Multidisciplinary landslide assessment – a systematic and practicable approach for pipeline projects

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Abstract

Ground movements, with the clear majority being landslides, have caused several pipeline incidents worldwide in recent years. This, and experiences obtained from major engineering projects, shows that a systematic approach for the assessment of landslides is essential. A best-practice multidisciplinary workflow, based on detailed terrain analyses, has been applied in recent projects, each comprising a large variety of landslide assessments. The suggested approach is based on detailed landslide inventory databases and maps, susceptibility analyses, as well as landslide hazard assessments and risk classifications. The outcome of this workflow is a project-specific landslide priority register, which provides a sound basis for decision-making, for planning hazard management and for assessing the potential costs and losses caused by landslide-related pipeline damages.

1 Introduction

Due to their large spatial extents, pipeline corridors often cross areas characterised by adverse geotechnical conditions and by a variety of natural hazards. The assessment and management of geological hazards, such as earthquakes (ground shaking, fault ruptures and secondary phenomena such as liquefaction, subsidence and landslides) as well as gravitational hazards (landslides) are thus of major importance for the successful design, construction, operation and maintenance of pipeline systems (see Sweeney 2005, Baum et al. 2008, and references therein).

According to the 10th Report of the European Gas Pipeline Incident Data Group, different types of ground movements have been responsible for approximately 15% of pipeline incidents observed during the last 10 years. Among these, the clear majority of incidents were related to landslides (depending on the period considered, approximately 65-90% of ground movement incidents related to landslides, EGIG 2018). Pipeline exposures, ruptures and shutdowns resulting from landslide events are global phenomenona since they occur in different geological settings (see e.g. Geertsema et al. 2009, Hählen 2010, Lee et al. 2016, and references therein).

The term “*landslide*” may be briefly defined as “*a movement of a mass of rock, earth or debris down a slope*“ (Cruden 1991) but comprises a large variety of different gravitational slope processes characterized by different types of materials, movements, geometries and status of activities. In view of this complexity, several international publications and guidelines for landslide hazard/risk assessment and management have been established (see Section 7 References). However, putting clear numbers to landslide hazard and risks still remains challenging because of the heterogeneity of site-specific geological settings, often poorly known to unknown geotechnical and hydrogeological landslide parameters (such as slope deformation activities, residual shear strength and pore pressures) and behaviour under varying external conditions (e.g. site-specific groundwater conditions and seismic events) as well as often poor information concerning potential first-time slope failures.

This and experiences obtained from major engineering projects show that multidisciplinary approaches are essential for successful landslide assessments and for the design of appropriate mitigation measures. A best-practice workflow to deal with landslides along pipeline corridors, which has been applied in recent projects (each comprising a large quantity and variety of landslide assessments), is presented here. The suggested workflow is based on systematic terrain analyses comprising of i) compilations of landslide inventories, ii) susceptibility analyses of terrain units, and iii) landslide hazard assessments and risk classifications. The outcome is a project-specific landslide priority register, which provides a sound basis for decision-making when defining hazard management, monitoring and maintenance plans.

2 Landslide Inventories

2.1 General

Landslide inventory databases and maps document the landslide features and different descriptive landslide parameters in a project region. A comprehensive inventory dataset is a fundamental input for route optimisations (for example to avoid landslides to best possible extent) and for further landslide investigations (susceptibility, hazard and risk analyses).

Most commonly, qualitative (heuristic) approaches are used for landslide analyses, since quantitative (probabilistic) approaches require an increased amount and higher quality of input data (e.g. multi-temporal assessments and monitoring of landslide features, as well as hydrogeological and hydrological parameters). Empirical heuristic inventory maps depict the actual status of existing landslides, and thus enable identification of critical pipeline sections where further steps such as rerouting (to avoid certain landslide features), technical measures (removal and/or stabilisation of instable materials) or acceptance/monitoring may be required. However, these inventories do not provide information on future landslide activities or potential first-time failures (triggered e.g. by earthquakes, rainstorms or construction works). In this regard, susceptibility maps based on weighted statistical parameters are helpful indicators for landslide-prone pipeline sections (see Section 3).

For a comprehensive landslide inventory (and subsequent hazard/risk analyses), the following characteristics (attributes), at least, should be documented systematically:

- Location (from pipeline KP - to KP, and location relative to the pipeline e.g. above, below, left/right lateral or atop centreline);
- Morphological setting (e.g. ridge geometries, longitudinal or side slopes, gully features, etc.);
- Types of landslide features (scarps, tension and shear cracks, gully head instabilities, toe bulges, source, transit and/or accumulation areas, etc.); important differentiation shall be made between displaced materials with potential for reactivations and “stable” features (e.g. ancient debris fans, rock fall deposits);
- Engineering geological classifications of materials (soils, rocks, rock masses incl. major discontinuities) according to international standards;
- Type of movements (fall, topple, slide, flow, spread, or complex), classification according to terminology by Cruden & Varnes 1996 and Hungr et al. 2012;
- Landslide depth (shallow, medium, deep seated; using different categories of depth classifications provided in literature), based on subsurface investigation/monitoring data and/or subjective ratings based on field observations;

- Status of activity (active, inactive, reactivated, stabilised, etc.) according to terminology given in Turner & Schuster 1996, based on monitoring data and/or subjective ratings based on field observations; plus information on whether first-time failures or reactivated features, date/time of historic events, and whether constantly (e.g. creeping some mm/cm per year) or episodically active with increased displacements (e.g. some cm/dm per months, accelerated/triggered for example by snowmelt, intense rainfall and/or earthquakes);
- Hydrogeological setting (qualitative and/or quantitative information concerning groundwater observed and/or inferred, seepage, sinks, etc.);
- Distance/proximity of landslide features to pipeline centreline, including information on whether features (cracks, displaced ground) are observed atop and/or behind pipelines (i.e. potentially retrogressing landslides which may affect pipe integrity);
- Pipeline depth of cover (relevant regarding depth/thickness of landslide materials, potential failures of loose fill materials, etc.);
- Information on geotechnical surveys and tests (trial pits, boreholes, field and laboratory tests, landslide monitoring points etc.).

