Strength parameters of a tectonized clay for the design of a large dam

Les paramètres de résistance d'une argile tectonisée pour le projet d'un grand barrage

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SYNOPSIS - Stiff tectonized clays are formed by tightly interlocked sharp-edged small clay fragments, and are often referred to as chaotic, due to the difficulty of surveying and of unraveling their structural pattern. In the paper results of in situ and laboratory testing activity on such a clay - on which an embankment dam 70 meters high is to be founded - are discussed. A painstaking survey permits to conclude that the structural arrangement of the clay mass can not be taken as chaotic or random. Factors and tentative criteria for the selection of design values of shear strength parameters are suggested. It is stressed that the choice of values of parameters is not independent of the possible failure mechanisms and, in general, of ultimate limit states of the foundation - dam system.

1 INTRODUCTION

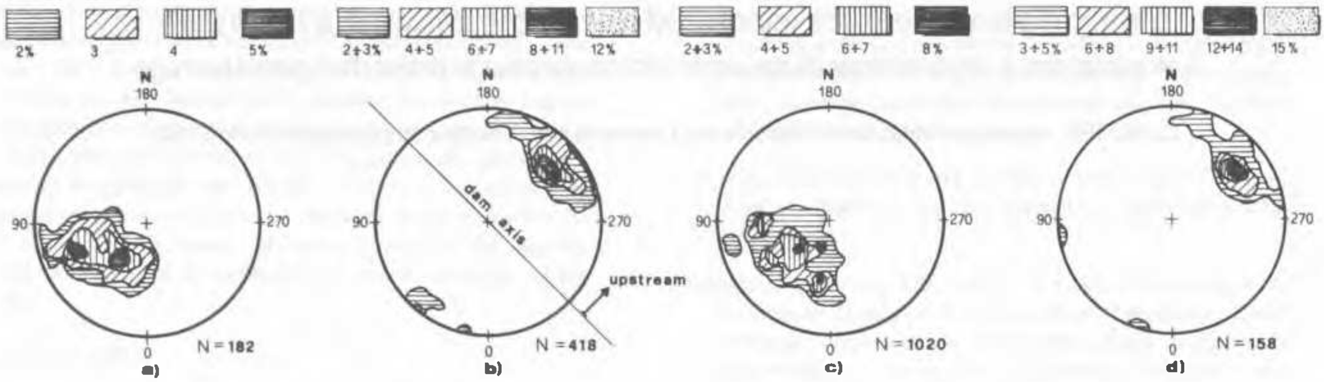
The mechanical response of soil masses formed by interlocked stiff clay fragments, or scales, is strongly influenced by the presence of structural discontinuities, by their arrangement within the volume of foundation soil relevant to the behaviour of the structure to be built. Moreover, the response of the system structure foundation-soil depends on the type and size of the structure, on the spatial variability of the structural features of the soil mass, on the strength and deformability properties of the different types of soil of which it is composed and on the strength along joints and contacts between soil portions, each with different structural features and intrinsic mechanical properties (VALORE, 1978, 1983, 1985; JAPPELLI & VALORE, 1980).
Much research work has been carried out on clays of the type under discussion (JAPPELLI et al., 1977; JAPPELLI, 1978; AGI, 1979; VALORE, 1980; D'ELIA, 1977; EVANGELISTA et al., 1977). However, the prediction of the mechanical behaviour of natural masses formed by these clays is still far from being satisfactory.

In the paper results of an in situ and laboratory research programme on a clay deposit of Oligocenic age, on which a dam 70 meters high is to be founded in Sicily, in the valley of the Imera M. River, are discussed.
Special attention is paid to the structural arrangement of the clay mass, and to the shear strength parameters as determined on soil specimens of different size, tested in laboratory and in situ by means of plate tests carried out at the bottom of exploratory shafts.
Factors and tentative criteria for the selection of design values of shear strength parameters are suggested for the foundation - dam system referred to. It is believed that these criteria may prove to be useful, as well, for other clay masses with similar structural features.

