Moreover, the project focuses on training of local geologists from the partner organisations, such as the Instituto Nicaragüense de Estudios Territoriales (INETER), Servicio Nacional de Estudios Territoriales (SNET) in El Salvador and Dirección de Geología y Minas (MINAE) in Costa Rica. Some of them are trained directly in the field, and they are also helpful during Final reports compilation.

PHILOSOPHY AND METHODOLOGY OF THE GEOHAZARD STUDIES

The study of natural hazards is focused especially on the geodynamical phenomena. However, other natural hazards like hydrometeorological and anthropogenic ones have been studied too, since they can cause casualties and serious material losses. They are often triggers of the exogeodynamical phenomena as well.

The methodology is inspired especially by geohazard projects in the Czech Republic and several years lasting experiences of the CGS expeditions to the Central America, Peru and other countries. The principal philosophy of the projects is to produce susceptibility maps to site-specific geohazards (e.g. slope instabilities). They are based on geological maps and geomorphic maps, which include also inventory of existing slope failures. The geomorphic maps perform features and landforms that reflect the geodynamic processes, whose have formed them in relation to the local lithological, tectonic, geomorphic and climatic settings. This way these processes could be identified.

Whilst the principal method to establish the geological map is field mapping, complemented with petrological analyses in the lab, the main tools of the geomorphic analyses are:

- Satellite images interpretation: Landsat 7 and SRTM (Shuttle Radar Topography Mission) in resolution of 90 m and interpolated 30 m;
- Stereoscopic photo-interpretation at different scales;
- GIS based analyses of digital elevation model (DEM);
- Field reconnaissance, geomorphic and engineering-geological mapping, sedimentological logging, verifying and measuring the tectonic zones, paleostress analyses etc.

Based on the knowledge of the principal on-going hazardous processes obtained from geomorphic analysis, complemented with slope analysis, information about the geological structure and analysis of seismic tremors activity and distribution, the geohazard susceptibility map is established. For the slope-failure susceptibility map in the Miramar area (Costa Rica) numerical ArcGIS-based model was applied. Slope, lithology, landuse, distance from tectonic fractures, slope exposition, shape of the slope (convexity X concavity), distance from river and mountain ridges and distribution of precipitation were the main factors of the model. These products serve to local authorities and the co-operating institutions for more effective urban and landuse planning.

CASE STUDIES

The paper presents the results of three case studies in different geological and geomorphic settings.
Figure 1. DEM-based map of a part of Central America with location of the case study areas (red rectangles).

Metapán (NW El Salvador)

The first presented case is the Metapán area in NW Salvador (Figure 1). The area consists of low hills, mountains and basins composed of Mesozoic sediments and andesites, Tertiary ignimbrites and tuffs, and very young Quaternary basalts and gravel accumulations at presently extensional NW edge of the Caribbean plate (Chortis block). This is the second driest region (1606 mm/year) of El Salvador.

The map sheet of the Metapán area covered 235 km² and it was surveyed in 2005. In total, thirtyseven slope failures, displayable at the scale 1:50,000 were recorded (Figure 2a). They covered 3.1% of the area. By mechanism of the mass movement, three types of slope failures have been distinguished, i.e.: 1) topples and rockfalls, 2) slides and 3) debris/mud flows.

Topples and rockfalls were relatively rare and occurred on rock cliffs of competent, usually sub-horizontally bedded or massive and densely jointed competent beds of ignimbrites, granitoides and rhyolites or coarse pyroclastic agglomerates of the Rana formation. Seismic shaking seems to be the main trigger of rockfalls there. The anthropogenic-induced rockfalls were quite common in the limestone quarries. However, the trajectories and expected displacements of fallen or rolled boulders were quite short throughout all the mapped area and the hazard was rather low.

