# Extended TOBIA model for the assessment of deep-seated geological induced landslides

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## Introduction

Slope stability is connected to different kind of conditioning factors[1]. Past studies have shown that geological and structural settings play an important role in controlling the occurrence of landslides[2,3]. The geometrical information of bedding planes such as dip angle and dip direction are usually obtained through geological field mapping. However, mapping information for larger areas is resource intensive and time-consuming. This restricts the possibility of using bedding and structural data for the assessment of landslide susceptibility. The wide availability of computer-based methods and digital elevation model data offers new opportunities in structural terrain analyses of large regions.

## Methods

Semi-automatic method to extract information on the orientation of bedding planes through the visual interpretation via high-resolution digital terrain models (HRDTM) in which geological settings are perfectly visible by eyes in universal Hillshades.

## Morpho-Line Concept

Uses HRDTMs to digitalize bedding traces which are characterized by clear edges of terrain and elevations which repeat periodically in one direction (Fig. 1). To model locations without MLs and validate the calculated bedding orientations field measurements were carried out in selected areas.

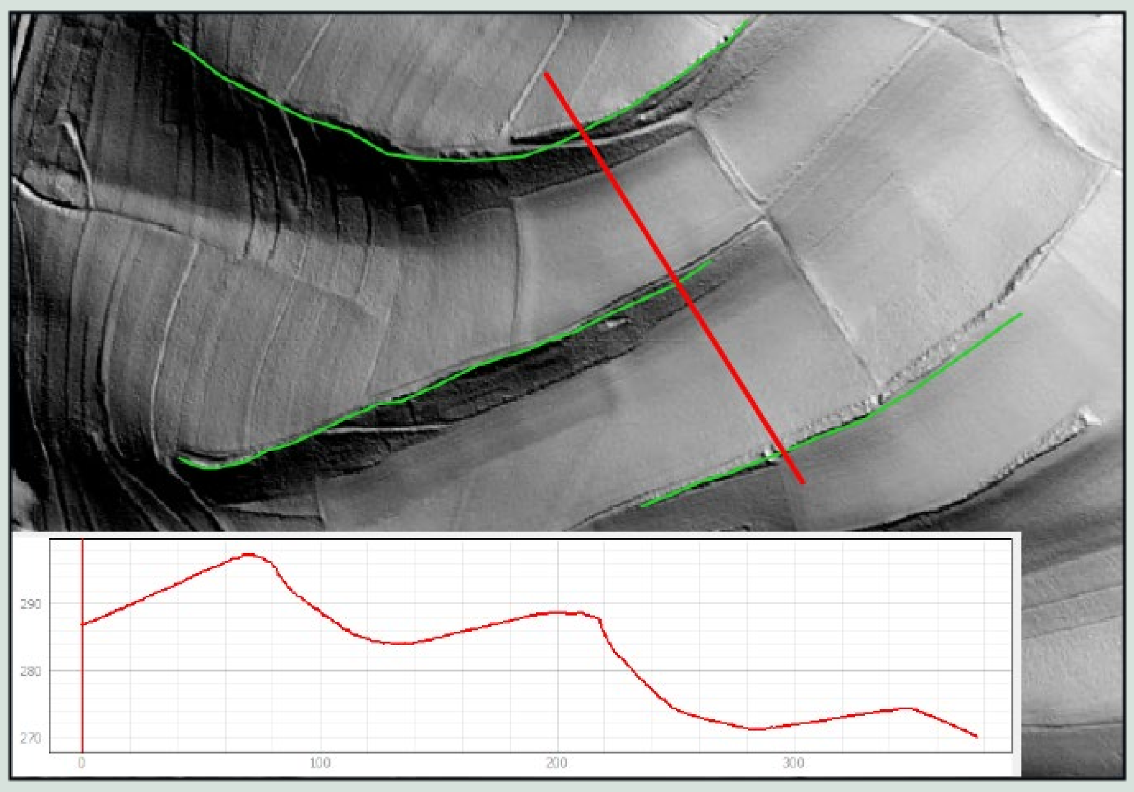


*Fig.1: Display of Morpho-Lines (green) capturing terrain edges with the corresponding topographic profile (red). It shows the typical stepwise (periodically) geometry of bedding traces.*

