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Residual Strength Parameters From a Slope Instability

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SYNOPSIS The study attempts to determine the in situ shear strength parameters of a stiff clay from a back analysis of a well documented landslide. The relatively small extension of the instability, as well as the homogeneity of the clay formation and the defined slip surface, allows a consistent evaluation of shear strength parameters.
The study is also supported by ring shear tests, and microscopic analysis performed on undisturbed thin sections , by means of scanning electron microscopy.
The results of back analysis are in good agreement with laboratory tests and microscopy observations.

INTRODUCTION

The instability phenomena in stiff clay slopes are always controlled by residual strength parameters related to a pre-existing sliding surface(Skempton , 1985). Movements of such a type are mainly dependent on allowable strenght and loading variability. Instead the geometry of sliding surface is generally known.
The instability loading may be represented by static or dynamic horizontal and vertical forces , and by pore pressure variation inside the slope. On the other hand, the pore pressure distribution can be affected by meteoric and anthropic events, especially for relatively shallow sliding surfaces. This paper deals with back analysis simulation of a real instability phenomenon in stiff clay slope which occurred in Toscana (Italy).
The landslide , of limited extension , fig.1, affected the hill for a linear extension of 50.0 m., a width of 30.0 m. and a maximun depth of 6.0 m. The instability developed suddenly due to both the excavation of toe slope and the simultaneous raising of phreatic level during an intensive rain-fall.
The in situ investigations performed, just after the event , have indicated the presence of a well-defined sliding surface in residual strength conditions. Such an evidence makes it possible to use some exemplifications in back analysis with regard to the definition of sliding surface and to the assessment of failure progress. The interest was related to a correct definition of shear strength parameters and their effects in stability analyses.

GEOTECHNICAL SOIL CHARACTERIZATION

Geotechnical investigations after the sliding, have been carried out by means of in situ and laboratory tests.

Fig. 1. Landslide view

The slope which has been affected by instability phenomena is located in a stiff clayey-marl formation, more degraded and fissured in the shallow portion.
The index parameters of fine fraction are showed in the Casagrande soil plasticity chart, fig.2. It may be pointed out the inorganic nature of high plasticity clays. The natural water content, in the order of W_n=21%, always appear lower than the plastic limit, in agreement with the high overconsolidation ratio of the soil.
Activity index attains values of the order of AI=0.76, in accordance with a medium colloidal activity of clay mineralogical compounds.
Chemical compounds, showed in fig.3 and in tab.1, were determined by means of X-Ray-Fluorescence.

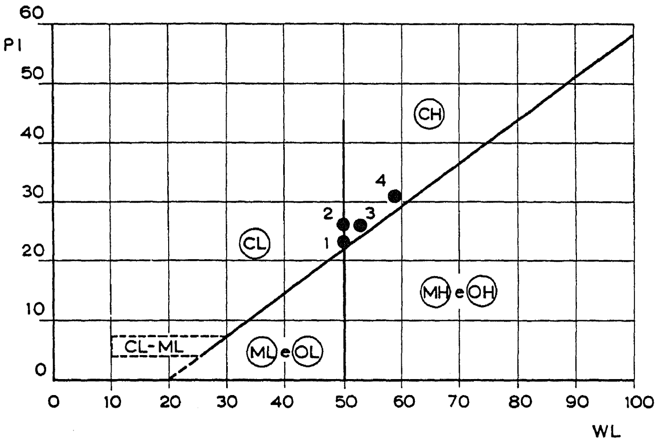

Fig. 2. Casagrande soil plasticity chart

Some shear strength characterization was carried out by using pocket-penetrometer, during soil sampling, and by unconfined compression tests. In the former case, values in the range of 300-400 kPa were found in the upper fissured portion of layer, and higher than 450 kPa in the more stiff lower portion.

