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

[1]Samyn K., [1]Cerdan O., [1]Grandjean G., [1]Bitri A., [1]Bernardie S., [2]Ouvry J. F.

[1]BRGM, Orléans, France
[2]AREAS, Saint-Valery en-Caux, France

1. Introduction

The purposes of the multidisciplinary DIGISOIL 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 characterising 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 with 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 geometrical point of view, a SASW system adapted to soil characterisation is proposed in the DIGISOIL 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 exceeds soil production (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.

Figure 1: a) Photography showing critical soil's thickness; b) map of soil erosion rates in Europe.

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 mounted by a layer of clay with flint which is even covered with loess material. The accumulation of loess deposits in the basin is due to tray's erosion mechanism. We are then expecting variations in soil's thickness at the catchment scale.

Figure 2: 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). 13 sections were investigated in the direction of slopes (profiles 1 to 13 on Figure 3a) and 3 sections in the transverse direction (profiles 14_T to 16_T on Figure 3a). Measurements cover a zone of 140mx150m i.e. 2.1 Ha. Parametric penetrometric studies were also conducted along profile 5 to characterize the contact between loess material and clays (Figure 3b).
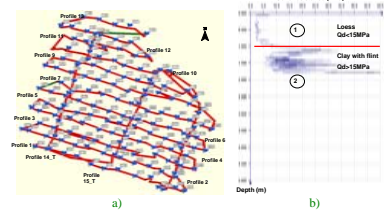

Figure 3: a) Measurements coverage; b) Cone resistance profile showing the stiffness difference between loess and clays

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. We focus on the exploitation of surface waves by analysing its dispersive behaviour i. e. the dependence of phase velocity with frequency. Low frequencies bring informations on shallow layers while low 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 (p–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 *y* data of the inverse problem. The inversion process consists in finding a set of parameters *x* which minimizes these residues in the least square sense. The parameters *x* are linked to the data *y* through a model, which consists in a non linear relation (Tarantola, 1987). This non linear problem can however be linearized to an iterative problem defined by:

$$[(Ax-y)'(Ax-y)+\sigma^2 x'x]=MIN$$

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

$$A=U\Lambda V'$$

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

$$x=V(\Lambda^2+\sigma^2 I)^{-1}\Lambda U'y$$

The matrix of the *a posteriori* covariance gives an estimation of the trust interval of the model:

$$C=V(\Lambda^2+\sigma^2 I)^{-1}\Lambda^2(\Lambda^2+\sigma^2 I)^{-1}V'$$

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

$$R=V(\Lambda^2+\sigma^2 I)^{-1}\Lambda^2 V'$$

A weighting factor *W* was 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 *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 qd 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 the stiffness of the material and the shear waves velocity using the shear modulus. Correlation between Vs and qd is shown on figure 4.
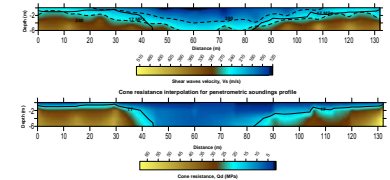

Figure 4: Comparison between shear waves velocity section and cone resistance section from penetrometric measurements.

4. Results

According to penetrometric soundings, the bedrock is reached for qd=15 MPa. This corresponds to about 230 m/s on the seismic section (Figure 4). This velocity value is then extracted from the 3D seismic velocities distribution to create an isosurface 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 isosurface. 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 map of the mean shear waves velocity of soil should be a strong input for the assessment of soil susceptibility to erosion, as regions of low stiffnesses can easily be eroded.
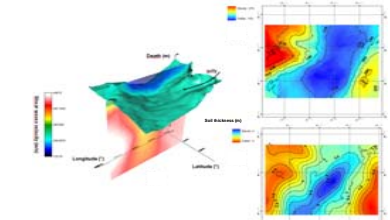

Figure 5: a) representation of the 230 m/s isosurface (soil-Bedrock limit) in the 3D seismic velocity gather; b) map of the mean shear waves velocity; c) map of the soil thickness.

5. Conclusion

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.

6. Acknowledgment

7. References

Gourvès, R., Barjot, R., 1995. Le pénétromètre dynamique léger Panda. Comptes rendus, 11ème congrès Européen de Mécanique des Sols et des Travaux de Fondations, Copenhague, vol. 3, 83-88.
Grandjean, G., DIGISOIL team 2008. DIGISOIL: an integrated system of data collection technologies for mapping soil properties. EGU General Assembly, Vienna. Abstract and Poster.
Lunne, T., Robertson, P., Powell, J., Cone Penetration Testing in Geotechnical Practice, , Blackie Academic and Professional, London (1997).
Mayne, P. W., Rix, G. J., Correlations between shear wave velocity and cone tip resistance in natural clays, *Soil and Foundations* 35 (1995) (2), pp. 107–110.
Tarantola, A., 1987. Inverse problem theory: methods for data fitting and model parameter estimation. Amsterdam: Elsevier Science Publishers.

k.samyn@brgm.fr