2 CONSTITUTION AND STRUCTURAL FEATURES OF THE CLAY MASS

Three main types of clays can be distinguished within the mass under study:
- AB variegated, brecciated clays;
- AS variegated, intensely sheared clays;
- AM marly, fissile clays.

Most of the structural discontinuities are of tectonic origin, and are associated with the transport and emplacement of the clay formation. Rare, broken, disarticulated layers of marly limestone are included in the mass.
Typical index properties of each clay unit are summarized below:
CF 25-57%; w_n 10-18%; γ_{sat} 20-22 KN/m^3; LL 0,7-1,1; PI 0,40-0,65; S = 1; γ_s 27,3 KN/m^3.
The three clay do not differ as to the composition and the Atterberg limits.
Each units forms large lumps and bands, several meters thick. These lumps, however, do not conform to a precise simple structural arrangement; the contacts among the different lumps appear to be irregular.
The mass on the whole resembles an articulated system of large irregular blocks of marly clays AM and of brecciated clays AB interacting through bands of intensely fissured and sheared clays AS.
The structural pattern of the mass is usually described as "chaotic" or completely random. As the question is of paramount importance for the definition of geotechnical problems, a detailed survey of structural features of the mass has been undertaken. The survey has been carried out on the walls of large exploratory trenches, up to 10 m deep, and in an exploratory adit, 50 m long. The orientation of 1440 discontinuities has been determined. The survey has been confined to joints and discontinuities with a "persistence" of at least some tens centimeters, and frequetly higher than 1 m.
Some results are summarized in fig. 1. They show that the structural pattern is far from being random. On the contrary, discontinuities group into three distinct sets, A, B, C. Their orientation relative to the dam may be deduced from fig. 1. The persistence of the joints does not appear to exceed 10 m. Joint spacing is about 10 centimeters; in some zones it is even more small.
On the right valley bank the scatter of the dip as well as of the dip direction, is of the order of ± 13° and ± 24°, respectively.
The spatial variability of the structural pattern is ap-



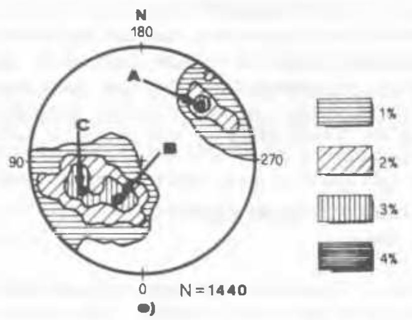


Fig. 1 - Structural conditions of the clay mass within the relevant foundation volume of the dam: contours of the pole density: a) Marly fissile clays of the right bank; b) discontinuities of left bank; c) discontinuities of the right bank; d) marly fissile clays of the left bank; e) all surveyed discontinuities

preciable over distances of the order of 10 meters.
The most persistent discontinuities are bedding planes, dipping toward the valley floor, and directing slighthy upstream.

For the purposes of this paper, it must be added that valley slopes are inclined more than 25°, are higher than 80 m and do not show instability signs.

3 SHEAR STRENGTH OF THE VARIOUS SOIL UNITS AND OF JOINTS

Shear strength parameters of each different clay type have been determined by means of drained direct shear tests on square and circular specimens with side or diameter equal to 60 or 100 mm. Eight plate loading tests have also been carried out in situ at depths up to 15 m from the ground surface in shafts with diameter of 2 meters; in all cases the plate diameter was 560 mm.
Some results of laboratory tests summarized in Table I, are available for four different clay types each differing from the other as to the structural characteristics. All tests were drained.

- AS-F: finely "tectonized" clay; platy clay fragments, whit dimensions less than 2 mm; isoorientated along the imposed shear plane;
- AS: tectonized clay; dimensions of fragments up to 1 cm; fragments tightly interconnected;
- AS-G: Tectonized clay; sharp-edged fragments with max dimension up to 2 cm;
- AM: fissile stiff clay; fissility planes parallel to imposed shear plane.