Further information for example volume estimations and potential triggering factors (rainfalls, earthquakes, man-made etc.) should be considered at least for the construction works, operation and maintenance (as part of a multi-temporal landslide inventory, i.e. living database covering the considered project lifetime). In order to provide an improved inventory mapping and classification, for regions characterised by complex landslides or landslide clusters it is often not reasonable to map “simple” boundaries of the overall landslide bodies (i.e. the enveloped area representing a spatially “homogeneous” hazard class polygon), but rather to differentiate between individual sub-features characterised by spatially and/or temporally variable deformation behaviour and individual hazard potentials (see e.g. Zangerl et al. 2019).

Comprehensive and high-quality landslide inventories may be obtained from various sources and by using different methods (e.g. Baum et al. 2008, Highland & Bobrowsky 2008, AGS 2007, Guzzetti et al. 2012, and others), mainly from analyses of various archive data and from geological field mapping campaigns (see below).

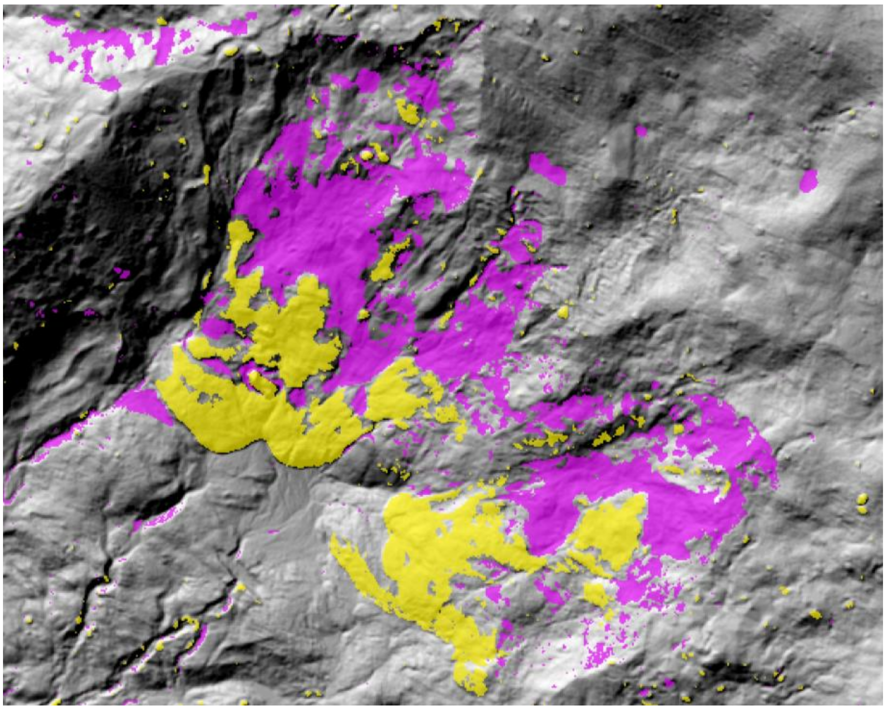
2.2 Desk studies and data analyses

Comprehensive compilations and analyses of available archive data (desk studies) are essential for high-quality landslide inventories. Alongside existing engineering geological and landslide maps, visual geomorphological analyses of various remote sensing data are a major source of information for identifying and mapping landslides. Especially in early project stages, aerial photographs and ortho-corrected optical satellite imagery are fundamental for landslide inventories. However, quality of the outcome of such desk studies strongly depends on image and terrain characteristics, such as spatial resolution, illumination, clear ground view, whether open land or covered by ice, snow and/or vegetation. In advanced project stages and for photogrammetric monitoring purposes, high-quality imagery, acquired specifically for the project, is required. Multispectral imagery (e.g. Landsat data) can further contribute to the mapping and classification of terrain units including landslide features, but are often not available in adequate high spatial resolution.

More detailed information on terrain morphology and landslide features can be obtained from high-resolution topographic LiDAR (light detection and ranging, synonym laser-scanning) survey campaigns. For linear pipeline projects, airborne laser-scanning (ALS) is an ideal and powerful tool to survey larger areas. Similar to aerial photographs, ALS surveys can be performed using manned aircraft or unmanned aircraft vehicles (UAV). In contrast, ground-based terrestrial laser-scanning (TLS) is limited to surveying and monitoring selected critical sites. Laserscan technology permits a detailed, area-wide and three-dimensional survey of terrain surfaces. LiDAR 3D point cloud data and processed derivatives such as digital elevation models (DEMs), contour lines, hillshade images and classified slope inclination maps provide crucial information on terrain characteristics. In contrast to optical imagery, where terrain features may be shielded by vegetation, vegetation features can be extracted from the LiDAR point cloud data, enabling critical features (such as landslides, erosion, sinkholes, etc.) to be clearly identified and mapped.