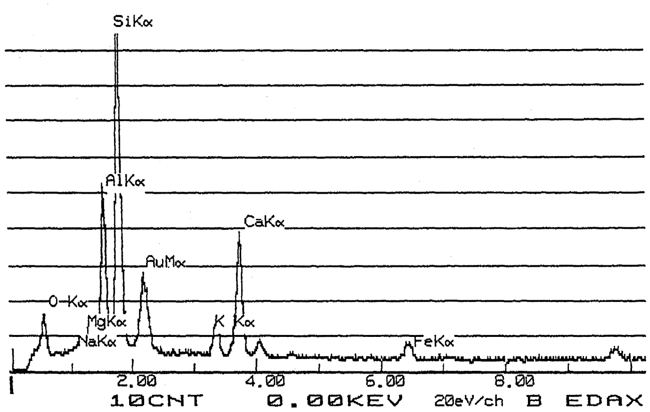

Fig. 3. X-Ray-Fluorescence analysis

TABLE I. Clay mineralogical compounds

ELEM	CPS	WT % ELEM
O K	19.513	7.496
NA K	4.925	1.921
MG K	20.325	3.022
AL K	84.838	13.872
SI K	209.275	39.358
K K	20.650	2.834
CA K	76.287	18.696
FE K	13.600	12.801
TOTAL		100.000

Unconfined compression tests have provided compressive strength q_u in the range of 775-1140 kPa depending on the fissured level of samples. The tests results are shown in fig.4 and in tab.2 in which can be marked how the deformation was always lower than 11% and how the stress-strain behaviour was of softening type.
Residual strength parameters were evaluated by means of ring shear tests performed with Bromhead's apparatus (Bromhead 1979).

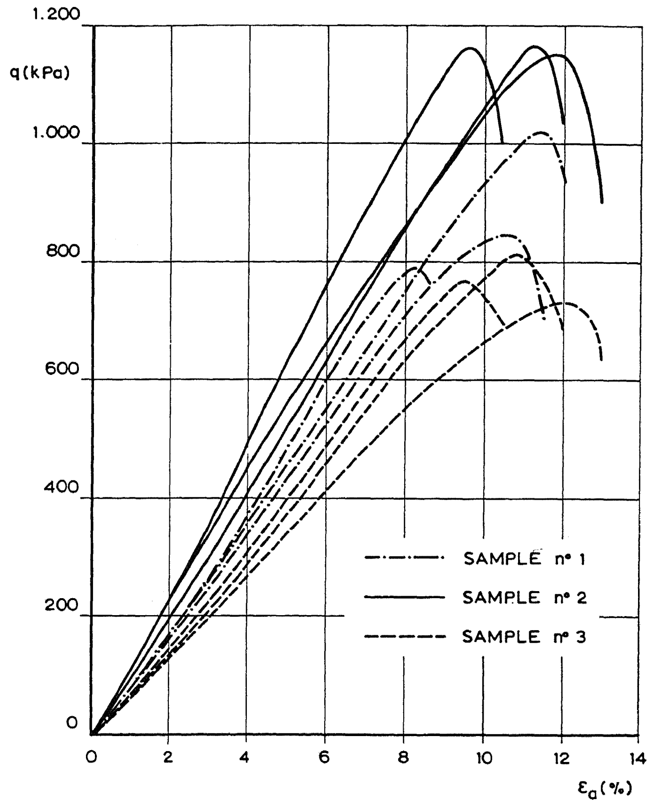

Fig. 4. Unconfined compression tests results

TABLE II. Laboratory tests results

Sample	w_l	w_p	PI	w_n	CF	AI	q_u	PP
-	%	%	%	%	%	%	kPa	kPa
1	50	28	22	18	34	0.6	876	425
2	51	24	27	21	33	0.8	1140	≥450
3	53	27	26	23	32	0.8	775	≥450
4	59	28	31	-	40	0.8	-	-

RING SHEAR TESTS

The aim of the ring shear tests was to asses some aspects of residual shear strength of stif clayey-marls. In this case Bromhead's apparatu was employed, which allows to perform residua shear test on remolded samples with an initia

thickness of 5.0 mm. The inner and outer radius of the annular cell were respectively equal to 35.0 mm and 50,0 mm.
The samples were prepared using the soil fraction passing to N.40 ASTM sieve, at an initial water content equal to 75%. As well known, the ring shear tests allows deformation of prefixed shear surface on which large displacements are carried out until shear stresses are completely stabilized. Under such a condition, relevant parameters of residual strength are determined; on the contrary no information may be obtained regarding the initial stress-strain behaviour before failure.
In this research the effect of normal consolidation stress and aging time on shear surface was investigated.
The influence of normal stress was investigated in the range of 25-1200 kPa maintaining a fixed shear velocity equal to $\dot{\delta}$= 0.445 mm/min (Bellino-Maugeri 1985, Favaretti 1982) ; so doing, results can be retained homogeneous. The failure envelopes determined were found to differ in the case of low and high stresses. For stresses less than 400 kPa the failure envelope may appear curvilinear , fig.5, with local

