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Pressuremeter test in glaciated valley sediments (Andorra, Southern Pyrenees) Part one: An improved approach to their geomechanical behaviour

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The Andorra Glaciated Valley

Setting

The Principality of Andorra is a little county (465 km^2) located between France and Spain (42°30'N, 1°30'E), at the foothills of the SE Pyrenees. The tributary valley system has an "Y" shape and at the Upper Pleistocene different glaciers came together (Turu et al. 2007) to the main valley, where actually is locate the biggest city (Andorra la Vella) of Andorra. Understanding the stratigraphy of the glacial loaded sediments of Andorra is particularly important for civil engineers (Turu 2000). Glacial sediments produced during Quaternary glacial periods are widespread in both mountainous and lowland zones and influence many construction projects. One of the characteristics of such sediments is the great variability and unpredictability of the consolidation state and accurately geotechnical and geophysical surveys are needed.

Geomechanical data, pressuremeter tests

Intensive investigations of the architecture and character of valley floor sediments have been undertaken in the main Valley, in association with site investigations for major constructions until 1995 (see Turu et al. 2007) with up to 900 geotechnical surveys in the country.

The conclusion of all those surveying years is that the best geotechnical data to obtain the stress/strain behaviour of glaciated sediments are pressuremeter tests data.

The theoretical basis for this test was provided by Ménard and Baguelin et al. (1978) who also created a commercial design. Interpretation procedures are described by AFNOR (1999, 2000). In this test, a pneumatic cell, with flexible walls in a metallic slotted-tube is pushed into a pre-existing bore-hole. This push-in technique (Reid et al. 1982; Fiffle et al. 1985) reduces possible soil disturbances. A hydro-pneumatic system controls cell pressure, and expanding cell walls exert a horizontal stress on the bore-hole walls, whose deformation is concurrently measured by the expansion of the cell wall. Once the test is ended the pneumatic cell and the slotted-tube are extracted, cleaned, eventually repaired and calibrated.

Basically, when a certain pressure threshold is exceeded, volume expansion of the pneumatic cell increases rapidly, marking the change from elastic to plastic soil behaviour.

Rheological interpretation is based on the assumption of radial expansion of a cylindrical form in an isotopic elasto-plastic medium (Cassan 1982), and the test also yields the Young's modulus of the soil for a given value of Poisson ratio.

Stress/Strain analysis, the pressuremeter data

The most relevant data obtained will be synthesised in this paper without taking into account their geological setting, specifically data obtained from pressuremeter tests.

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As previously stated, this test has been performed in bore-holes, introducing the cell at depths between 5 and 25 meters which, in the best case scenario, implies ground pressures acquired according to a gravitational gradient between 0.1 to 0.5 MPa. However, with pressuremeter tests, overconsolidation pressures up to ten times greater than these have been obtained, implying that glacial sediments may be strongly consolidated.

Stress/strain data (pressuremeter P/V data) obtained permit us distinguish basically three types of charts (see Fig. 1):

- Type 1: P/V evolution with a single yield point
- Type 2: P/V evolution with various yield point
- Type 3: P/V evolution without any apparent yield point and strain rebounds are observed (ratcheting)

Type 1 P/V evolution is that which is most commonly described in the literature, a linear stress/strain behaviour from elastic domain is observed until a yield point is reached where start non-linear stress/strain behaviour from the plastic domain. Type 2 P/V evolution may appear in the literature, but is generally interpreted in the same manner as type 1, and in certain cases this type of curve is attributed to poor e xecution of the test, perturbation of the ground tested or the influence of large boulders near the pressuremeter testing cell; but since the same kind of diagrams in widespread glacial sediments is observed (subglacial tills, melt-out tills, glaciotectonites, lateral tills), we should think as inherent to those sediments, only in soft rocks with penetrative cleavage had been also observed (Devinzenci, Turu 1999). Type 3 P/V evolution is generally interpreted in the literature as corresponding to very compact ground, ratcheting is observed by strain rebounds on that type 3 diagrams, but no notice is known int the specialised literature about that phenomenon. The exact value of the critical state or yield point being usually unknown.