Multi-temporal differential LiDAR data provide evidence of whether landslide features have been pre-existing, or related to specific events (like earthquakes, rainstorms, etc.) or construction works, and also enable the quantification of landslide mass wastes and accumulation (Figure 1) as well as of construction-related earth works (determination of cut and fill volumes). In addition, multi-temporal point cloud data can provide information on 3D displacement vectors (to as resolution of some dm), meaning that 3D survey can be performed and monitoring data be gathered without direct site access being required (Fey et al. 2015, Pfeiffer et al. 2019).

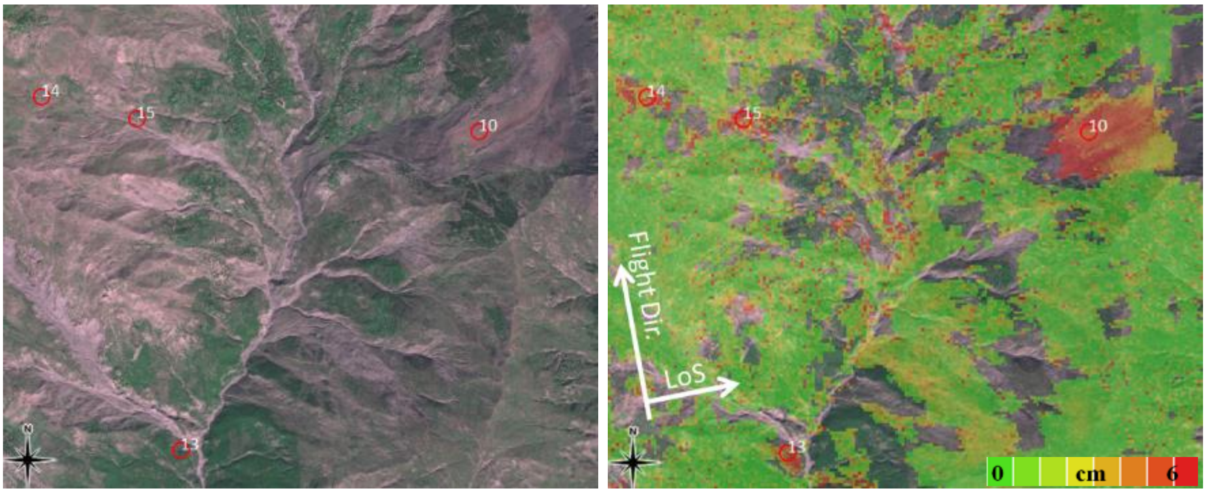
Figure 1: Differential ALS hillshade image depicting quantified landslide mass wastes and accumulations. *Magenta*: source areas with negative vertical displacements (terrain subsidence -0.5 to -2 m). *Yellow:* positive vertical displacements (uplift +0.5 to +2 m) due to mass accumulations.



Further information on terrain (in-)stability can be derived from satellite-borne interferometric synthetic aperture radar (InSAR) data (e.g. Rott & Nagler 2006). Multi-temporal radar images cover large areas (up to hundreds of km^2) and can provide information on locations and amounts of ground deformations (landslide and earthquake displacement maps; see Figure 2).

Major advantages of InSAR analyses are i) the high resolution of data, which enables detection of very slow landslides with displacements of some mm-cm/year, and ii) the amount of archive data, which now cover several years of earth observation and thus enable retrospective monitoring of large project areas and critical sites (Prager et al. 2009, Intrieri et al. 2018). However, limitations for InSAR techniques are given by topographic settings (slope aspect and steepness, as well as shading effects, etc.) and by snow, ice and/or high vegetation cover.

Figure 2: Landslide-prone badland terrain captured as an optical satellite image (*left*) and InSAR displacement map (*right*, calculated by Enveo Ltd. from ALOS PalSAR L-band 23cm, dates 2007-2008) showing stable and/or insignificant terrain units (*green*) and displaced ground (*orange to red*, i.e. erosion features and active landslides; *red circles* indicate major displacements of up to 6 cm/year).



In addition to analyses of remote sensing data, various other archive data sources including geodetic surface monitoring data, geotechnical subsurface monitoring data, historic chronicles of events, personal information from local residents and others such as radiometric age dating data can contribute to landslide inventories. Age dating data can provide crucial information for differentiating between landslide and non-landslide deposits (e.g. between earthflow or rock avalanche deposits and glacial till) and may form a basis for the establishment of landslide chronologies and time-series for hazard assessments (concerning recurrence intervals, frequencies, and failure probabilities).

2.3 Geological field investigations

Geological field investigations comprise the assessment of lithological, structural, geotechnical and hydrogeological characteristics of landslide areas. The respective information can be obtained from field mapping campaigns, field measurements and subsurface investigations (trial pits, boreholes including in-situ tests and monitoring). Detailed lithological mapping of landslide source and accumulation areas can enable a correlation of geological units and materials, and thus provide crucial input for process analyses (e.g. of landslide mechanics and deformation/runout behaviour, if single or multiple landslide events, etc.) (e.g. Prager et al. 2009, Dufresne et al. 2016).