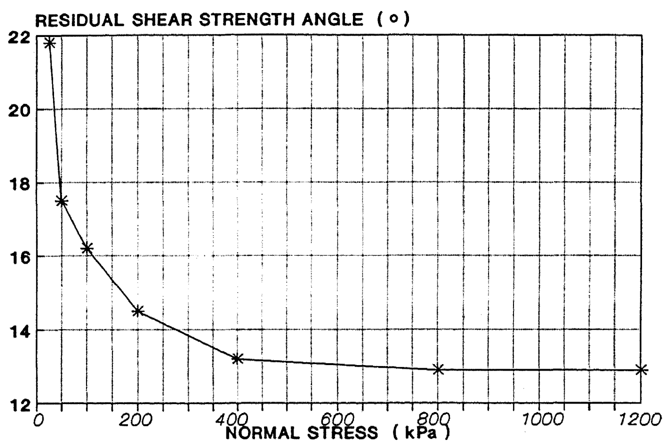

Fig. 5. Influence of normal stress on residual shear strength angle

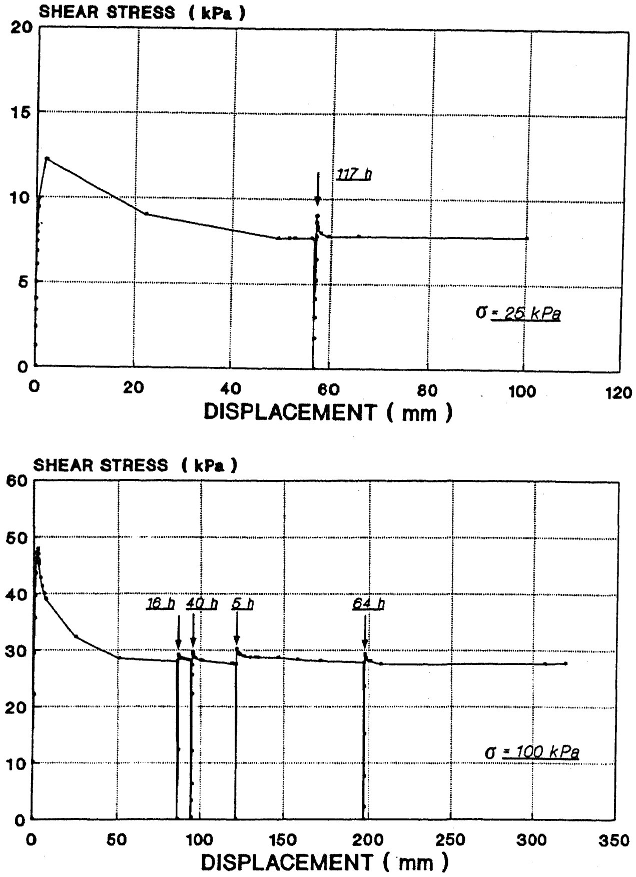

Fig. 7. Tixotropic effects on shear strength

residual friction angle varying between 13°-22°; the lower residual shear strength angle is related to higher vertical stress of 400 kPa, instead, the higher value was obtained for lower stress of 25 kPa. At high stresses (≥ 400 kPa) the failure envelope is linear, fig.6, with a residual shear strength angle equal to 13°. Such an evidence may involve some important considerations in stability analyses of slopes with shallow sliding surfaces.