Discussion

The discussion deals with the purpose of this paper, the rheological interpretation of type 2 and type 3 pressuremetric curves. I will begin by explaining type 1 and continue with the subsequent types.

Type 1 P/V curves

These present a unique yield pressure which may correspond to pressure that is gravitational (normally consolidated), or perhaps greater than gravitational (overconsolidated). Commonly type 1 diagrams are interpreted using elasto-plastic models (i.e. Modified Cam-Clay), where the elastic behaviour is equivalent to those obtained in oedometric tests (one dimensional compression tests with lateral constraint), and the plastic behaviour is interpreted using the Coulomb failure criterion (Fig. 1a).

In Andorra this curve can be obtained if the effective pressure in the system has always been increasing or constant, with no load or unload cycles due to an ancient subglacial drainage. Usually the sediments showing type 1 diagrams had not shear strain structures, so the consolidation of those sediments were acquired in a low subglacial shear stress context.

Type 2 P/V curves

More than one yield point is observed in that type of diagrams (Fig. 1b). We can attempt to interpret that behaviour by continuous hyperplastic constitutive model in which continuous stress/strain memory (Einav et al. 2003) is related. So in type 2 diagrams the tensional history of the sediment is archived.

Usually the sediments showing type 2 diagrams have shear strain structures, like most of the subglacial tills (Evans et al. 2006). Hyperplasticity is based in the modified cam-clay constitutive model (Einav et al. 2003), and some particularities should be taking in account when pervasive subglacial shear stress is present.

The zone of till where the available shear strength is less than the constant pervasive subglacial shear stress imposed by the overlying glacier ice, undergoes critical state consolidation (Quan, 2005). That can be explained by modified Cam-Clay constitutive model, where small load-unload hydrological cycles produce that the stress state of the subglacial sediment moves away or close from the critical state line (Fig. 2a). Such consolidation is known as critical state consolidation (Quan, 2005) and can be more than 1.8 times greater than the isotropic consolidation. In other hand if the available shear strength is beyond the constant pervasive shear stress, the effective stress path goes away from the critical state at constant shear stress. Such consolidation acquired with constant shearing (Quan 2005) is lesser than the isotropic consolidation, especially for low effective pressure increments.

From geomorphology data (high position of lateral moraines) is possible to say that preconsolidations obtained from type 2 diagrams in Andorra, are always lesser or quite equal to the gravitational ice consolidation. In that sense something happen that inhibit the critical state consolidation in Andorra.

In that sense is known that for temperate glaciers, meltwaters drainage is subjected to climatic, annual and even diurnal cycles (see i.e. Boulton et al. 2001). All the subglacial hydrology is ruled to those melting cycles, the load and unload cycles transmit pore water pressure variations in the subglacial aquifer. Crit-