Findings from field mapping campaigns should be digitally recorded e.g. by using tablet-borne software applications. This enables offline navigation and waypoint mapping (including relevant site-specific information) using various kinds of project-specific information and maps (such as topographic maps, optical and LiDAR imagery, pre-assessed landslide features, pipeline centrelines, KPs, etc.).

In order to assess structural and geotechnical field parameters for landslide analyses and planning of mitigation measures, geological and geotechnical field measurements (spot measurements) are to be performed at representative outcrops in accordance with international standards and guidelines. This comprises measurements of the spatial orientations of exposed main discontinuities (stratification or bedding planes, major fractures, etc.), the assessment of engineering geological rock mass parameters, and performing geotechnical field measurements in soils and weak rocks.

Based on the findings from geological field surveys, detailed geotechnical subsurface investigations (trial pits, rotary core drillings including in-situ tests, and geotechnical lab analyses) may be required at selected landslide locations. The geological profiles obtained therefrom can provide evidence of displaced materials e.g. varying degrees of weathering/disintegration and/or sheared soils/rocks. Equipped with groundwater standpipes or inclinometer, borehole locations can also yield essential monitoring data concerning time-dependent landslide behaviour and for hazard assessments.

3 Landslide Susceptibility Analyses

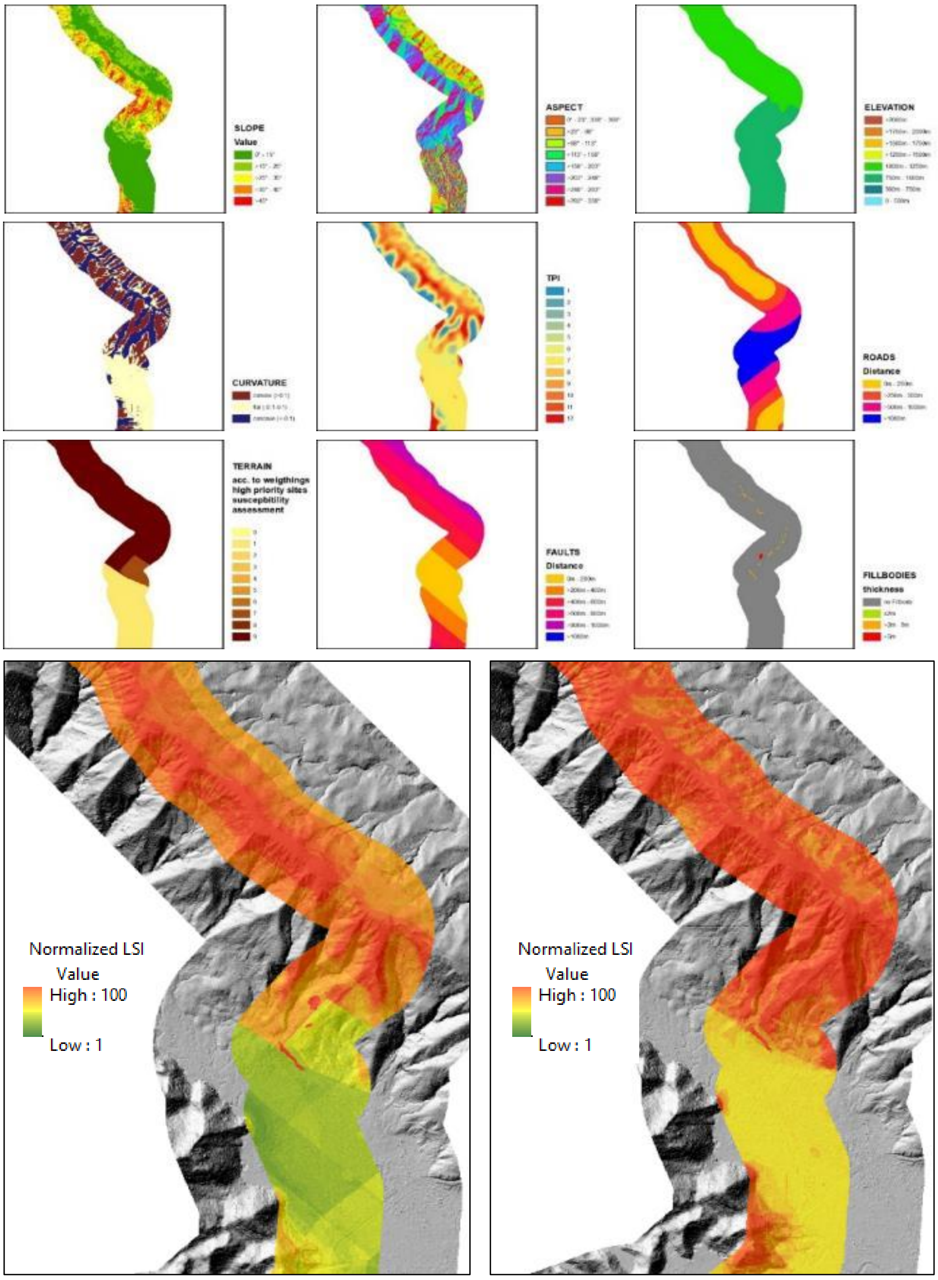
Landslide susceptibility analyses (LSA) based on weighted statistical parameters represent a powerful tool for assessing sections of landslide-prone terrain (potential first-time failures) and for subsequent hazard evaluations. The required input data comprise a variety of field information (lithological, geotechnical and geomorphologic terrain units/maps, landslide inventory, man-made deposits, etc.) as well as different high-resolution remote sensing data. The main relevant geo-information includes data derived from digital elevation models (e.g. slope inclination and aspect, altitude or terrain curvature, topographic position index TPI, watersheds and stream networks, etc.), and multispectral imagery (such as land use classifications, normalized density vegetation index NDVI) (van Westen et al. 2008, Corominas et al. 2014, and references therein).