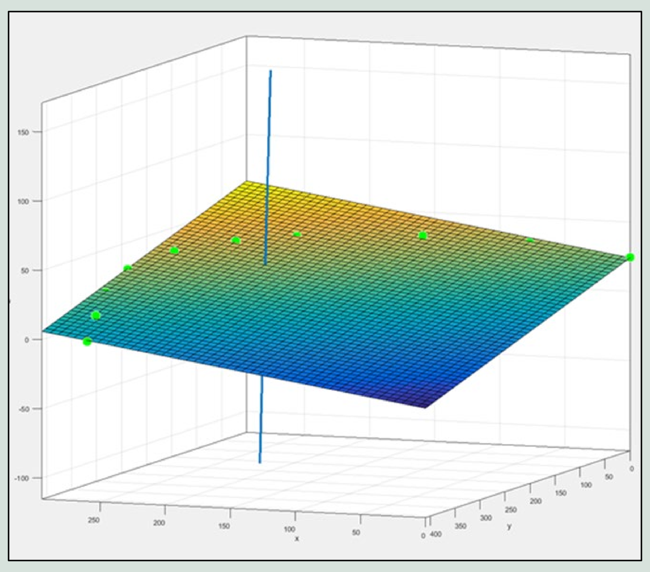


*Fig.2: Example of interpolated plane from morpho-lines*

## Calculation of bedding attitude

A MatLab Script calculates dip and dip direction with the error deviations $r^2$ and RMSE by means of the plane equation. It interpolates planes from point data (x,y,z) using the least squares fitting method. After that, the normal vector $(\vec{nv})$ is calculated from this plane. Then dip and dip direction are derived from $\vec{nv}$ (after Santangelo et al., 2015).

## Interpolation of bedding orientation

To interpolate digital and field measurement data into the area, the "accumulated cost" module in SAGA GIS was used. This method takes valleys and faults (breaklines) into account when interpolating bedding orientation values. The Accumulated Cost (AC) tool provides a layer that allocates dip and dip direction to polygons considering borders of and within a grid (Fig.3).