Similarly to rockfalls, the lithology and relief energy were the main factors controlling the slides evolution. Subsequently, high precipitation or seismic tremors have been triggers of the movement acceleration of the unstable mass. The slides were identified in different lithological settings. Rather small and shallow to intermediate slides occurred within the area of the Mesozoic sediments. Although, the lithological susceptibility of the Mesozoic sediments in the center of the map to sliding was rather high, the relief energy was relatively low in the most of the area. Erosional or human-induced cutting of the slopes triggered most of these slides (both rotational and planar ones as well). These slides could endanger the limestone-mining activities in the quarries or damage a local infrastructure such as local roads only; they do not represent great hazard to human lifes.

Deep-seated slides which have developed in weathered ignimbrites and tuffs in the NW edge of the map are the most problematic. They are situated especially on the slopes of the valley of La Cañada or along the state border with Guatemala in the Guayabillas valley (“1” in Figure 2a). Several residential houses were built on the slides bodies. Several deep-seated rotational slides developed in tuffs, pyroclastic rocks of the Rana Fm., basalts and gravels...
about 1 km SE from Metapán (“2” in Figure 2a). The slides affect important roads leading to the areas E from Metapán (Sta. Rosa Guachipilín). Large deep-seated rockslide occurs at the edge of the lava plateau about 3 km SW from San Jerónimo, where the blocks of basaltic rocks and ignimbrites, superimposed to red beds, slid down along probably rotational or composed shear zone. The slide is about 2 km wide and movement, as expected, was not too fast (“3” in Figure 2a). A slide at the La Vega de la Caña volcano represents very specific type of the slides (“4” in Figure 2a). The northern part of the cinder cone collapsed forming this about 500 m wide slide with the most probably rotational base. Its age is unknown and the triggers could be endogenous.

**Figure 2.** Slope instability maps of the Metapán area (NW El Salvador). a) *Slope-failures inventory map.* Landslide bodies are displayed as red; accumulations of debris flows are yellow. See the potential landslide on the Mt. Montecristo in the red ellipse that could be a source for future moderate to large debris flows. b) *Slope-failure susceptibility map.* Legend: dark red = already registered slope failures; light red = areas extremely susceptible to landsliding (both deep-seated and shallow ones), earth flows and high erosion; yellow = areas less susceptible to landsliding and erosion; orange arrows = potential tracks of debris flows. The blue line is the eastern edge of the mapped area.

A huge rockslide E from the village of San Diego is another specific case (“5” in Figure 2a). We speculate that it was originally a subsidence ring structure cut by a system of normal faults. Unstable and elevated material probably slid down subsequently. The hypothesis should be verified by geophysical and drilling surveys only. The remote-sensing interpretation as well as the field observation of the slides in the northern part was a bit ambiguous due to very intensive effect of young strike-slip-related transpressional tectonics on the relief shape.
Combination of slides, debris flows and mudflows represents quite serious hazard on the slopes of the Montecristo influencing also the eastern part of the map-sheet area. The accumulations form huge gravel and debris lobes occurring along the Río Chamalapa and the Río San José at places, where their channels reach the gentler slopes in the basins. The amount of transported material is very large and this phenomenon represents a great exogeodynamical hazard in the area in the past and could be recurrent.

**Esteli**

The second case was the mountainous area near the city of Esteli in N Nicaragua (Figure 1). It consists of table-mountains and large relicts of volcanoes up to 1,300 m a.s.l. high, deep erosional valleys and canyons, large extensional basin on NNE-SSW trending sinistral strike-slip zone and subsidence caldera about 13 km in diameter. The main bedrock is composed of Tertiary volcanic rocks such as ignimbrites, tuffs and andesites, much younger Upper Tertiary/Quaternary basalts and Quaternary laterites, slope sediments and fluvial deposits.

In comparing to the previous case, the map sheet of the Esteli covered much larger area. It was performed in 2006 and it covered the area about 600 km² large. In total, 192 slope failures, displayable at the scale 1:50,000 were recorded (Figure 3a) which covered 58.6 km² (9.1% of the area). We distinguished four types of slope failures by mechanism of the mass movement, i.e.: 1) topples and rockfalls, 2) slides, 3) debris/mud flows and 4) rock avalanches.

Rockfalls and topples are quite common there. They occurred on rock cliffs of competent, usually sub-horizontally bedded or massive competent beds (ignimbrites, andesites, coarse agglomerates) following deep erosional valleys and large fault slopes throughout the map.