LSA can be performed using qualitative and/or quantitative approaches (Chae et al. 2017). Qualitative or knowledge-driven (empirical) methods are based on weighting of predisposing factors by experts, and therefore may involve a considerable degree of bias (due to the subjectivity of experts' ratings). In contrast, quantitative methods are based on physical process analyses or data-driven analyses (statistical relationships between predisposition factors and landslide occurrences). Physically-based approaches (e.g. infinite slope models, 3D runout analyses) are generally complex and computationally intensive, and thus preferentially applied to individual slopes or rather small areas. Data-driven approaches, on the other hand, can be used to cover large regional extents (pipeline ROWs) and provide a sufficient statistical robustness for the large amount of input datasets. Besides, several data-driven models can be easily implemented in a Geographic Information System for further data processing.

In view of this, data-driven bivariate statistics are commonly applied for large-extent pipeline corridors. Using bivariate methods, statistical relationships between known landslide locations and various terrain factors that potentially contribute to landslides can be analysed (e.g. slope geometries, soil/rock properties, drainage patterns, fault vicinity, man-made cuts or fills, etc.). Thus, a practicable workflow using a combination of two methodologies, namely Frequency Ratio (FR) and Weight of Evidence (WoE), has been established, which provides a satisfactory compromise between computational effort and predictive power of results.

For both approaches (FR and WoE), each input factor is categorised into a set of classes (based on literature reviews and expert knowledge) and tested for its spatial relationship with the landslide inventory. Both approaches allow the calculation of the probability of landslide occurrence, i.e. landslide susceptibility index (LSI) as a measure for identifying landslide-prone locations (see Figure 3) (Bonham-Carter 1994, Bonham-Carter et al. 1989, Lee & Choi 2004). For reasons of comparability, the predictive power of results is verified by computing the receiver operating characteristic (ROC) curves and the area under the curve (AUC) values (Chung & Fabbri 2003). The full model workflow can be implemented in ArcGIS 10.6 by using the spatial analyst extension and the ArcSDM toolbox for WoE.

Figure 3: Exemplary landslide susceptibility maps depicting a normalised landslide susceptibility index LSI calculated using the FR (*figure lower left*) and WoE approaches (*figure lower right*). Both computed models based on selected input parameters (*smaller figures above*, e.g. slope characteristics, TPI, buffer distances to road cuts and faults, expert judgements of soil/rock characteristics).



4 Landslide Hazard Assessments

Natural hazards may be defined as "*the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon*" (Varnes & IAEG 1984). Landslide hazards may be defined as the probability of slope failure, which can be statistically assessed based on geotechnical parameters and/or empirically based on expert judgements (Turner & Schuster 1996). This implies the magnitude of landslide events (destructive power) within a given area (geographic locations of landslide occurrences) and given period (temporal frequency of occurrence and recurrence) (Guzzetti 2006, AGU 2007).

In general, for landslide hazard assessments different approaches may be required: i) site-specific geotechnical slope stability analyses, ii) comprehensive regional (ROW) analyses and iii) runout studies for rapid landslides (on individual local and/or regional scale). The locations, stability conditions and expected magnitudes of landslides can be obtained from detailed inventory data (including geotechnical and geodetic surface and subsurface information) and susceptibility analyses (see above).

Area-wide hazard maps related to the failure (release) of landslides can be assessed using probabilistic and deterministic approaches. Probabilistic landslide hazard maps show the spatio-temporal probabilities of landslide occurrence (in the range 0-1). Deterministic landslide hazard maps delineate between hazard areas and non-hazard areas (showing a factor of safety or landslide depth), and are directly related to trigger events of a defined magnitude or frequency (such as intense rainfalls or earthquakes). In principle, both types of landslide hazard maps can be established using several methodological approaches (see Chapter 7 References):

- Physically-based hazard maps may be based on modelling e.g. rainfall infiltration, pore pressure or seismic accelerations, and deriving a factor of safety. Since specific geotechnical parameters are required, this approach has been preferentially applied to selected critical regions. However, by varying the input parameters also probabilistic slope scenarios can be calculated (sensitivity analyses);
- Statistical methods: the spatial probability of landslides may be derived by relating the landslide inventory to a set of susceptibility layers (e.g. slope inclination, lithology, land cover) by using various approaches. If the inventory implies temporal information, probabilistic hazard maps can be derived. Statistical approaches may also be applied to assess triggering thresholds (or probabilities) of defined rainfall or earthquake scenarios by relating the landslide inventory to meteorological or seismic records (assessment of worst-case landslide scenarios or scenarios with a certain probability of exceedance for defined triggering events, etc.).
- Rule-based methods: a number of well-documented landslide areas are selected to develop a rule-based approach by means of statistical analyses, physically-based modelling and/or morphometric analyses, in combination with expert knowledge. These rules obtained from selected well-documented landslide regions may be transferred to other less documented areas.

