Evaluation of horizontal stress in a landslide

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Summary

The numerical modelling of landslide behaviour requires a constitutive model for the ground and the definition of an initial state of stress. This paper describes the use of various testing methods to evaluate the state of stress within a natural unstable slope. The selected site has been studied for more than fifteen years: displacements of the sliding mass, pore pressures and rainfall amount have been regularly measured. Self-boring pressuremeter tests, dilatometer tests and hydraulic fracturing tests were performed. Total pressure cells were also installed and strain controlled triaxial tests were carried out. The results are presented and discussed in this paper.

1. Introduction

Landslide studies usually deal both with the assessment of instability hazard and with the evaluation of potential displacements. This last problem can be solved by numerical modelling, in which case an initial state of stress must be assumed. The well known K_o concept, lateral stress ratio at rest, can not be used readily for landslide modelling, because the basic assumptions of zero horizontal strain and horizontal/vertical directions of principal stresses which prevail for horizontal deposits at rest are not fulfilled in a slope. Moreover, the stiff clays usually involved in landslides are overconsolidated, which affects the K_0 value, since this parameter depends on the overconsolidation ratio (R_{oc}) [TAVENAS & LEROUEIL, 1987].

Field measurements of the state of stress in slopes are thus needed in order to get data for numerical modelling and possibly validate specific methods for estimating the state of stress in natural slopes. Various in situ and laboratory measurement techniques were recently experimented to assess lateral stresses in the ground, in a slow active landslide located at Sallèdes [CARTIER & POUGET, 1988].

2. Methods to evaluate horizontal stress

Horizontal stresses in the ground can be assessed by direct measurement of the pressure acting on a vertical plane, or derived from measurements of one or more parameter(s) related to horizontal stresses using a simple empirical laws. Various methods were experimented in the Sallèdes landslide: pushed-in total pressure cells, dilatometer testing, hydraulic fracturing, self-boring pressuremeter, strain controlled triaxial tests.

Glötzl total pressure cells were pushed into the ground from a preformed borehole. These cells enable to measure the normal pressure acting on them, as long as excess pore-pressures generated during boring are allowed to dissipate. Glötzl cells were therefore placed 30 days before the measurements were completed at the Sallèdes site.

The dilatometer probe is a steel blade with a circular flexible membrane fixed on one of its sides. The blade is pushed from the ground surface into the soil. Every 20 centimeters an expansion test is performed and two pressures are measured: the initial pressure p_o and the pressure p_1 obtained when the membrane has reached 1 millimeter displacement. MARCHETTI [1979] gave an experimental relationship between K_o and the measured pressure p_o: $K_o = \left(\frac{p_o - u_o}{2\sigma'_{vo}}\right)^{0.47} - 0.6$. The pressure p_1 is used to give an estimate of the soil modulus.

Hydraulic fracturing is performed by injection of water into the ground, using a piezometer. Long piezometers (300 mm long, 30 mm in diameter) were used in order to obtain vertical cracks, according to the method presented by LEFEBVRE *et al.* [1991]. The test is carried out by increasing hydraulic pressure at constant rate. Injection is stopped when the peak in water pressure is reached. At this state, the applied hydraulic head steadily reduces and an observable change occurs when fractures close. The actual horizontal stress in the ground is assumed to be equal to the hydraulic closing fracture pressure.

All these methods induce some kind of disturbance in the soil, with this effect being minimized in the case of the self-boring pressuremeter. A pressuremeter based on the British probe modified by BENOÎT & CLOUGH [1986] was used in this experiment. This pressuremeter (Fig. 1) consists of a hollow cylinder covered with a rubber membrane inserted into the ground by self-boring. The test is carried out after some stabilization period. It consists in inflating the expanding membrane and monitoring the internal pressure, the pore pressure in the soil, and the movement of 9 points of the membrane by means of 9 feeler arms. Those feeler arms are disposed in 3 different horizontal planes, and along 3 independent directions on each plane. According to BENOÎT & CLOUGH [1986], the horizontal stresses can be derived from a direct analysis of the pressure vs. strain curves and observation of lift-off pressure values (Fig. 2).