AS-F, AS-G and AS all belong to the AS clay unit.

Dilatancy occurs almost always for vertical pressure lower than about 300 KN/m^2. When the vertical pressure is lower than 100 KN/m^2, the shear surface is not well developed; on the contrary the disconnection of the clay fragments takes place; the fragments, thus, may rotate without shearing and are, near the shear surface, are in a "turbulent" condition (LUPINI et al., 1981). For $\sigma'_v >$ 800 KN/m^2 the shearing surface is well defined; the angle of dilatance at peak is almost always nil.
The shear surface is never perfectly smooth.

Results of plate loading tests are given elsewhere (VALORE, unpublished report). Failure pressure qult ranges from 800 to 1400 KN/m^2. No definite trend with depth is detected in the values of qult. The duration of tests ranges from 8 to 12 hours. The rupture surface is always conchoidal. The interpretation of these tests is affected by uncertainties on the excess pore pressure condition (MARSLAND, 1973).
Values of c_u = 140-240 KN/m^2 may be deduced if the test is taken as undrained: these values are scarsely meaningful, due, among other things, to the nature and the characteristics of the clay. If ϕ' is put equal to 25°, values of c' in the range 35-63 KN/m^2 are obtained.
The range of c' and ϕ' values is similar to that obtained from 200 mm plate tests at Bifarera damsite (JAPPELLI et al., 1979).

Special attention has been given to strength of joints.

Table I - Summary of peak shear strength parameters of the various clay types from direct shear tests; vertical pressure range: 200 ÷ 1200 KN/m^2; c': cohesion intercept; ϕ': angle of shear strength; τ_r: strength after 8 mm displacement; τ_f: peak strength

Clay type	c' [KN/m^2]	ϕ' [°]	τ_r/τ_f
AFS	40	12.4	0.8 ÷ 1
AS	10	15.6	0.4 ÷ 0.7
ASG	20	17	0.7 ÷ 1
AM	10	23.7	0.6 ÷ 1

The influence of the initial geometry (asperities) of the joints and its changes during the shearing process have been investigated. Joint walls were initially relatively regular, with small asperities; infilling material was 1 mm thick, and was formed by dickite. The joint walls were striated and shiny. The tests have been carried out on square specimens, 60x60 mm; the rate of shearing displacement was 0.0024 mm/min (drained tests). A few of the available results are shown in fig. 2. The shear strength of joints, when their surface was not initially smooth, strongly depends on the cumulated shearing displacement $\Sigma\delta$. It was observed that the height of the asperities and their distribution over the joint walls changed as a result of shear displacement. The strength increases with the rate of shear displacement.
The following values of shear strength parameters have been obtained:

$c' = 0$; $\phi' = 14°$ peak strength;

$c_r^* = 10$ KN/m^2 ; $\phi_r'^* = 8°$ strength for cumulated shearing displacement $\Sigma\delta > 100$ m

$c_r' = 0$; $\phi_r' = 6°$-$7°$ residual strength.

The available shear strength along joints is therefore considerably higher than residual, despite the past large displacement along the joints. This behaviour is very different from that reported for discontinuities of other clay masses (SKEMPTON, 1985).