The best applicable approach depends on the quality and quantity of the available input data. Physical-based approaches require a certain amount of geotechnical data and may preferentially be applied to some selected areas. Statistical approaches, on the other hand, are applicable for regions with a high-quality landslide inventory. If the quality of the landslide inventory is insufficient, rule-based approaches may be applied (however, this may lead to results which do not represent hazard maps but rather susceptibility or hazard indication maps).

In addition to slope stability and failure assessments, also landslide hazard maps related to the transit and accumulation paths of landslides may be required. Such runout studies can be performed by using specific modelling software (see for example Dorren et al. 2006, Hungr & McDougall 2009, Gruber & Mergili 2013, Hergarten & Robl 2015). On the one hand, landslides with runouts initiating from the ROW can affect third parties below. On the other hand, long-runout landslides such as major rock avalanches and debris flows may have sources far beyond ROWs (see e.g. Geertsema et al. 2009, Dufresne et al. 2016), and therefore sometimes affect pipeline corridors rather unexpectedly if not been considered by extensive regional studies. Therefore, the hazard classification of identified landslides should be based on expert judgments of the observed terrain features. It is also important that differentiation is made between landslides with active movements and/or potential for renewed movements along pre-existing sliding zones (i.e. rock/soil slides and/or flows) and landslide deposits which represent rather “stable” accumulation features (e.g. ancient debris fans, rock fall and rock avalanche deposits, etc.). Another important hazard threat to pipelines, and thus also to be considered, is possible retrogression of steep and high, bare cliff sections.

In complex landslide settings (cf. Section 2.1., p. 3), the hazard rating may locally differ from the general classification scheme, because for example i) slope failures can change slope geometries and stresses, and thus trigger adjacent instabilities, or ii) in landslide clusters, individual failures situated upslope of a certain location may load and thus reactivate older landslides further downslope, or vice versa iii) erosion of landslide toes by torrents and rivers may retrogress and cause failures further upslope. Thus, depending on the local site conditions, also apparently “negligible” to “very low” hazard landslides may be classified as “low” to “medium” hazard features (even if they are a distance away from the centreline), since these landslides may potentially influence landslides closer to the ROW).

The information obtained from inventory, susceptibility and hazard assessments can be summarized in a landslide hazard/risk classification scheme (Figure 4) and applied to indicative hazard maps. This aims to provide data in such a form (decision matrix) that it then can be used for the classification of route corridors, the selection of preferred centrelines and for route optimisations. For construction and long-term pipeline integrity, detailed risk determination (incl. pipe stress analyses), designing mitigation measures, and establishing monitoring concepts and maintenance plans (incl. priority ranking of potential landslide-related repair works) is mandatory.

5 Landslide Risk Assessments

Concerning risk, literature offers a large variety of definitions and assessment procedures, with a conventional risk definition expressed by the product of probability (of a hazard) and consequences. According to Varnes & IAEG 1984, (landslide) risk may be defined as the expected losses, damages or disruption of economic activities due to a particular natural phenomenon. For pipelines, landslide risk may be viewed as the probability of undesirable consequences and expected degree of damage (vulnerability), such as pipeline exposure, freespan, bulging and/or rupture.

As hazard assessments, also risk assessments may be based on quantitative and qualitative approaches (see references, e.g. Guzzetti 2006, AGS 2007).

Figure 4: Brief description and hazard classification scheme of identified landslide features (qualitative and semi-quantitative).

Description	Hazard Class	Indicative Hazard/Risk to Pipeline
• Landslide boundary (scarp, flank or toe) > 100m distance from centreline.	**H0 negligible**	General threat (exposure, critical freespan or rupture) not credible to barely credible
• Landslide boundary (scarp, flank or toe) 50-100m distance from centreline; or: • minor and shallow landslide within ROW, but hazard feature entirely removed by construction works.	**H1 very low**	General threat (exposure, critical freespan or rupture) barely credible to rare.
• Landslide boundary (scarp, flank or toe) 25-50m distance from centreline; or: • minor and/or shallow landslide within ROW, but mitigated by construction works.	**H2 low**	General threat barely credible to unlikely. Exposure unlikely; Critical freespan (project-specific) rare; Rupture barely credible to rare, only under exceptional circumstances (< 0.1% chance of occurrence during project lifetime).
• Landslide boundary (scarp, flank or toe) 10-25m distance from centreline; or: • minor and/or shallow landslide on centreline, but mitigated by measures (at and beyond ROW); (detailed assessments and measures required, reroute recommended).	**H3 medium**	General threat rare to possible. Exposure possible; Critical freespan (project-specific) unlikely; Rupture during project lifetime rare to unlikely (0.1% to 1% chance of occurrence during project lifetime).
• medium-/deep-seated landslide 0-10m distance from centreline; (reroute strongly recommended).	**H4 high**	General threat possible to likely. Exposure likely; Critical freespan (project-specific) possible; Damage or rupture during project lifetime possible (1% to 10% chance of occurrence during project lifetime).
• deep-seated landslide or landslide-cluster 0-10m distance from centreline; (reroute inevitable).	**H5 very high**	General threat likely to almost certain Pipeline rupture during project lifetime almost certain (> 10% chance of occurrence during project lifetime).

Quantitative (probabilistic) landslide risk analyses are based on numerical parameters (e.g. landslide frequencies, magnitudes) to estimate objective probabilities of pipeline damage. Concerning the indicative ranges of annual probabilities for different types of landslides (see e.g. AGS 2007), the specific input data on activity and recurrence intervals (radiometric age dating data, chronicles, time series, statistics, mid-/long-term monitoring data, etc.) are often incomplete or not available, especially on a regional scale. Thus, temporal/spatial probabilities related to 25- or 50-year project lifetimes can often hardly or not seriously be quoted as an input for risk calculation.