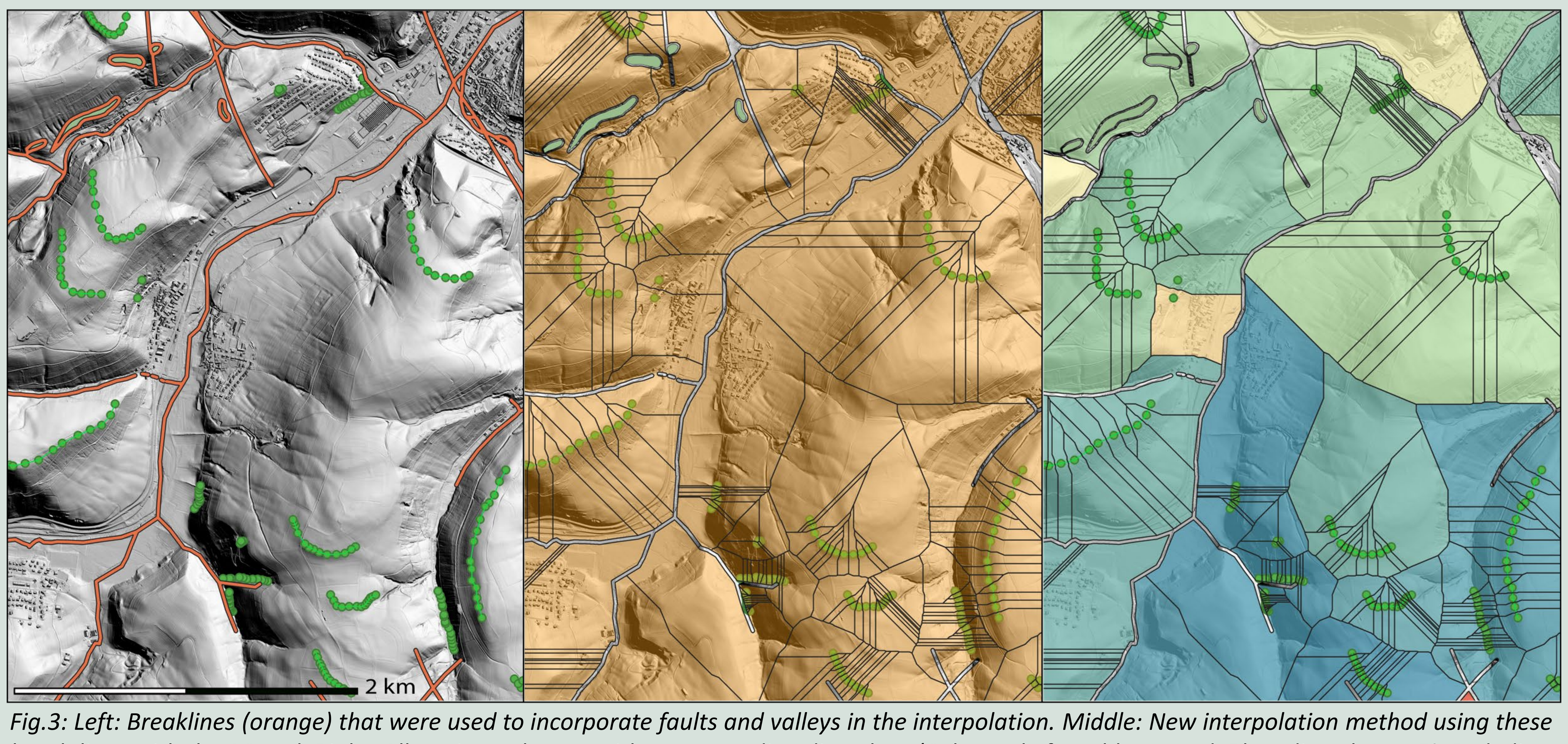
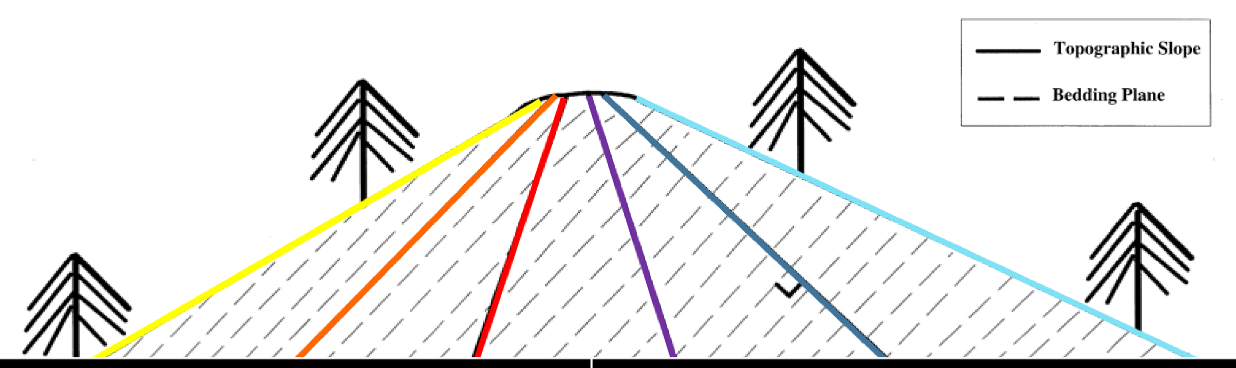



*Fig.3: Left: Breaklines (orange) that were used to incorporate faults and valleys in the interpolation. Middle: New interpolation method using these break-lines with the AC tool. Right: Allocation polygons with corresponding dip values (Color scale from blue to red. Blue: dip values ≤ 5°. Red: dip values >45°).*

## Extended TOBIA model

The TOBIA (Topographic Bedding Intersection Angle) model by Meentemeyer and Moody (2000) is used to determine the angle between topography and geological layer surfaces.