4 FACTORS IN THE SELECTION OF SHEAR STRENGTH PARAMETERS FOR THE DESIGN OF LARGE DAMS

The use of the results of laboratory and of in situ tests for the prediction of the behaviour of clay masses of the kind considered in this paper is still faced with uncertainty, due to many often interrelated factors. Among these, the following play a fundamental role:

Intrinsic factors

- the constitution of the mass and the geometry of the contacts among the various "pieces" (lumps, bands) composing it, their state (asperities, undulations, striations, etc.); the geotechnical properties of these interfaces;
- the structural features of each "lump", and its spatial variability; the spacing and the persistence of joints; the influence of these characteristics can not be stated in absolute terms but is to be evaluated in relation to the scale of the problem i.e. to the size of the involved potential failure mechanism or to a characteristic dimension of the structure to be built;

Factors depending on the structure to be built

- stress level, rate of stress increase or decrease; stress and strain path;
- size of the structure to be built (dam, spillway, intake tower, outlet gallery, etc.);
- relative stiffness of the structure, on which the capability of the dam to condition the movement of the foundation soil, in correspondence of the founding level, depends; this factor may prove to be decisive for the non-relevance of "local" failure mechanisms, that may be otherwise associated with the presence of discontinuities with small or medium persistence or of iso-orientated sheared clay fragments.

The type and the size of potential rupture mechanism depend on both groups of factors; the selection of the strength parameters greatly depends in turn, on the size of the mass involved in the failure mechanisms.
The behaviour of the mass when subjected to shear stres-

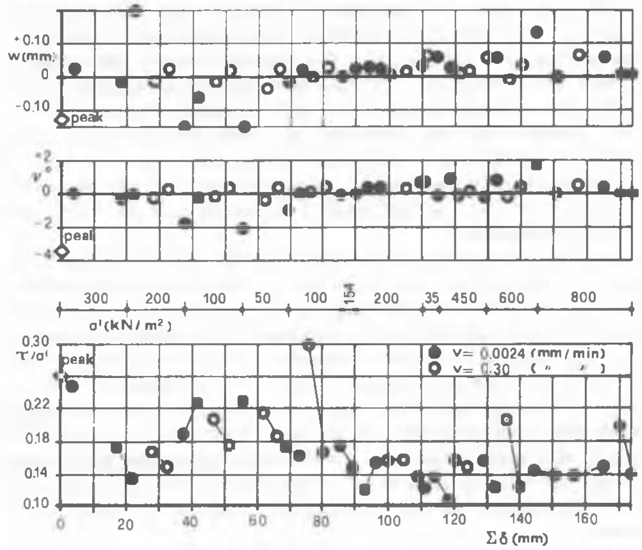


Fig. 2 - Results of direct shear test on a joint infilled with dicktite (specimen 456/B-1): τ shear resistance; σ' vertical effective pressure; ν dilatancy angle; w vertical displacement (positive is directed upwards); Σδ cumulated shear displacements; v shear displacement rate

ses may be of the "laminar" or the "turbulent" type (LUPINI et al., 1981), depending on structural pattern, the failure mechanism and, again, its size. The terms "laminar" and "turbulent", as used here, do not imply the attainment of the residual state, and are taken to describe the tendency towards the alignment of the "scales" - or clay fragments ("laminar"), or towards an irregular tridimensional arrangement ("turbulent").
The soil mass under study may indeed be thought of as a system of interacting, non-rigid clay "lumps".
The process of choice of the parameters should start with, and be guided primarily by the comparison between the size of the structure with the spacing and the persistence of the discontinuities present in the mass, as well as by the degree of spatial variability of the structural features of the mass over distances of the same order of magnitude of a characteristic dimension of the dam.

5 DISCUSSION AND CONCLUDING REMARKS

On the basis of the results of studies and investigations already carried out, it seems possible to attempt an inventory of "knowns", of "unknowns" whose existence is however well known, and of uncertainties needing further clarification.

- The strucutral pattern of the clay mass is far from being random; the discontinuities group into a few sets. The spacing of joints rarely exceeds 10 cm; their persistence - taken as the maximum length of the discontinuity surface - is generally low, while that of the surveyed joints equals some tens centimeters; it almost never exceeds 10 meters. The spatial variability of the structural pattern is appreciable over distances of the order of some meters. The quantitative deterministic description of this variability is feasible, and is currently being undertaken.