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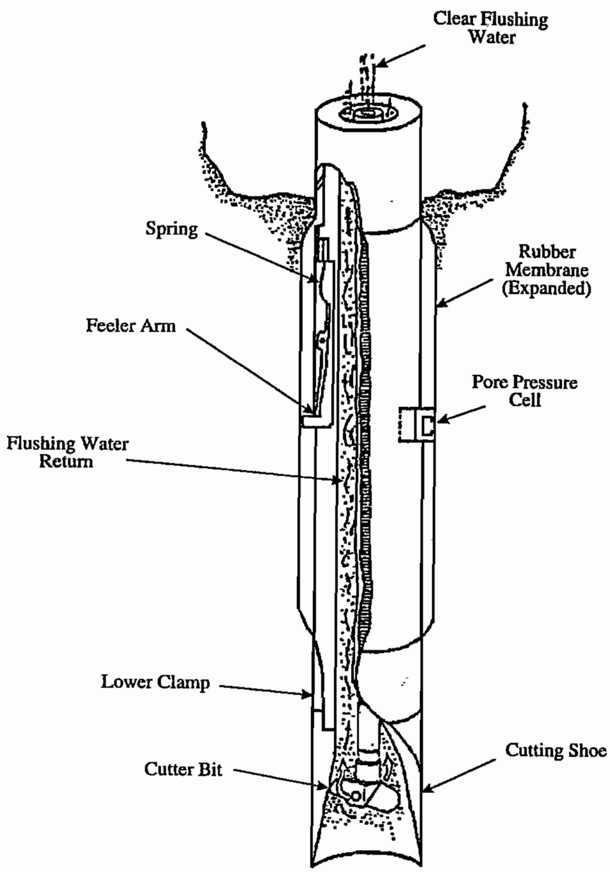

Fig. 1 – Self-boring pressuremeter probe.
Fig. 1 – Pressiometro autoperforante.

Drained K_0 strain controlled triaxial tests were also carried out. According to GARGA & KHAN [1991], the method is based on the concept that if an undisturbed overconsolidated soil sample is isotropically consolidated to the in situ effective vertical stress, σ'_{vo}, and the radial stress is subsequently increased while maintaining σ'_{vo} constant, significant axial strain only appear when the radial stress exceeds σ'_{ho}. The tests were conducted by increasing the applied radial stress σ'_r and monitoring the axial strain. A typical test curve, providing the axial strain vs. σ'_r, is plotted in figure 3. The horizontal effective stress in the ground is assumed to be equal to the value observed when the strain rate increases sharply.

3. The Sallèdes landslide

The Sallèdes landslide [CARTIER & POUGET, 1988] occurred on a smooth slope (10°) of medium stiff clays. An experimental embankment was built on the site in 1980. Amounts of rainfall, displacements and pore pressure along the failure surface have been monitored since then. The slope consists mainly of marls, which have been remoulded by the extrusion of the basaltic dike nearby uphill. The marl substratum is overlain with clayey colluvia. The soil characteristics in the sliding zone are: I_p = 40 - 60%; percentage of clay: 40 - 55%; c_u = 40 - 100 kPa; c' = 15 kPa; φ' = 25°; φ'_R = 9°.

The tests were performed in three zones defined in figure 4. Zone 1 is located uphill, far from the embankment influence; zone 2 is just above the embankment; zone 3 is at the toe of the embankment.