| Cataclinal slopes | Anaclinal slopes |
|---|---|
| **Underdip Slope** (Slope less steep than the dip) S < θ | **Steepened escarpment** (steeper than the bedding plane) S > θ |
| **Dip Slope** (dip slope = bedding dip) S = θ | **Normal escarpment** (perpendicular to the dip of the bedding plane) S = θ |
| **Overdip slope** (slope steeper than dip) S > θ | **Subdued escarpment** (less steep than bedding plane ) S < θ |

*Fig. 4: TOBIA classification of cataclinal and anaclinal slopes after Meentemeyer and Moody (2000). The calculation requires four parameters: slope S (0-90°), aspect A (0-360°), dip direction α (0-360°) and dip θ (0-90°). The categorical TOBIA classifies slope types through the alignment of bedding planes to topography. The chord length (L) is used for classification[4].*

$$L = \sqrt{(\cos\alpha - \cos A)^2 + (\sin\alpha - \sin A)^2}$$

**Acknowledgments**

In Orthoclinal slopes, slope and bedding are perpendicular to each other independent of the general spatial position. Thus the original classification does not give any information about the angular relationship between bedding layer and slope. This requires an additional classification of orthoclinal slopes, which was integrated and tested in the new extended TOBIA model. The chord length (L) and the angle difference of slope and dip was used to further classify the orthoclinal slopes.

| classification | slope type | angle | orientation | L | further terms |
|---|---|---|---|---|---|
| Cataclinal (CAT) | underdip | S < θ | Δ α - A = 0°* | 0 ≤ L ≤ 0.7654 | θ – S > 5° |
| | dip | S = θ | Δ α - A = 0°* | 0 ≤ L ≤ 0.7654 | -5° ≤ θ - S ≤ 5° |
| | overdip | S > θ | Δ α - A = 0°* | 0 ≤ L ≤ 0.7654 | θ - S < -5° |
| Anaclinal (ANA) | steepened | S > θ | Δ α - A = 180°* | 1.8478 ≤ L ≤ 2 | θ – S < -5° |
| | normal | S = θ | Δ α - A = 180°* | 1.8478 ≤ L ≤ 2 | -5° ≤ θ - S ≤ 5° |
| | subdued | S < θ | Δ α - A = 180°* | 1.8478 ≤ L ≤ 2 | θ - S > 5° |
| Orthoclinal (OCL) | CAT underdip | S ⊥ θ | Δ α - A = 90° or =270°* | 0.7654≤ L ≤ 1.4142 | θ – S > 5° |
| | CAT dip | S ⊥ θ | Δ α - A = 90° or =270°* | 0.7654≤ L ≤ 1.4142 | -5° ≤ θ - S ≤ 5° |
| | CAT overdip | S ⊥ θ | Δ α - A = 90° or =270°* | 0.7654≤ L ≤ 1.4142 | θ - S < -5° |
| | ANA steepend | S ⊥ θ | Δ α - A = 90° or =270°* | 1.4142 ≤ L ≤1.8478 | θ – S < -5° |
| | ANA normal | S ⊥ θ | Δ α - A = 90° or =270°* | 1.4142 ≤ L ≤1.8478 | -5° ≤ θ - S ≤ 5° |
| | ANA subdued | S ⊥ θ | Δ α - A = 90° or =270°* | 1.4142 ≤ L ≤1.8478 | θ - S > 5° |

*Tab. 1: Classification of slope types according to the extended TOBIA. Modified after Meentemeyer and Moody (2000). *± 45°. The red circled part shows the new subclasses of the orthoclinal slopes.*

## Results

The bedding values were validated using field measurements. The dips (θ) of the Morpho-Lines are usually between 0-17° below the values of the terrain measurements. For the dip direction the values differ on average by ±25° from the field measurements. Fig. 5 suggests that deep-seated landslides (LS) are abundant in the cataclinal slopes, particularly in dip slopes.

