Soil thickness mapping using seismic surface waves for the assessment of soil vulnerability to erosion

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1. Introduction

The purposes of the multidisciplinary DIGISOL project are the integration and improvement of in situ and proximal technologies for the assessment of soil properties and soil degradation indicators.

Foreseen developments concern sensor technologies, data processing and their integration to applications of (digital) soil mapping (DSM). Among available techniques, the seismic one is, in this study, particularly tested for characterizing soil vulnerability to erosion. The spectral analysis of surface waves (SASW) method is an in situ seismic, non destructive technique used for evaluation of layers thickness and the associated shear waves velocity (Vs) with depth in layered systems. The method is based on the propagation of mechanically induced Rayleigh waves. By striking the ground surface with a hammer, seismic waves are generated, including surface Rayleigh waves. During their propagation, they are recorded by seismic receivers (geophone sensors) regularly spaced along a profile to produce a seismogram. The particularity of Rayleigh waves lies in the dependence of their velocity on frequency, a phenomenon called dispersion. A profile of Rayleigh wave velocity versus frequency, i.e., the dispersion curve, is calculated from each recorded seismogram before to be inverted to obtain the vertical profile of Vs. Areas of different properties are then easily distinguishable as the Vs in a material is directly linked to its stiffness. Then the stiffness of the medium as a function of depth can be obtained. This last information is a good indicator to identify the boundary between regoliths and bedrock. From a geometric point of view, a SASW system adapted to soil characterization is proposed in the DIGISOL project. This system was tested for the digital mapping of the thickness of loamy material constituting the soil over clayey bedrock, in a catchment of the European loess belt. Parametric penetrometric studies and drillings are also conducted for the purpose of verifying the accuracy of the procedure and evaluating its limitations.

Soil erosion is recognized as a major threat (Figure 1a) through off-site pollution and muddy floods and its impact on On-site production of biomass, environmental filter and organic matter content. In the European loess belt, soil erosion rates often exceed soil production rates (Figure 1b). As a consequence, a precise spatially characterisation of the soil thickness is required to assess the vulnerability of the soil to different land uses and to investigate its past erosion history.

2. The field experiments

The studied site is situated in the European loess belt. Figure 2b shows the geological context of the area. The white chalk base is covered by a layer of clay with fine silt which is even covered with loess material. The accumulation of loose deposits in the basin is due to tuya’s erosion mechanism. We are then expecting variations in soil’s thickness at the catchment scale.

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3. Theory and basic principles of the SASW method

The spectral analysis of surface waves (SASW) method is an in situ seismic, non destructive technique used for evaluation of layers thickness and the associated shear waves velocity (Vs) with depth in layered systems. The focus on the exploitation of surface waves by analyzing its dispersive behavior, i.e., the dependence of phase velocity with frequency. Low frequencies bring informations on shallow layers while high frequencies inform on deeper layers. Three steps are involved in a surface wave test: (1) field testing for recording surface waves, (2) determination of the experimental dispersion curve from the field data, and (3) inversion of shear wave velocity profile from the experimental dispersion curve.

2D wavefield transform method is used to determine experimental dispersion curve. Wavefield transformation methods involve a 2D wavefield transform in which the data are transformed from space–time domain into a more convenient domain (σ, ω). The dispersion curve, i.e., the plot of phase velocity versus wavelength (or frequency), is associated with the peaks in the transformed spectrum.

The inverse problem aims at finding the parameters which characterize in the best way the medium (here the Vs and thicknesses of layers). The real dispersion curves, compared to synthetic curves, create residues of phase velocity, which constitute the set of parameters which minimizes these residues in the least square sense. The parameters are and linked to the data  through a model, which consists in a non linear relation (Tarantola, 1987). This non linear problem can however be linearized to an iterative procedure defined by:

\[ \sigma = \sqrt{W} (A + \Lambda \chi)^{-1} \]

Where is the matrix of the partial derivatives of phase velocity with regard to the parameters (Vs and thicknesses of layers) and contains the a priori information about the model. The matrix A can be decomposed as a function of its values (A) and main vectors (U and V) in the following way:

\[ A = U V^T \]

Then, the solution of the problem by decomposition in singular values is:

\[ \sigma = \sqrt{W} U (V^T \Lambda V + I)^{-1} V^T \]

The matrix of a posteriori covariance gives an estimation of the true interval of the parameters A

\[ \sigma \approx \sqrt{W} U (V^T \Lambda V + I)^{-1} \]

In the same way, the resolution matrix is obtained with:

\[ \sigma \approx \sqrt{W} U (V^T \Lambda V + I)^{-1} V^T \]

A weighting factor W is introduced in order to control the variation of the parameters of the model for each iteration.

4. Retrieval of the soil properties

Some empirical relationships can be found between stiffness and shear wave velocity Vs. We use an in situ geotechnical parameter qd, which is the dynamic resistance measured with the PANDA penetrometer. Some studies (Gourves and Barjot, 1995) have highlighted correlations between qp and qc obtained from the static penetrometer CPT. On the same way, empirical relations are established between maximum shear modulus Gmax and qc, for various types of soils (Lunne et al. 1997), (Mayne and Rix, 1995). Then we have a correlation between Vs and qd using the shear modulus. Correlation between Vs and qd is shown on figure 4.

4. Results

According to penetrometric soundings, the bedrock is reached for average 230 m/s on the seismc section (Figure 4). This velocity is then extracted from the 3D seismic velocities distribution to create an interface representing the contact between soil and bedrock (Figure 5a). The soil thickness is obtained, calculating the difference between the topography values and the 230 m/s isourface. Figure 5b and c shows the map of the soil thickness, and the map of the mean shear waves velocity of soil for the studied site. Areas of sedimentary accumulation can easily be distinguished, regarding the soil thickness. The mean of the shear waves velocity of soil should be a strong indicator of the susceptibility to erosion, as regions of low stiffness can easily be eroded.

5. Conclusion

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6. Acknowledgment

References


Figure 4: Comparison between shear waves velocity section and core depth distance from perentrometric measurements.

Figure 5: a) representation of the 230 m/s isourface (soil-bedrock limit) in the 3D seismic velocity gather; b) map of the mean shear waves velocity; c) map of the soil thickness.

a) Photography of the studied area; b) Associated Geological section

157 seismic shots were performed along a regular grid with measurements every 12m (Figure 3a). 11 sections were investigated in the direction of slopes (profiles 1 to 13 on Figure 3a) and 3 sections in the transverse direction (profiles 14, 15 to 18, 19 on Figure 3a). Measurements cover a zone of 140mx15mx5m. The main parameters were also conducted along profile 5 to characterize the contact between loess material and clays (Figure 3b).

Figure 3: a) Measurements coverage; b) Cone resistance proiel shown the stiffness difference between loess and clays

The map of the soil thickness is coherent with the impact of the expected erosion phenomenon at the catchment scale and allows to provide indications of historical erosion events. This methodology will help to target conservation measures to the most threatened areas, i.e. areas that show a reduced depth to bedrock associated with high soil erosion vulnerability.

Figure 1: a) Photography showing critical soil’s thickness; b) Soil erosion rates in Europe.

Figure 2: a) Photography of the studied area; b) Associated Geological section

Figure 3: a) Measurements coverage; b) Cone resistance profile showing the stiffness difference between loess and clays

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