of the area in relation to accessibility and safety of workers and the public,
  - Environmental constraints, such as the impact on the archaeological, historical and visual/landscape value of the locale,
  - Pre-existing structures and infrastructure that may be affected, directly or indirectly, and
  - Capital and operating cost, including maintenance.

Measures to Reduce Hazard

Mitigation measures which aim to reduce the hazard must reduce the probability of triggering of the landslide(s) which the specific measure is intended to address. Since triggering is caused by a decrease in shear strength $\Sigma\tau_r$ and/or an increase in driving shear stress $\Sigma\tau_d$, mitigation measures which aim to reduce the hazard of landslides occurring must act in the system in the opposite direction, by increasing the resisting forces; and/or decreasing the driving forces.

Whilst it is clearly recognized that landslides are almost always the result of a combination of processes, in the Compendium hazard mitigation measures are subdivided in relation to the physical processes involved, as summarized in Table 1.

Each class of hazard mitigation measures is briefly described and discussed in the main text of the Compendium and in greater detail in fact sheets attached thereto. Each fact sheet includes a brief description, guidance on design, schematic details, practical examples and references, as well as subjective (provisional) ratings of the applicability of the specific mitigation described in relation to the descriptors used for classifying landslides. Figure 2 shows sample pages from a typical fact sheet.

The Compendium also includes a review of triggering and hazard mitigation measures investigated by physical models, including interaction of a row of piles with an unstable soil layer, reinforced soil retaining wall under dynamic loading, reinforeced soil structures, rainfall induced landslides, thawing of ice in rock joints and rock anchors, stabilisation effects of plant roots, soil nailing and monitoring the integrity of ground anchorages.

Measures to Reduce Vulnerability

Mitigation measures which aim to reduce vulnerability consist of “passive” solutions which are not intended to prevent the triggering of the landslide but to reduce the resulting degree of loss. The measures described in the Compendium can be subdivided in two main categories, as detailed in Table 2.

Measures to Reduce the Elements at Risk

Mitigation measures which aim to reduce the elements at risk are particularly cost effective, especially when the number of elements at risk is small in relation to the extent of the landslide. The measures described in the Compendium can be subdivided in two main categories, as detailed in Table 3. A fact sheets on mitigation through reduction of exposed population through early warning systems is included in the Compendium. Further details can be found in the relevant deliverables of the SafeLand project on this subject.

Measures to Share Residual Risk

Among the possible strategies to manage landslide risk, techniques can be identified to increase the tolerance towards the residual risk that typically characterizes real situations even after implementing all other (technically and economically) possible mitigation measures.

Table 1 Hazard mitigation measures (Adapted from Popescu and Sasahara 2009)

Physical process	Brief description of mitigation
Surface protection; erosion control	Vegetation (hydroseeding, turfing, trees/bushes)
	Fascines/brush
	Geosynthetics
	Substitution; drainage blanket
	Beach replenishment; rip-rap
	Dentition
Modifying the geometry and/or mass distribution	Removal of material from the area driving the landslide (with possible substitution by lightweight fill)
	Addition of material to the area maintaining stability, with or without gravity, catilever, crib/cellular and/or reinforced soil walls
	Reduction of the general slope angle
	Scaling (removal of loose/unstable blocks/boulders)
Modifying surface water regime, surface drainage	Diversion channels
	Check dams
	Surface drains (ditches, piping) to divert flows from the slide area
	Sealing tension cracks
	Impermeabilization
	Vegetation
Modifying groundwater regime, deep drainage	Shallow or deep trenches with free-draining geomaterials and geosynthetics
	Subhorizontal drains
	Wells and caissons (with or without secondary subhorizontal drains); self draining or drained by siphoning pumps or base conductors
	Drainage tunnels, galleries, adits, with or without secondary drains
Modifying the mechanical characteristics of the unstable mass	Substitution
	Compaction
	Deep mixing with lime and/or cement
	Permeation or pressure grouting with cementitiuous or chemical binders
	Jet grouting
	Modification of the groundwater chemistry
Transfer of loads to more competent strata	Shear keys: counterforts, piles; barrettes (diaphragm walls); caissons
	Anchors: soil nails; dowels, rock bolts; multistrand anchors (with or without facing consisting of plates, nets, reinforced shotcrete)
	Anchored walls (combination of anchors and shear keys)
Retaining structures are an additional class of hazard mitigation measures, even though they do not address a specific physical process	

Of particular interest are risk sharing arrangements, which can be either voluntary or enforced. The two main mechanisms for this are:

(a) Voluntary or compulsory insurance;
(b) Compulsory systems based on taxes and public intervention in case of need.

The role and mechanism of insurance (private or public) is of particular interest and is discussed in detail in the Compendium, together with an overview of the natural hazard insurance system in Switzerland.

