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Geophysical investigation for mechanical properties of a glacier

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In glaciology the mechanical properties of ice and snow, stratigraphy, depth of ice are useful in order to predict the movement and breakup of glaciers over time as glacial flow and crevasse formation (Petrovic, 2003). In such a context, geophysical investigation using georadar (GPR) and seismic are well known investigating techniques for getting information on iced areas. Examples of GPR surveys in Alps (e.g. Navarro et al. 2005) and in polar environment for detecting structures inside the glacial ice in Antartica are well known (e.g Arcone et al. 1996). Eisen et al. (2003) analysed GPR profiles in conjunction with ice core data to obtain information about internal features of an alpine glacier.

Moreover many authors as Kohnen and Bentley (1973) and recently King and Jarvis (2007) used seismic refraction data to infer about P and also S-wave velocity in polar environment. They obtained vertical velocity profiles within the snow/firn and ice showing a smoothed increase of seismic wave velocity with depth. Seismic wave velocities are related to the material stiffness, their value increase as the bonding between grains became stronger and could slightly decrease with density increments; the behaviour of the seismic wave velocities with depth is then influenced by the balance of these two factors.

The aim of the present work is to show the capabilities of the geophysical techniques in studying the behaviour of temperate glaciers and illustrate how they complement to each other in accomplishing firn and ice properties in alpine environment. We evaluated the glacial layering and ice thickness by means of GPR survey. Seismic surveys were focused in estimating the compressional (P) and shear (S) wave velocity of the shallow firn and ice; snow density have been derived applying empirical formulas and subsequently mechanical properties like as bulk and shear modulus and Poisson ratio were computed.

The study is based on a geophysical survey performed in May 2010 on the Prè de Bar Glacier in Aosta Valley (Italy). The Pré de Bar is a small valley glacier situated in the northern part of the Mont Blanc Massif, at the end of the Ferret Valley, the border edge between Italy, France and Switzerland. The glacier covering is characterised by a variable seasonal snow depth during the winter (average of 5-6 meters in the investigated area) and a layer of older snow and firn in the order of some meters, overlying the glacier ice.

We performed two GPR transects in continuous reflection mode with a 70 MHz bistatic antenna. GPR traces were carried out both along and orthogonally the ice flow direction, geographical positioning of radar traces was provided by GPS (Global Positioning System) in real time kinematic acquisitions.

Wide Angle Reflection and Refraction (WARR) was performed for velocity analysis; the data processing by the application of the semblance analysis method permitted to estimate the vertical profiles of radar velocity to a depth of 10-12 meter from the surface; this allowed the seasonal and older snow layering and the layer density to be estimated.

Seismic acquisitions were performed with a 24 channel seismograph and vertical 4.5 Hz geophones. A sledge-hammer with a plastic plate (50 x 50 cm) let to apply an adequate energy at the snow surface. Geophones were directly driven in the superficial snow. We achieved P-wave velocity profile with the procedure adopted by King and Jarvis (2007), based on the Herglotz-Wiechert approach (Aki and Richards, 2002). The procedure allow to estimate a vertical smoothed profile of the P-wave versus depth.

The S wave velocity profiles were achieved analyzing the dispersive characteristics of the surface waves propagating in the shallow firn and ice. The gradual increase of the mechanical properties with depth causes a dispersion of seismic waves; the dispersion curve of the phase velocity of the surface wave is analysed by f-k spectrum; the shear wave velocity profile (1D) is computed by stochastic and deterministic inversion of the fundamental mode of the dispersion curve.

The main results can be summarised as follows: GPR sections showed a marked stratified structure of the glacier; coherent continuous reflections are present along the two profiles. The bottom glacier reflection is well detected; the maximum ice thickness was estimated in about 28 m considering a mean wave velocity of 0.17 m/ns. Seismic wave velocity profiles were estimated from the surface to a depth of about 25-30 meters.

Poisson ratio were derived from the P and S-wave profiles and density profile was estimated with the Kohnen empirical relation (Kohnen, 1972). P-wave velocity changes with depth from 1500 m/s on the surface to 3600 m/s at deeper level, while S-wave velocity varies from 800 m/s to 1500 m/s. Subsequently bulk and shear modulus profiles were computed: estimated values are in according with the results reported in the literature.

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