Landslides were identified in several different lithological and geomorphic settings. The largest and the most deep-seated ones were registered within young tectonic zones related to regional NNE-SSW trending sinistral strike-slip fault in the western part of the map. Some of the failures reached dimensions larger than 1 km and expected thickness up to 200 m. They have rotational as well as translational base (large lateral spread in the S, Figure 4a); one of them has a vedge shape due to intersection of two normal faults at the edge of a table mountain (Figure 4a). These failures are too large to be easily verified in the field and they are very close to the conceptional limit between slope-failures and tectonic features. Other setting is represented by steep slopes in the SW edge of the map, on deep-valleys slopes along Río Isiqui and Río Viejo rivers in the NE part, on outer slopes of a subsidence caldera Tomabú in the center of the map and along table-mountains. Deep-seated rotational landslides, shallow slides and earthflows are typical slope instabilities there. The central part of the subsidence caldera Tomabú is characteristic with rather shallow or deep-seated landslides and earthflows, which are very large in their area (Figure 4b). They have developed on relatively moderate slopes, composed of laterites, thick regolith and intensively weathered andesites. The peak of Tomabú is toppled with presence of cleft caves. The high mountain areas (over 1,100 m a.s.l.) of lateritic weathering are very similar setting like the central part of the caldera. The evolution of landslides is evidently intensified by strong deforestation and pasturing in the area.
Figure 3. Slope instability maps of the Estelí area (N Nicaragua). a) Slope-failures inventory map. Landslide, earthflow and rock avalanche bodies are displayed in red. b) Slope-failure susceptibility map. Legend: violet lines = rock cliffs, susceptible to rockfalling; dark red = already registered slope failures; light red = areas extremely susceptible to landsliding (both deep-seated and shallow ones), earth flows and high erosion; beige = areas very susceptible to rather shallow and large landslides, earth flows and gully erosion on laterites and thick regolith; green = areas susceptible to rather smaller landslides and intensive erosion; yellow = areas less susceptible to landsliding and erosion.

Figure 4. Interpreted aerial photos: a) Area SW from Estelí with marked-on masses of deep-seated slope failures (yellow = rotational slides along the edge of the Cerro Grande plateau, red = wedge failure along two intersecting normal faults at the plateau edge, green = large scale lateral spread within the young NNE-SSW trending sinistral fault zone); b) Area within the subsidence caldera Tomabú (yellow = landslides, beige = earth flow).
Earth flows are relatively rare in the area and all of them are situated within the structure of subsidence caldera Tomabú (Figure 4b). They are closely related to deep-seated landslides and developed due to liquefying of the landslides accumulations. The earth flows are rapid and relatively very dangerous. The last recorded type of a slope failure was rock avalanche. Two several-km-large scree fans occur on gentle slopes of 6-8° N from Estelí. They belong to large and probably seismically induced rock avalanches. The southern avalanche (that one lying on the map) has had additionally more complex evolution, because its source area was covered with young basalts from the Cerro La Campana Volcano. The competent basalts covered and loaded unstable mass of former avalanche accumulation and caused subsequent block landslide there.

A slope-failure susceptibility map was established on the basis of the geomorphic analysis and geological map of the area (Figure 3b). A combined quantitative-qualitative scale for different geohazard groups was established and six main susceptible regions related to slope failures were distinguished, i.e.: 1) rock cliffs, susceptible to rockfalling; 2) already registered slope failures; 3) areas extremely susceptible to landsliding (both deep-seated and shallow ones), earth flows and erosion; 4) areas very susceptible to rather shallow and large landslides, earth flows and gully erosion on laterites and thick regolith; 5) areas susceptible to rather smaller landslides and erosion; 6) areas with low susceptibility to landsliding and erosion.

Miramar

The last case, the Miramar area (NW Costa Rica, Puntarenas; Figure 1), was performed in Tilaran Mts. built up with the lower Tertiary and upper Tertiary andesites of the Aguacate and Monteverde Formations. The bedrock is strongly broken by ENE-WSW and ESE-WNW dextral tectonic ruptures and it underwent intensive hydrothermal alteration and fast regional uplift. The precipitation reaches up to 5,000 mm per year.