Instead, qualitative (heuristic) approaches may be more applicable. Qualitative ratings are relative and descriptive, with inferred likelihoods based on geological and morphological site information (i.e. multi-temporal landslide inventories and hazard scenarios) and expert judgements, and may also consider literature data on landslides in comparable settings. In some projects, landslide risk has been simply based on the location and distance of individual landslide features to the RoW (centreline).

For a more detailed risk assessment, landslide parameters such as kinematics (velocities, potential accelerations and stabilisation), geometries (thickness/depths) and potential for landslide expansion should also be considered (see also Chapter 6 Hazard Assessments). Based on experiences, several landslides such as earth flows in cohesive soils or deeply weathered claystone units, in principle have the potential to be re-activated within a specific pipeline lifetime, but also previously stable or marginally stable slopes can be affected by first-time failures (see susceptibility analyses above). Concerning potential impacts on pipelines, several slow to very slow ("creeping") landslides often do not cause pipe exposures and/or freespan but rather mid- to long-term deformations and potentially critical pipe stress and strain. Thus, and because changing boundary conditions like earthquakes and/or intense rainfalls can affect especially such pre-existing landslides (i.e. reactivations or accelerated movements are generally more likely than major first time failures), potentially critical sites should be further assessed by monitoring (concerning direction and rate of movements, potential accelerations) and pipe stress analyses (for quantifying potential stress and strain, and identifying vulnerable sections of a pipeline).

Based on the investigations described above (landslide inventory, susceptibility and hazard assessments), a landslide register depicting the landslide-related risks can be established. This should comprise all landslide features mapped within a defined buffer distance around the pipeline, giving descriptions of and qualitative/quantitative information on:

- setting, landslide features, materials, etc. (as documented in the inventory; see Section 2);
- individual landslide hazard classes (H0 negligible to H5 very high; see above);
- probability/likelihood of pipe exposure, freespan or loading scenarios;
- pipe stress and strain (quantified by specific analyses);
- pipeline integrity (hazard/risk) assessment;
- recommended actions (indicative);
- terms for additional measures (very short- to long-term) and priority ranking of landslide site.

These landslide descriptors can be used for pipeline risk evaluation and defining site-specific mitigation measures (e.g. geotechnical installations, monitoring). Thus, the register provides the fundamental input parameters for a risk matrix, which in turn enables the further assessment of potential costs and losses (due to pipeline repair works or shutdown).

6 Conclusions

The suggested workflow presented herein aims to contribute to a practicable and effective assessment of critical landslide locations along pipeline ROWs and to an improvement of landslide management during all stages of pipeline projects (from pre-FEED to operation and maintenance). Based on long-term experiences obtained from several major engineering and research projects, the most essential input for landslide hazard and risk analyses is a comprehensive inventory database (since quality and quantity of inventory datasets are fundamental for hazard/risk models).

The inventory and hazard risk models should be planned as a living system, meaning they should be re-interpreted and updated as soon as new survey/monitoring data are available, and/or when terrain changes are observed (new and/or expanded landslide features, man-made activities e.g. construction works or material deposition).

An overview of the main relevant information on landslide hazards and risks can be provided in a landslide hazard register. This indicates the locations at which potential pipeline damages (due to exposures, freespans, bulging and/or ruptures) have to be expected during a project´s lifetime. Based on this, further investigations and site-specific mitigation measures to reduce the landslide hazards and guarantee pipeline integrity can be planned (i.e. close-out, avoidance to the best possible extent, rerouting, monitoring, stabilization measures and maintenance plans); furthermore, risks concerning potential costs and losses (due to pipeline harm) can be assessed.

7 References

AGS, 2007: Landslide Risk Management. - *Journal and News of the Australian Geomechanics Society 42/1*.

Baum R.L., Galloway D.L., Harp E.L., 2008: Landslide and land subsidence hazards to pipelines. - *U.S. Geological Survey Open-File Report 2008-1164, 192 pp*.

Bonham-Carter G.F., 1994: Geographic Information Systems for Geoscientists, Modeling with GIS. - *Pergamon, 416 pp.*

Bonham-Carter G.F., Agterberg F.P., Wright D.F., 1989: Weights-of-evidence modeling: a new approach to mapping mineral potential. - *Agterberg F.P. et al. (eds.), Statistical Applications in the Earth Sciences, 171-183*.

Chae B.-G., et al., 2017: Landslide prediction, monitoring and early warning: a concise review of state-of-the-art. - *Geosciences J. 21/6, 1033-1070*.

Chung C.F., Fabbri A.G., 2003: Validation of spatial prediction models for landslide hazard mapping. - *Natural Hazards 30/3, 451-472*.

Corominas J., et al., 2014: Recommendations for the quantitative analysis of landslide risk. - *Bull Eng Geol Environ 73, 209-263*.

Cruden D.M., Varnes D.J., 1996: Landslide types and processes. - *Turner A.K., Schuster R.L. (eds.), Landslides: Investigation and Mitigation. Transp. Res. Board, Spec. Rep. 247, 36-75*.

Cruden D., Fell R. (eds.), 1997: Landslide Risk Assessment. - *Taylor & Francis, 384 pp*.