Reference in the Compendium to insurance and reinsurance companies can be taken to refer equally to private and public institutions, depending on local practice. Where Public Authorities replace private insurance companies, they face the same issues and have the same overall objective of loss reduction and efficiency.

Select National Experience

The Compendium includes an Annex which details National experience with landslide risk management in Romania, Slovenia and Switzerland.

The contribution on experience in *Romania* includes a general discussion on the national policy and practice in disaster management, risk assessment and systems for post-disaster impact assessment, which provides the backdrop for the presentation of national practice on landslide hazard mitigation.

The contribution on experience in *Slovenia* focuses on landslide hazard mapping, databases and the use of neural networks as tools underlying current practice in landslide risk management in the country.

MITIGATION THROUGH REDUCTION OF HAZARD

6 TRANSFER OF LOADS TO MORE COMPETENT STRATA

6.2 PILES

Description

Piles can be placed in earth and debris slopes, either at regular 2D spacing over the whole slide or portion thereof, to act as isolated dowels, or, more commonly, at close spacing along one or more specific alignments to form piled walls across the direction of movement (Ito et al., 1982; Hassiotis and Chameau, 1984; Soric and Kleiner, 1986; Popescu, 1991; Reese et al., 1992; Polysou et al., 1998; Poulos, 1999) - Figure 1.

Typically, large diameter bored cast-in-situ piles are used, with diameter 800 to 2000 (most frequently 1200) mm and spacing 1.2 to 2 times the pile diameter. The advantages of this technique may be summarized as follows:

- applicable in a variety of topographical conditions, subject to access constraints;
- casings limit hole instability during construction and damage to green concrete in piles formed in moving slides;
- conventional equipment may overcome thin layers of rock.

Where access is difficult and/or the depth of sliding is modest, micropiles (200 to 300 mm diameter) are also used, normally reinforced by steel pipes to maximize bending and shear resistance of the micropiles.

Pile heads are usually completed by a capping beam to allow:

- redistribution of horizontal loads between piles;
- the installation of anchors, where required to improve the resistance of the wall;
- the installation of sub-horizontal drains, where required to reduce the thrust on the wall.

Examples of applications are provided by Wilson (1970), Palladino and Peck (1972), Nethero (1982), Oackland and Chameau (1984), Isenhower et al. (1989), Rollins and Rollins (1992), Reese et al. (1992), Leoni and Manassero (2003).

Design

The design load on the pile wall may be determined in 2D limit equilibrium analyses by calculating the reaction on the vertical section corresponding to the piled wall which is necessary to guarantee, with the appropriate factor of safety, the stability of the portion of the slide located upslope of the wall in the absence of the downslope portion; in any case, the load on the wall cannot exceed passive soil pressure.

The contribution of the downslope portion can be considered only if this portion remains stable with an appropriate factor of safety once the driving force from the upper portion is removed; even in this case, it may be prudent to consider this mass only as confinement for the stable soil below, since even very small deformation such as shrinkage in a dry season may be sufficient to reduce or completely remove downslope support to the wall.

The design loads and the stability of the downslope portion in seismic conditions are normally determined from pseudostatic limit equilibrium analyses, taking into account the excess pore pressures that may develop in the slope, where applicable.

Once the net actions imposed by the landslide on the pile wall are known, a suitable soil-structure interaction analysis is carried out by an appropriate method to determine both the reactions in the stable soil into which the piles are anchored and the effects of actions on the piles.

The spacing between the piles must be determined balancing:

- economy and the need to avoid interference between adjacent piles during construction and with natural drainage;
- ensuring that soil arching develops between adjacent piles and that the soil does not "flow" between the piles.

The check that soil arching develops between adjacent piles and that the soil does not "flow" through the piles can be done by means of analytical (simplified) tools (see for example Ito and Matsui, 1975) or 3D numerical analysis.

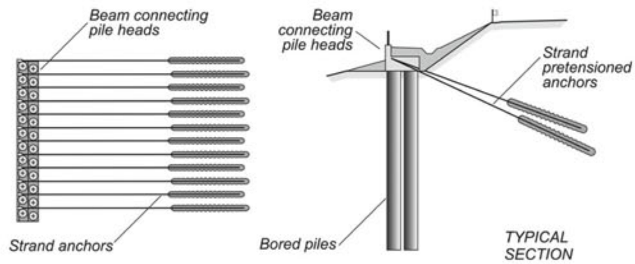
Provided soil arching is guaranteed, plain strain 2D soil-structure interaction analysis is representative of actual conditions, with the effects of actions on each pile being those derived from the 2D analyses, multiplied by the pile centre to centre spacing. The same analysis may be used to determine the optimal length of the piles and the benefit of anchors.

The calculation of the pile capacity in relation to the soil/structure interaction may be carried out according to several approaches and simplified methods (De Beer, 1977; Viggiani, 1981; Hassiotis and Chameau, 1984; Cantoni et al, 1989; Pearlman and Withiam, 1992).