- The clay mass is composed of large lumps and bands of clays, with different texture and structural features, and mechanical properties. The contacts among the various lumps are irregular, intricate, contorted, warped. However, the reconnaissance and the precise description of the geometrical and geotechnical features of these contacts is troublesome and truly uncertain.
- The mechanical behaviour of each clay type can be investigated by well established laboratory and in situ testing procedures.
Available data give some insight into size effects. It must be noted that the increase of the size of the specimen, or of the soil volume involved in the test, is frequently accompanied by an increase in the shear strength, on the contrary of what happens with other well known clays (for example London Clay, cfr. MARSLAND, 1973). This is due to the fact that the probability of the clay fragments and platelets being iso-orientated is higher in small specimens; besides, considerable bias may be introduced in the selection of "representative" samples, as when fragments are iso-orientated trimming of samples is easier.
There is some evidence that sample with sides or diameters equal to about 20-30 centimeters may adeguately represent the response of the different clay types. Appreciable effects, on shear strength, of stress level, stress and strain paths are anticipated; the research on these aspects has hardly been programmed.
- The angle of shearing strength along regular, striated shiny joints is almost double than that corresponding to the residual state, notwithstanding the considerable past displacements along the joints induced by intense and repeated tectonic actions.
- No unique couple of shear strength parameters is to be searched for the clay mass. The available shear resistance is everywhere higher than residual.
- The main factors for the selection of shear strength parameters have been pointed out; the spacing, the persistence and its spatial distribution are among the most influential ones.
The choice also depends on the type and the size of the failure mechanism, and in general, on the ultimate limit state of the system soil-dam being analysed. The mechanism, in turn, cannot be taken as independent of the kinematical and mechanical constraints imposed by the dam to the foundation soil. In this regard, the case of Piana dei Greci dam (BIGALLI et al., 1988) is relevant. This hand-placed masonry dam, 42 m high, is founded on a deposit of stiff highly fissured clays, similar as to the structural features to the clay mass under consideration, and the slope of both upstream and downstream shells is 1 V in 0.7 H. The successful performance of the dam during about 65 years greatly owes to constraints imposed to the foundation soil by the dam, which precludes the initiation of local failure processes.

Taking into account the above considerations, it was suggested in relation to the design of the dam on the Imera M. River, that: when the potential failure surfaces develops along highly persistent joints, corresponding peak shear strength shall be used; when the mechanism passes through the other clays, the strength parameters derived from in situ plate test with relatively large plate diameters may be introduced in stability calculations, whenever the largest dimension of the involved mass exceeds by a factor of say 3 or 4 the maximum persistence of the discontinuities. Sensitivity analyses of the factors of safety against failure of the dam - foundation soil system were performed for $c' = 10\text{-}30\ KN/m^2$; $\phi' = 22\text{-}25°$.
This suggestion derives in part from the consideration that the behaviour of the mass as a whole under shear stresses should essentially be of the turbulent type. It does not conflict with the observed behaviour of the valley slopes, and is supported by the successful performance of large dams founded on clay masses with similar structural features, such as Scanzano and Rossella dams (VALORE, 1978; JAPPELLI et al., 1979); Paceco dam (Author's personal files), and Piana dei Greci dam, already referred to. The hypotesis of turbulent behaviour in also supported by the results of backanalyses of Risalaimi slide (JAPPELLI & VALORE, 1980).
The above suggestion is valid provided that local failures processes do not propagate to larger soil volumes; to this purpose the control of the deformation process and of the possible disconnection of clay fragments is especially important and must be closely controlled. The role of geotechnical instrumentation is essential in this connection.
Note, explicitly, that the conservative use of residual strength parameters or of those pertaining to joints, in stability analyses, is not warranted, as it would openly conflict with the behaviour of existing slopes.

Many unsolved problems still persist. It is nevertheless hoped that the present contribution and the working hypotheses put forward, can help in focusing them and in directing research efforts in the prediction of the response of real soil masses.

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