Dai F.C., Lee C.F., Ngai Y.Y., 2002: Landslide risk assessment and management: an overview. - *Eng. Geol. 64, 65-87*.

Dorren L.K.A., Berger F., Putters U.S., 2006: Real-size experiments and 3-D simulation of rockfall on forested and non-forested slopes. - *Natural Haz. Earth System Sc. 6, 145-153*.

Dufresne A., Prager C., Bösmeier A., 2016: Insights into rock avalanche emplacement processes from detailed morpho-lithological studies of the Tschirgant deposit (Tyrol, Austria). - *Earth Surface Processes and Landforms 41/5, 587-602*.

EGIG 20118: 10th Report of the European Gas Pipeline Incident Data Group (period 1970 – 2016). - *Doc. VA 17.R.0395, 50 pp*.

Fey C., et al., 2015: Deriving 3D displacement vectors from multi-temporal airborne laser scanning data for landslide activity analyses. - *GIScience & Remote Sensing 52/4, 437-461*.

Geertsema M., et al., 2009: Landslides impacting linear infrastructure in west central British Columbia. - *Natural Hazards 48, 59–72*.

Gruber F.E., Mergili M., 2013: Regional-scale analysis of high-mountain multi-hazard and risk indicators in the Pamir (Tajikistan) with GRASS GIS. - *Nat. Hazards Earth Syst. Sci. 13, 2779–2796*.

Guzzetti F., 2006: Landslide Hazard and Risk Assessment. *Diss., 373 pp., Univ. Bonn*.

Guzzetti F., et al., 2012: Landslide inventory maps: New tools for an old problem. - *Earth Science Revs. 112, 42-66*.

Hählen N., 2010: Murgänge Spreitgraben Guttannen. - *FAN Herbstkurs 2010, 11 pp*.

Hergarten S., Robl J., 2015: Modelling rapid mass movements using the shallow water equations in Cartesian coordinates. - *Nat. Hazards Earth Syst. Sci. 15, 671-685*.

Highland L.M., Bobrowsky P., 2008, The landslide handbook - A guide to understanding landslides. - *U.S. Geological Survey Circular 1325, 129 pp., Reston*.

Hungr O., et al. (eds.), 2005: Landslide Risk Management. - *CRC Press, 774 pp.*

Hungr O., McDougall S., 2009: Two numerical models for landslide dynamic analysis. - *Computers & Geosciences 35/5, 978-992*.

Hungr O., Leroueil S., Picarelli L., 2012: Varnes classification of landslide types, an update. - *Eberhardt E. et al. (eds), Landslides and Engineered Slopes: Protecting Society through Improved Understanding, 47-58, Taylor & Francis*.

Intrieri E., et al., 2018: The Maoxian landslide as seen from space: detecting precursors of failure with Sentinel-1 data. - *Landslides 15, 123-133*.

Lee E.M., Jones D.K.C., 2004: Landslide Risk Assessment. - *Thomas Telford, 454 pp*.

Lee E.M., Fookes P.G., Hart A. B., 2016: Landslide issues associated with oil and gas pipelines in mountainous terrain. - *Quarterly J. Eng. Geology Hydrogeology 49/2, 125-131*.

Lee S., Choi J., 2004: Landslide susceptibility mapping using GIS and the weights-of-evidence model. - *Int. J. Geographical Information Sc. 18/8, 789-814*.

Mergili M., et al., 2014: Spatially distributed three-dimensional slope stability modelling in a raster GIS. - *Geomorphology 206, 178-195*.

Pfeiffer J., et al., 2019: Comparison and time series analysis of landslide displacement mapped by airborne, terrestrial and unmanned aerial vehicle based platforms. - *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., IV-2/W5, 421-428.*

Prager C., Zangerl C., Nagler T., 2009: Geological controls on slope deformations in the Köfels rockslide area (Tyrol, Austria). - *Austrian Journal of Earth Sciences 102/2, 4-19*.

Rott H., Nagler T., 2006: The contribution of radar interferometry to the assessment of landslide hazards. - *Advances in Space Research 37/4, 710-719*.

SafeLand, 2013: SafeLand, Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies. - *Final Report, related to various deliverables*.

Sweeney M. (ed.), 2005: Terrain and Geohazard Challenges Facing Onshore Oil and Gas Pipelines. - *Thomas Telford, 758 pp.*.

Turner A.K., Schuster R.L. (eds.), 1996: Landslides: Investigation and Mitigation. - *Transp. Res. Board, Spec. Rep. 247, 673 pp.*.

Van Westen C.J., van Asch T.W.J., Soeters R., 2006: Landslide hazard and risk zonation - Why is it still so difficult? - *Bull. Eng. Geol. Env. 65, 167-184*.

Van Westen C.J., Castellanos E., Kuriakose S.L., 2008: Spatial data for landslide susceptibility, hazard and vulnera assessment: An overview. - *Eng. Geol. 102/3, 112-131*.

Varnes D.J., IAEG Commission on Landslides and other Mass Movements on Slopes, 1984: Landslide hazard zonation: a review of principles and practice. - *Unesco, 63 pp*.

Zangerl C., Fey C., Prager C., 2019: Deformation characteristics and multi-slab formation of a deep-seated rock slide in high alpine environment (Bliggspitze, Austria). - *Bull. Eng. Geol. Env. 78/8, 6111-6130.*