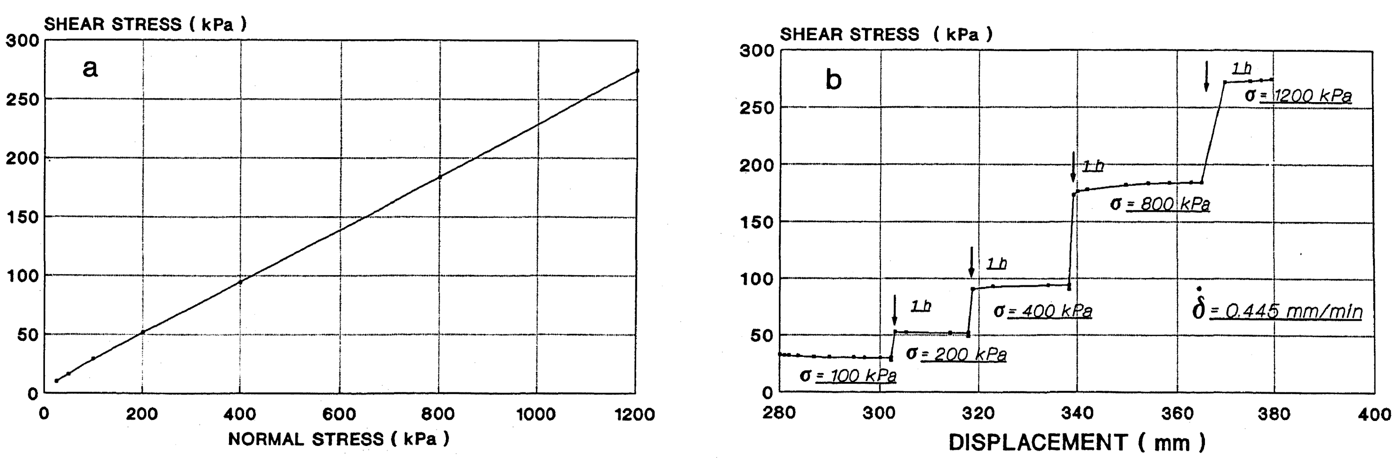

Fig. 6. a) Residual failure envelope
b) Stress-displacement relationships

Aging effects were investigated by maintaining the vertical consolidation stress on shear surface after the residual strength parameters were attained (Bjerrum-Lo 1962, Mitchell 1960). Performing another loading stage (in order to obtain the new residual strength) it was possible to investigate the tixotropic effects. The results of these tests shows an initial strength increment followed by a suddenly softening behaviour until residual strength was obtained.
This behaviour is related to tixotropic hardening and is dependent on either the lasted time and the mineralogical clay compounds. The fig.7 shows the tixotropic effects for aging time greater than 5 h . The tixotropic effect produces an increment of mobilized shear strength at the first displacements on pre-existing shear surface. So, mobilized shear strenght may attain higher values than residual. Assuming the intercept cohesion equal to zero it was found, in the actual case, that tixotropic effects produce an increment about of 2° for mobilized shear strength angle.

BACK ANALYSIS

Some back analyses of landslide were carried out . Starting from in situ measurements, it was possible to define the geometry of both slope and sliding surface. Also, relevant measurements of piezometric level were performed; the obtained data indicates a large pore pressure variation related to rain- fall apport which was more evident in the upper fissured clayey marl. So it was decided to analyse two extreme configurations: one with low water table and the other one a with high water table inside the slope, fig.8. The analyses were carried out using limit equilibrium methods as Janbu (1957), Bell (1968) and Morgenstern-Price (1965). The mobilized shear strength angle at which the unit security factor was attained depended on the water level considered. In the case of low water level there was found $\phi'_m = 17.5°$, while in the case of the high water table there was found $\phi'_m = 21°$.
Tab.3 shows some results of numerical analysis.