In contrast to the previous cases, map sheet of the Miramar area in NW Costa Rica covered the smallest area of about 127 km², but performed the highest density of slope failures (17.3 % of the map area). The study was performed in 2006 and about 50 slope failures, displayable at the scale 1:50,000 were registered (Figure 5a). In total, the failures covered the area of about 22 km². Deep-seated landslides clearly prevailed over debris- and mudflows or rock avalanches, but most of them were complex. Topples and rockfalls were distinct due to intensive lateritic weathering, quasihomogenous bedrock and absence of rock cliffs.

The longest registered slope failure was the Lagunilla landslide about 3 km long. The deepest one was the Peñas Blancas landslide with expected thickness of the landslide body about 500 m. The elevation between the crown and toe was about 750 m and this landslide was triggered at least 925-1415 yr AD (radiocarbon dating of wood fragment within the near-scarp depression).

The high susceptibility of the area to landsliding is documented also by occurence of the famous landslide and rock avalanche Arancibia that developed about 12 km N from the northern edge of the map. The slide has a volume about 25 Mil. m³ covering the area of 2.6 km²; it killed 8 people (Alvarado 2003). Intensive erosion related to fast tectonic uplift, tropical weathering combined with the hydrothermal alteration of the bedrock, seismicity, tectonic fracturing and high precipitation were the main factors of such intensive slope-failure development in the area.

The slope-failure susceptibility map of the area (Figure 5b) was established by using a numerical ArcGIS-related model. However, the output needs to be calibrated and further developed in the future.
DISCUSSION AND CONCLUSIONS

The presented study of slope-failure distribution and susceptibility analysis in the three different geological, climatic and geomorphic settings documented great mass movements in the region of Central America due to high precipitation, weak bedrock lithology, tectonic structure and activity, seismic tremors, intensive weathering, great relief energy, slope geometry and sometimes by human activities. Such interdisciplinary approach enabled effectively identified individual slope failures in large areas around the most vulnerable places, such as cities, villages or important roads. We tried also to develop easy-to-use methodology to forecast the future occurrence of slope instabilities by establishing the susceptibility maps, because the main projects goal is not to study much the present catastrophic failures, but to identify the places of greatest hazard in the future. Two different concepts were performed, i.e.: combined quantitative-qualitative expert and field-observation based (knowledge-driven) approach (Metapán and Estelí areas) and numerical-based (data-driven) one in Miramar. The first one uses a combined scale for different geohazards in each susceptible region of the map and it is expert-experience dependent; on the other hand, the data-driven approach is strictly focused on slope instabilities, but some of the existing slope-failures (especially the deep-seated ones) do not correlate much with the most susceptible areas. Therefore, a combination of the both approaches seems to be essential for each assessed area, due to lack of “intuition” in the numerical models and lack of objectivity in the expert-based one.

Figure 5. Slope instability maps of the Miramar area (NW Costa Rica). a) Slope-failures inventory map. Landslide, earthflow and rock avalanche bodies are displayed in red. b) Numerical based slope-failure susceptibility map. Legend: red = areas more susceptible to landsliding; yellow = areas less susceptible to landsliding; no color = stable areas.
In the future, the numerical analyses for assessing the slope-failure susceptibility in large areas will be improved and calibrated. For very specific sites, e.g. steep slopes over densely inhabited cities, a geotechnical numerical codes (Flac 5.0 or PFC) will be more intensely applied to confirm the field observations and to enable better development of emergency scenarios. The methodology is still not finished and it is being flexibly developed. It should be comparable within all the studied countries and with the local approaches (e.g. Muñoz et al. 2005). The methods should be still discussed with other methodologies of international projects, e.g. PRACC (2003), COSUDE or Norlat et al. (2003) dealing with natural hazards susceptibility mapping in the region. The main goal is, namely, more effective helping the local authorities and the co-operating institutions to predict possible catastrophies and to more effectively plan urban development and landuse.

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