Finite elemnt methods may be used instead to provide a simultaneous and consistent estimate of the soil-structure interaction both with the sliding mass and with the underlying stable soil. Finite element analyses in the time domain can also be used to refine the evaluation of the performance of the structure under seismic conditions.

The mechanical charateristics of the piles must be adequate to sustain the actions and the effects of actions on the piles. The structural checks must satisfy all applicable codes and standards on the subject.

Figure 1: Schematic section and layout (source: SGI-MI project files)



Picture 1: Double row of large diameter piles (source: SGI-MI project files)

MITIGATION THROUGH REDUCTION OF HAZARD

6 TRANSFER OF LOADS TO MORE COMPETENT STRATA

6.2 PILES

APPLICABILITY

Class	Descriptor	Rating	Notes
Type of movement (Cruden & Varnes, 1996)	Falls	0	Best suited to slides and the slide-like portion of complex landslides. May be applicable in some cases to prevent the triggering of slides with the potential to turn to spreads or flows, but are substantially ineffective once fuidification has occurred.
	Topples	0	
	Slides	8	
	Spreads	4	
	Flows	4	
Material	Earth	8	Difficult, very expensive and typically inappropriate in rock. Tools and temporary hole support to be selected taking into account ground conditions. Special care must be excercized where the ground contains large boulders which preferably should be overcome without causing excessive vibration.
	Debris	8	
	Rock	0	
Depth of movement	Superficial (< 0.5 m)	0	Typically: • best suited where the movement is medium deep (3 to 8 m), • inappropriate in shallower movements because excessive, • difficult (large diameter, multiple rows) in deep movements, • not applicable in very deep movements.
	Shallow (0.5 to 3 m)	4	
	Medium (3 to 8 m)	8	
	Deep (8 to 15 m)	4	
	Very deep (> 15 m)	0	
Rate of movement (Varnes, 1978)	Moderately to fast	0	Workers' safety and end result require construction to take place when movement is extremely slow or very slow (maximum 1.5 m/year, corresponding to approximately 5 mm/day). Under special conditions and taking due precautions (permanent casing; drilling non-stop to avoid blokage and brocken piles, it may be carried out when movement is "slow" (up to 1.5 m/month, corresponding to 5 cm/day) .
	Slow	4	
	Very slow	8	
	Extremely slow	8	
Groundwater	Artesian	2	High groundwater levels can be dealt with by standard pile construction procedures, bu artesian groundwater conditions pose special problems during construction, possibly making piles not feasible in extreme cases.
	High	6	
	Low	8	
	Absent	8	
Surface water	Rain	8	Water courses need to be temporarily diverted or reliably dry during construction. Potential pollution of watercourses by piling operations (for example by drilling fluid and/or by grout) may impose restriction on construction procedure. No problems once the works are completed, except possibly when piles provide an undesired "hard bank" to watercourses.
	Snowmelt	8	
	Localized	8	
	Stream	2	
	Torrent	2	
	River	2	
Maturity		10	Technique and design process are well established and widely used in suitable conditions.
Reliability		8	Reliable performance in well characterized landslides; in first time slides it depends on estimate of piezometric regime and apprporiate operational strength parameters of soil, which can be problematic; problems may occur during construction, for example if unforeseen boulders are encountered.
Implementation		6	Requires specialist equipment and techniques; implementation may need temporary roads and working platform for safe operation.
Typical Cost		4	Relatively expensive.

Note
Ratings are given on a scale of 1 to 10; the higher the grade, the most suitable is the specific method under consideration to use in landslides of the given characteristics, evaluated individually. Overall suitability to specific case under consideration may be obtained by a weighted average of these ratings, with user defined weights. Zero rating means "not applicable"

Fig. 2 Selected pages from a typical fact sheet of hazard mitigation measure

Table 2 Vulnerability mitigation measures

Category	Brief description of mitigation
Measures to increase the resistance of elements at risk	Strengthening of shallow foundations and improved structural design to withstand predicted permanent ground displacements
	Deep foundations properly designed to accommodate the landslide effect
	Deep anchoring of foundation elements
Measures to stop or to deviate the path of the landslide	Diversion channels
	Re-modelling of the slope
	Planting and vegetation on the slope
	Catch trenches
	Rockfall barriers
	Rockfall nets (or drapery)
	Rockfall sheds

Table 3 Measures to reduce the elements at risk

Category	Brief description of mitigation
Measures to decrease the number of elements potentially affected	Zoning to prevent development in hazardous areas
	Traffic restrictions
Measures to decrease the probability that vulnerable elements will both spatially and temporally intercept ground movements	Moving non-stationary vulnerable elements to less hazardous locations
	Increasing awareness, detection and warning of hazards and subsequent avoidance

Finally, the contribution on experience in *Switzerland* describes a number of case histories, showing how different mitigation measures are used to suit the specific conditions of each site.

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