TABLE III. Back analysis results

Method	ϕ'_m	Water table High/Low	Safety factor
Janbu	17	L	0.972
Bell	17	L	0.963
Morgenstern	17	L	0.965
Janbu	18	L	1.033
Bell	18	L	1.024
Morgenstern	18	L	1.026
Janbu	19	L	1.094
Bell	19	L	1.085
Morgenstern	19	L	1.087
Janbu	19	H	0.893
Bell	19	H	0.885
Morgenstern	19	H	0.887
Janbu	20	H	0.944
Bell	20	H	0.935
Morgenstern	20	H	0.938
Janbu	21	H	0.996
Bell	21	H	0.987
Morgenstern	21	H	0.990
Janbu	22	H	1.048
Bell	22	H	1.038
Morgenstern	22	H	1.041

SCANNING MICROSCOPIC ANALYSIS

In order to investigate the fabric modifications near the sliding surface, microscopic analyses were performed by means of scanning electron microscopy (Lupini et alii 1981). At this regard undisturbed block samples were drawn on the real sliding surface. Vertical and horizontal sections of sliding surface were prepared employing air drying technique to dewater the samples. Exposure surfaces were made by means of levigation and piling techniques. These methods don't produce relevant modifications in the samples due to their low natural water contents.
The results obtained indicate how the instability is localized in a shear band of thickness in the order of microns. In this band the soil fabric is strongly oriented as reported in the vertical section of fig.9. The orientation of soil particles is concordant with the sliding surface as shown in the horizontal section of fig.10.