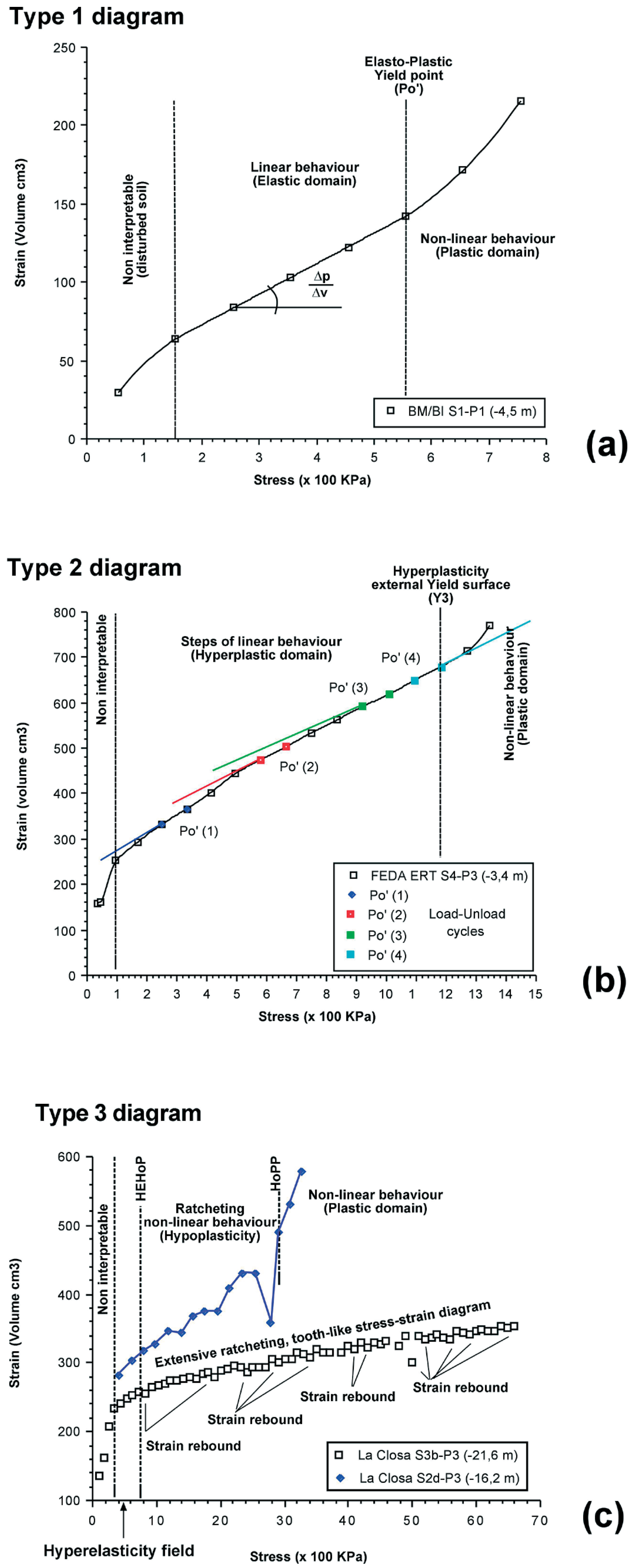

Fig. 1. Most representative type of stress/strain diagrams from pressuremeter data

a) Type 1 diagram showing an elasto-plastic behaviour. We can distinguish an elastic domain where deformation modulus is obtained by G = k ?p/?v (k is a pressuremeter constant). b) Type 2 diagram with a hyperplastic behaviour, showing the ability to record the stress/strain history of soil. Four pressure steps with a growing stiffness (less slope) of linear behaviour. c) Type 3 diagram showing strain rebound, called ratcheting as it is similar to those described in hypoplastic models. Two yield points can be distinguished were ratcheting happen between both, an hyperelastic yield point (HEHoP) and a Hypoplastic yield point (HoPP), over which failure criterion is reached