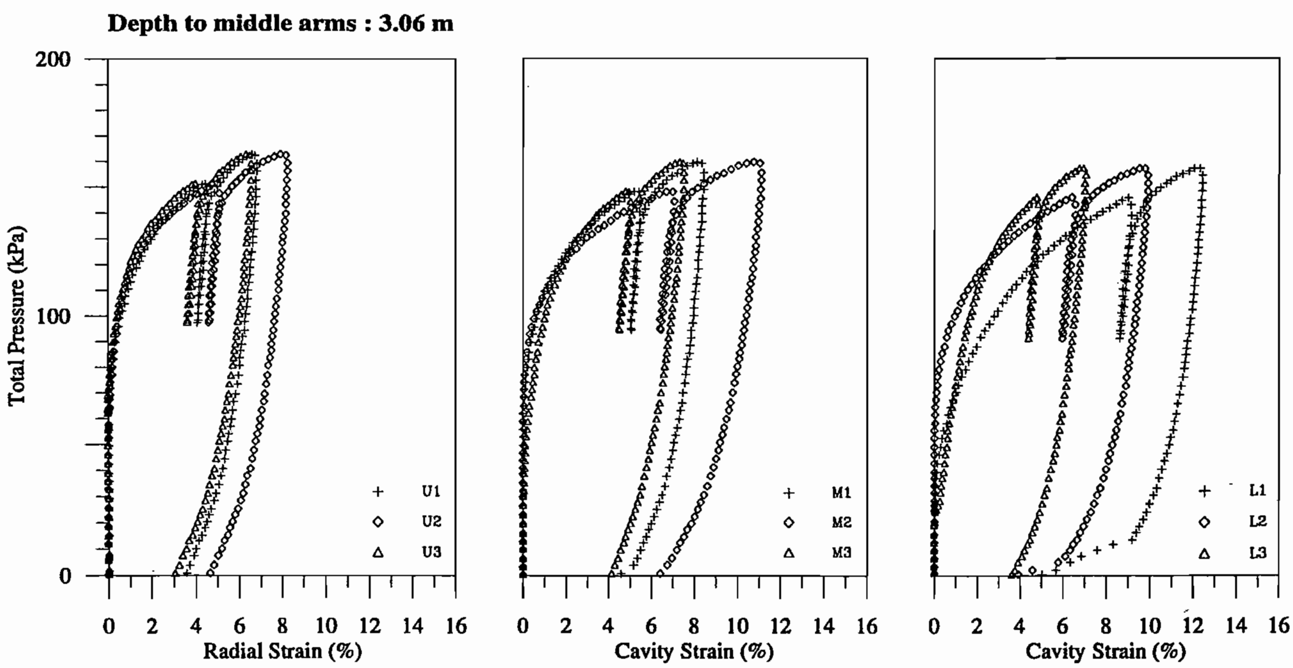

Fig. 2 – Self-boring pressuremeter curves from all nine strain sensors.
Fig. 2 – Curve ottenute mediante le prove pressiometriche.

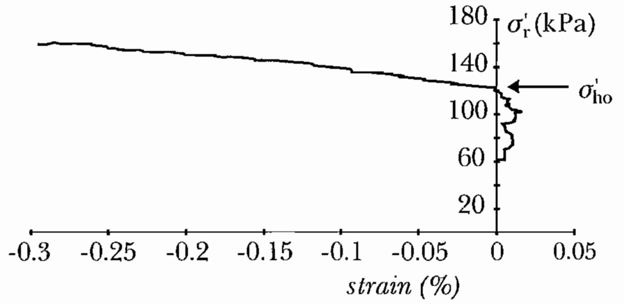

Fig. 3 – Radial strain controlled triaxial test.
Fig. 3 – Deformazioni radiali ottenute in una prova triassiale a deformazioni controllate.

4. Horizontal stresses obtained from different tests

The measured horizontal effective stresses are shown in Tab. I. They are obviously not in good agreement one to each other. Despite the numerous tests performed on the Sallèdes site, it is still undecided whether the effective horizontal stress at 3 m depth is 46, 21, 67 or 41 kPa.

Since the self-boring pressuremeter tests performed on the site did not allow to obtain significant differences between measured stresses in the x and y directions (σ_x and σ_y), the values shown in Tab. I are the average of the 9 measured lift-off pressures.

The heterogeneity of the site is clearly illustrated by the fact that profiles obtained with the same apparatus do not superimpose and greatly differ from on location to another.

It was not possible to observe any effect of the direction of measurement in the dilatometer and self-boring pressuremeter tests, this being probably due to site conditions.

We also expected to obtain significant differences between zone 1 and zone 2, on one hand, and 3, on the other hand but this is not the case.

Usually, for soft clays, according to BENOÎT & LUTENEGGER [1992], the self-boring pressuremeter provides a lower bound value for the in situ effective horizontal stress, while intrusive in situ tests provide a relatively good estimate of effective horizontal stress. This result was not observed with the Sallèdes clays.

The reliability of the horizontal stresses obtained by hydraulic fracturing depends on the verticality of the fractures created around the piezometer.

The degree of disturbance of the ground was shown to be crucial for any in situ test and especially in stiff soils.

Although it is still difficult to obtain accurate and relevant in situ states of horizontal stresses in stiff clays, this work provided us with a direct comparison of results obtained by different methods, including the self-boring pressuremeter, which was suggested by WROTH [1975] as a tool for measuring horizontal stresses in stiff and medium stiff clays.

5. Conclusions

Because of the importance to assess the state of stresses in a landslide for numerical modelling purposes, various in situ and laboratory measurement techniques were recently experimented to obtain lateral stresses in the ground. The selected site is a slow active landslide located at Sallèdes (France). Pushed-in total pressure cells, dilatometer testing,

Tab. I – Measured horizontal effective stresses.
Tab. I – Tensioni efficaci orizzontali misurate.