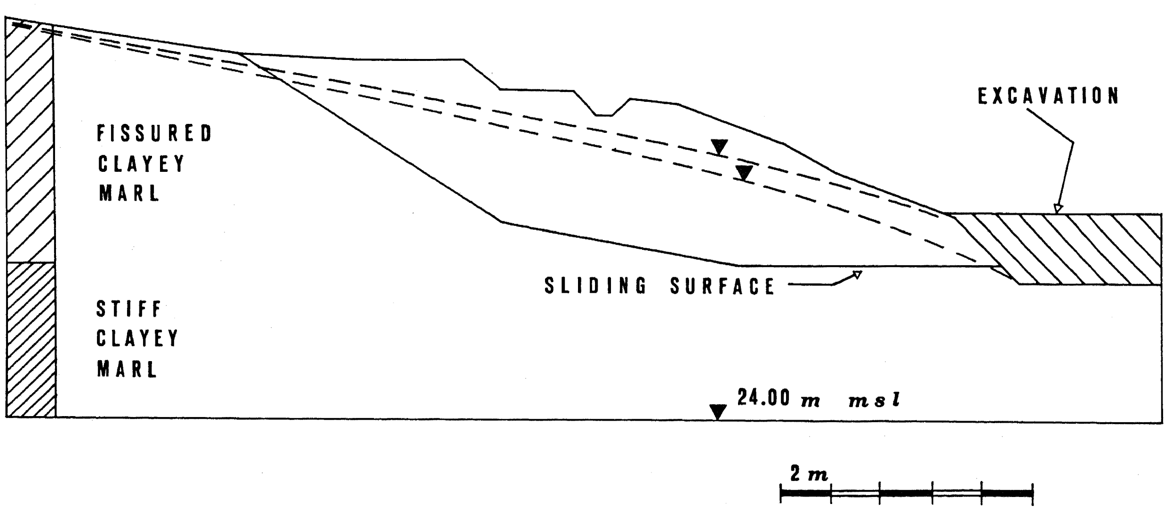

Fig. 8. Landslide section

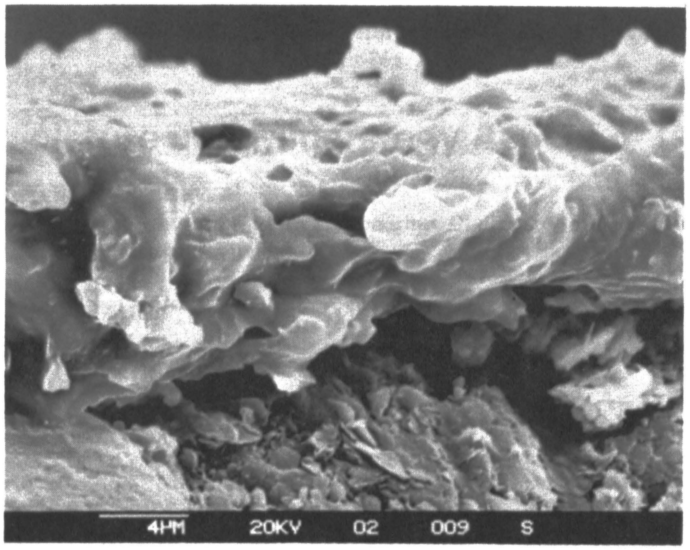

Fig.9. Scanning microscopic view of a vertical section of the sliding surface

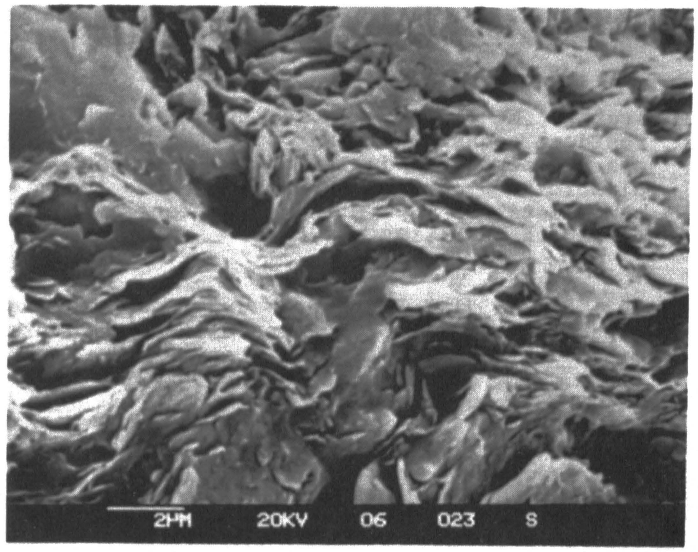

Fig.11. Scanning microscopic view of a vertical section of the ring shear failure surface

The same kind of results were found in horizontal and vertical sections obtained from the ring shear sliding surface, fig.11.

CONCLUSIONS

The back analyses carried out on a well documented case history makes it possible to establish the reasons of the landslide. In particular two limit equilibrium shear strenght angles were found for the slope, respectively in the low and high water table case. In these circumstances the mobilized shear strength angles were found to be equal to 17.5° in the low water table case and 21° in the high water table one.
Taking into account the level of effective stresses acting on the sliding surfaces (about 35 kPa) and the results of the ring shear tests

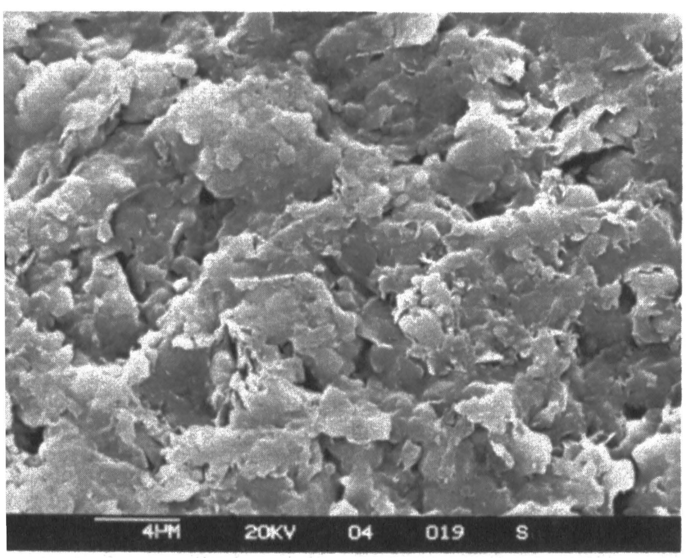

Fig. 10. Scanning microscopic view of an horizontal section of sliding surface

it appears clearly that the landslide occurred for both toe excavation and simultaneously water table rising.Infact the laboratory tests indicate a residual shear strength angle equal to 19°, value higher than the limit one in the case of the low water table.
Moreover, the limit value of the mobilized strength corresponding to ϕ'_m= 21° found in the case of high water table , corresponds to the value obtained by laboratory tests using ring shear apparatus, when taking into account the aging effects and the level of effective stresses acting on the sliding surface. So, the mobilized shear strength in the real case was not the residual but the one mobilized, on the pre-existing sliding surface, at the beginning of the sliding.
Finally, it must be underlined how the hypothesis of residual conditions on slippage surface used in the back analyses were widely confirmed by microscopic observations. These results clearly show an oriented fabric that develops in a very thin shear band in which the minimum shear strength is mobilized.

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