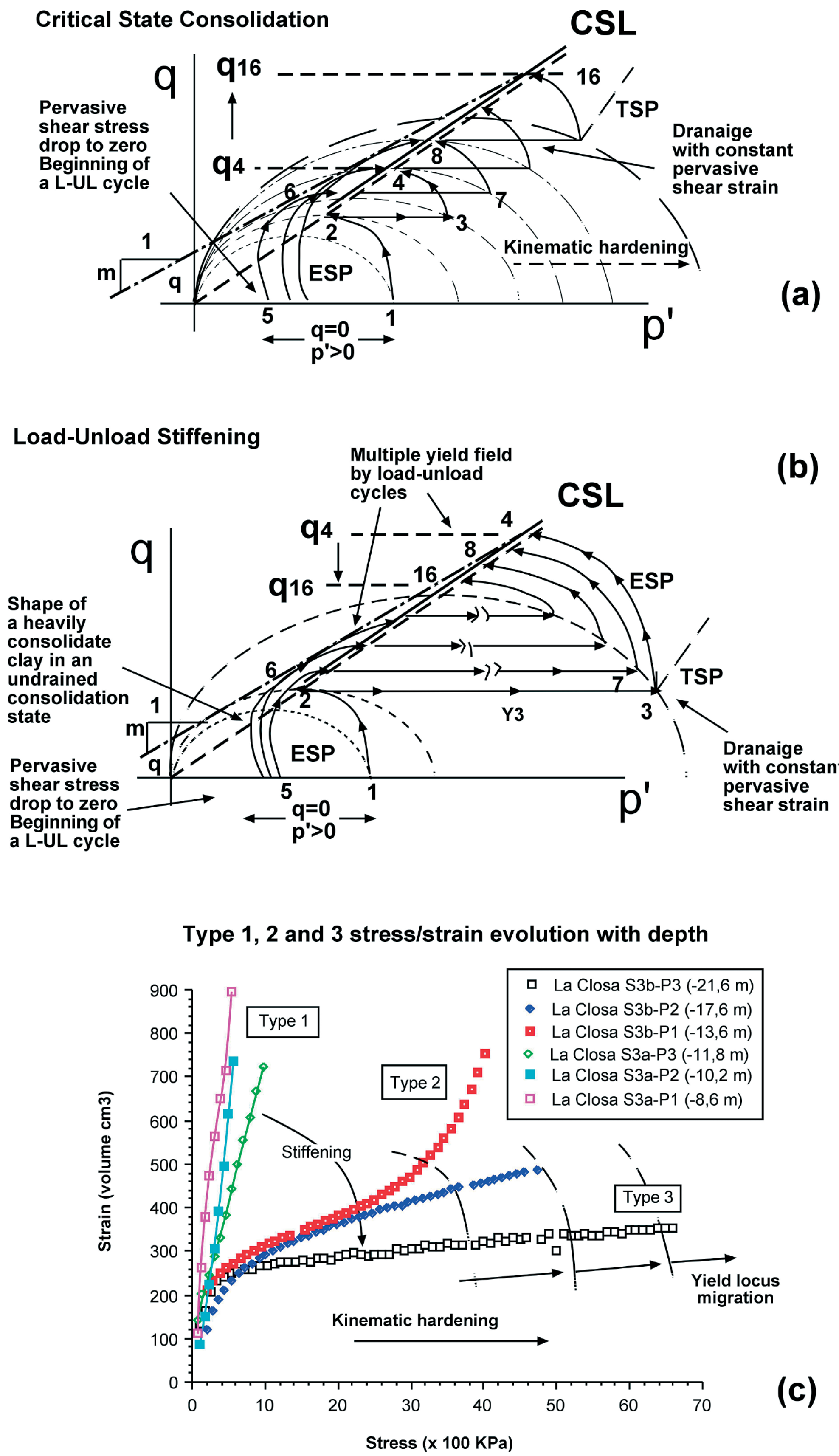

Fig. 2. Idealised behaviour of the glaciated sediments

a) Using a Modified Cam-Clay diagram of increasing or decreasing load-unload (L-UL) cycles. In a increasing strain/stress evolution, load and unload cycles with a constant pervasive shear stress can produce a critical state of consolidation. b) Using a MCC diagram in a decreasing stress/strain evolution the soil can show more than one preconsolidat,ions. c) Behaviour evolution from the pressuremeters diagrams in depth. Stiffening diminishes the slope of the stress/strain diagram and kinematic hardening produce the migration of the locus yield ical state consolidation can be inhibit after a load event with pervasive constant shear stress if the unload event is associated with a pervasive shear stress drop; or in other words, if the unload event is associated with a very bad drainage of the subglacial hydrologic system and the glacier lost contact (décollement) with its sole by flotation uplift.

If the net evolution of subglacial effective pressure over different cycles has been decreasing (Fig. 2b), it is known from constitutive models (elasto-plastic, hyperplastic, hypoplastic, hyperelastic, ...) that load and unload cycles stiffen consolidated sediments; and is manifested in the elastic field of the pressuremetric curve by a decrease in its slope (greater stiffness) by steps (Fig. 1b), with each step corresponding to a range of effective pressures of the load-unload cycles. The greater consolidation state can be rheologically assimilated to the expansion of the yield curve due to plastic hardening. If we follow the continuous hyperplasticity model (Einav et al. 2003) the outer most yield surface should be the Y3 hyperplastic yield surface (Fig. 2b). In the other hand, if the net evolution of subglacial effective pressure over different cycles has been increasing, the pervasive shear stress field consolidation can undergo the soil to critical state consolidation (Quan 2005). If pervasive shear stress is not negligible, increasing evolution of subglacial effective pressure over the different cycles will show preconsolidations greater than the decreasing evolution.