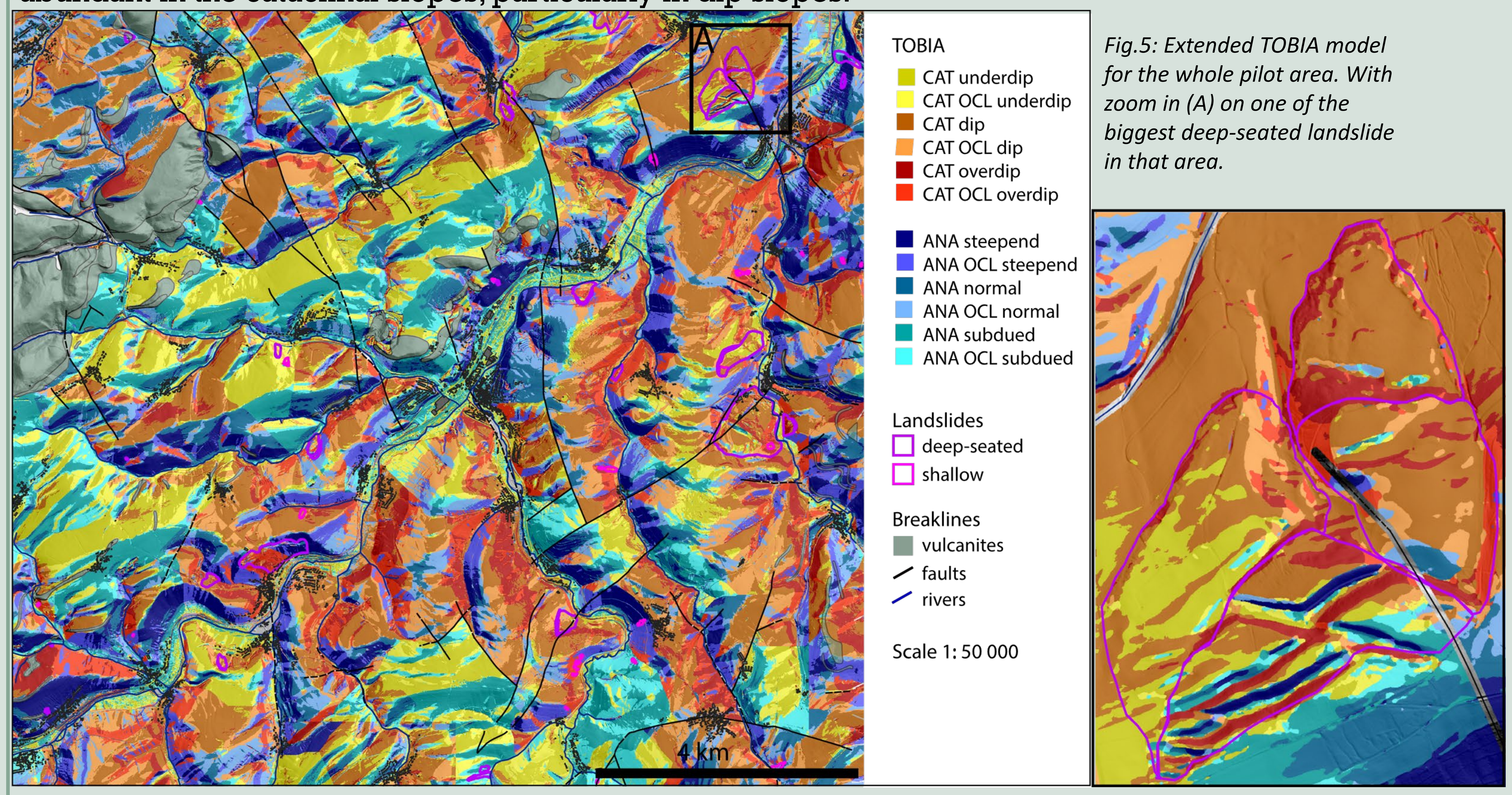



*Fig.5: Extended TOBIA model for the whole pilot area. With zoom in (A) on one of the biggest deep-seated landslide in that area.*

Figure 6 shows that he proportion of deep-seated LS in cataclinal slopes is over 50 %. The anaclinal slopes only cover 8% of landslide area and orthoclinal slopes cover almost 40%. When looking at the subclasses, 30% of the cataclinal class are dip slopes. For the orthoclinal class the cataclinal trends like dip and overdip slopes, have the highest percentage (12%).