Location	*Depth (m)*	*Vertical effective stress σ'_{vo} (kPa)*	*Pressuremeter σ'_{ho} (kPa)*	*Dilatometer σ'_{ho} (kPa)*	*Glötzl cells σ'_{ho} (kPa)*	*Hydraulic fracturing σ'_{ho} (kPa)*	*Pore pressure (kPa)*	*Triaxial test σ'_{ho} (kPa)*
zone 1	0.75	12.8	(21)	17				
	1.5	25.5		27	84			
	2	29	60	22			5	50
	3	34	46	21	67	41	17	
	4.5	46.5	59*	32	76	49	30	115
	6	57	73*	48	92	51	45	
zone 2	2.5	32.5	39	24				
	3.1	52.7	42	44				80
	4.5	61.5	(87)				15	120
	5.5	68.5	(77)				25	
zone 3	3	49	(60)*	36			2	
	4	57	105	41			11	
	5	68	119	65			17	

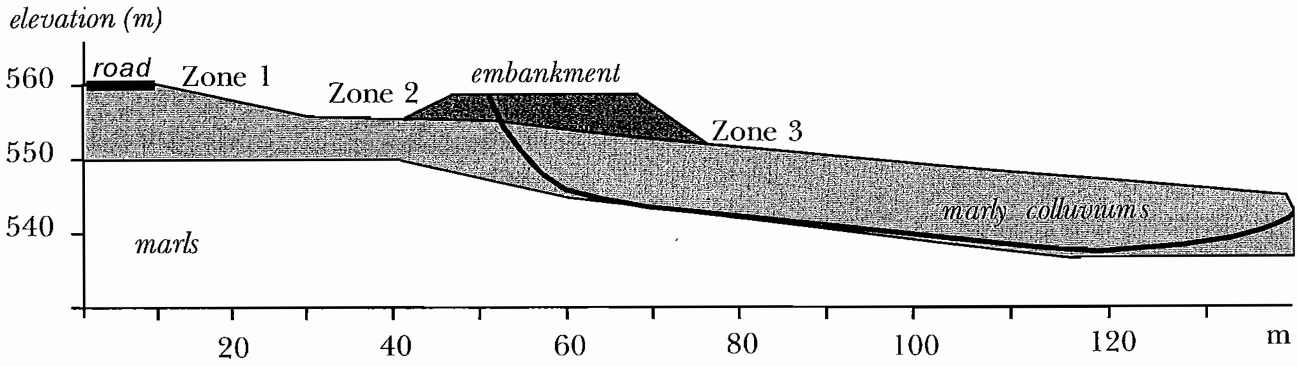

Fig. 4 – Geotechnical cross-section of Sallèdes landslide.
Fig. 4 – Sezione geotecnica della frana di Sallèdes.

hydraulic fracturing, self-boring pressuremeter and strain controlled triaxial tests were experimented.

Several discrepancies were found between the results obtained from different methods. Therefore, and despite the amount of tests performed, several uncertainties remain as of procedures that can be used for evaluating in situ horizontal stresses in stiff or medium stiff clays subjected to landslides.

The difficulties encountered on the Sallèdes landslide site included: the heterogeneity and stiffness of the colluvia, the presence of little basaltic inclusions in the clays, the difficulty to control the verticality of the probe during insertion into the ground.

A good in situ test is one which is simple, repeatable and well calibrated against field observations. Further research would be needed to help evaluate the capabilities of different techniques in estimating the in situ state of stress in stiff and medium stiff clays.

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Valutazioni delle tensioni orizzontali in una frana

Sommario

La modellazione numerica del comportamanto di terreni in frana richiede una legge costitutiva per il terreno e la definizione dello stato iniziale di tensione. Questo articolo descrive l'uso di vari metodi di misura dello stato di tensione in un pendio naturale instabile.

Il sito indagato è stato studiato per altri quindici anni: spostamenti della massa instabile, pressioni neutre e piogge sono stati misurati regolarmente. Sono state effettuate prove pressiometriche e dilatometriche e prove di fratturazione idraulica. Sono state anche installate celle di pressione totale ed effettuate prove triassiali a deformazione controllata.

In questo articolo sono presentati e discussi i relativi risultati.