In hyperplasticity constitutive models three yield surfaces are used, a inner yield surface (Y1) were stress-strain answer is purely elastic, an outer surface (Y2) representing the outer boundary of non-linear behaviour, and both yield surfaces inside of a third one from modified cam-clay large-scale yield surface (Y3) that is the outer boundary of plastic behaviour. Type 2 diagrams multiple yield zone should be interpreted as a multiple elastic soil behaviour below the Y3 yield point (Fig. 1b).

Type 3 P/V curves

These curves have lost their tensional history and I think that those diagrams correspond to an evolution toward the hyperelasticity and hypoplasticity of type 2 curves, let me explain:

The consolidation of the subglacial sediments situated near hydraulically singular points (subglacial tunnel drainage), is subject to an intense flow of water due to being situated near the place of drainage where there is a high hydraulic drop, and therefore also subject to greater high pervasive shear stress. If high water flow through porous media produce fine grain cleaning (supported by soil analysis and geophysical data in Andorra), subglacial shear stress can rearranges the sediment grains. The soil will appear to be undergoing consolidation when its stress state is close to critical state (Quan 2005), reflecting a consolidation pressure greater than the isotropic one (Fig. 2a).

The different load-unload cycles of subglacial drainage not only lend greater stiffness to the sediment in the elastic stage, but the progressive fine grain cleaning, together with the rearrangement of the grains, also provides denser packing leading the soil to reduce its void ratio to such a degree that granular contact does not permit it to consolidate further.

Dense packing of glaciated sediment grains was detected by Turu (2000) in Andorra comparing seismic shear modulus with the pressuremeter shear modulus.

Hyperelasticity can explain easily the behaviour of dense packing soils for small strains (see Niemunis 1996; Niemunis, Cudny 1998), where the stress is transferred through the porous media and small intergranular strain occurs without new rearrangement of grains, so the strain can be considered as reversible. Nevertheless different behaviour is expected for large deformations.

For extreme stress ubiquitous ratcheting effects may be possible (Niemunis com. pers. 2007) and has been observed in type 3 stress/strain diagrams (Fig. 1c). Typical saw-tooth-like stress-strain diagrams are obtained in the vicinity of yield stress predicted by the hypopasticity models, but since now not observed experimentally because the performance of the model in comparison to experiment were evidently poor (Niemunis, Triantafyllidis 2003).

So in type 3 diagrams different stress/strain behaviours can be observed. Hyperelasticity behaviour for intergranular small-strains (Niemunis 1996; Niemunis, Cudny 1998), while for larger strains extensive accumulation of deformation by load cycles leads toward an hypoplasticity behaviour (see Niemunis, Triantafyllidis 2003). Upon the hypoplastic yield stress more larger strains are obtained for small stress increments, leading towards a failure criterion behaviour.

Separation between hyperelastic and hypoplastic behaviours should corresponds to a inner yield surface (like Y1 hyperplastic yield surface) that we will call HEHoP; while an external yield surface (like Y3 hyperplastic yield surface), formed near the critical state, should corresponding to the separation between hypoplastic and failure behaviours that we will call HoPP (Fig. 1c).

Conclusions

The hyperelastic and hypoplastic behaviour of type 3 curves derive from previous hyperplastic behaviour from type 2 curves, while hyperplasticity of type 2 in turn derive from the elastic behaviour of type 1 curves. The principal mechanism to that evolution is due to load-unload (L-UL) cycles, producing stiffening and kinematic hardening of the subglacial sediment (Fig. 2c).

The evolution from type 2 to type 3 soil behaviour should start with a critical state consolidation (HoPP yield), wile the HEHoP yield point appear when the soil is led to a dense packing by further fine grain cleaning and rearrangement of grains. Between both, type 2 expansion of the yield curve due to plastic hardening by load-unload cycles derive to ratcheting in type 3 diagrams by extensive accumulation of deformation by those cycles.

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