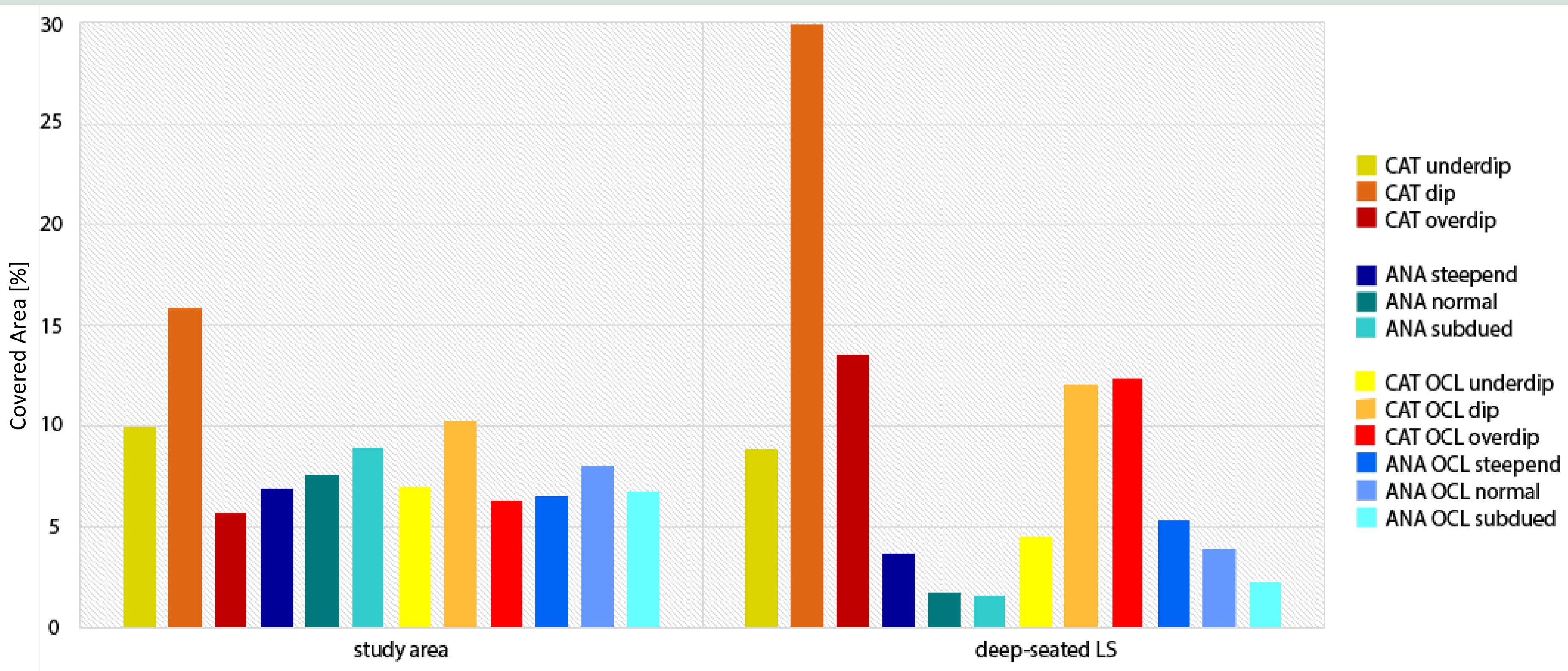



*Fig. 6: Histogram with extended TOBIA class distribution in percent. Left: Distribution of the whole area. Right: Distribution for deep-seated landslides.*

## Conclusion

- Digital and classical methods were used to investigate the relationship between the bedding orientation and the topography and its influence on landslide susceptibility.
- The extended TOBIA model is used to establish the relationships between bedding orientation and the attitude of the terrain
- **The analysis revealed that bedding conditions impact the susceptibility of slopes for deep-seated landslides. These are most abundant in cataclinal dip and over dip slopes.**
- **This accurate and spatially distributed information on slope types for large areas can be used to prepare more advanced landslide susceptibility maps.**

## References

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