U.S. State of the Practice in Sampling and Strength Testing of Overconsolidated Clays

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An indication of current sampling and strength-testing practices in stiff, overconsolidated clays across the United States has been obtained from a nationwide survey of private geotechnical consultants, state and federal highway engineers, and academic institutions. A diversity of sampling techniques, laboratory tests, and in situ field measurements is used in practice depending on the particular geologic setting, local conditions, economics, and experience. Problems involving overconsolidated clays appear primarily related to the proper site characterization and the determination of soil properties for analyses of slope stability, pile foundations, high shrink-swell subgrade soils, and deep excavations. Recent advances in laboratory procedures and in situ testing offer alternative means of assessing the stress-strain-strength behavior of stiff to hard and fissured clays, leading to better economy, reliability, and productivity.

Overconsolidated clays constitute a significant portion of the upper surficial soil formations of the North American continent. These clays, diverse and varied in origin, have primarily been formed by sedimentary deposition in shallow seas or lake beds, although a few clays occur as residuum formed by the in-place weathering of bedrock (*1*). A variety of geologic depositional processes, including marine, glacial, aeolian, lacustrine, alluvial, fluvial, diluvial, and deltaic, together with various time periods and differing environmental conditions, have resulted in a wide assortment of clay deposits found across the United States. As a consequence, each clay deposit is unique, with a different thickness, mineralogical composition, fabric, particle gradation, pore arrangement, geochemistry, and other microstructural features. Common periods of clay deposition resulting in sediment include the Quaternary (Holocene and Pleistocene), Tertiary (Pliocene, Miocene, and Eocene), and Cretaceous. Typical well-known clay deposits include the Pleistocene Beaumont clay of Texas (*2*), Pleistocene Seattle clay (*3*), Cretaceous Potomac Group formation of Washington, D.C. (*4*), Miocene Calvert clay of Richmond, Va. (*5*), Miocene Tampa Bay clay (*6*), and Cretaceous Benton Sea clays (*7*).

Since their deposition, these clays have been geoenvironmentally altered. They are much stiffer and harder than when initially formed as soft, normally consolidated sediments. Natural clays obtain overconsolidated characteristics, having been preconsolidated by one or more of the following processes: mechanical unloading (erosion and glaciation), desiccation, aging, secondary compression, cementation, groundwater fluctuations, freeze-thaw cycles, alternate wetting and drying, seismic events, and other environmental factors. Also, human construction activities such as excavation, preloading, surcharging, and ground improvement methods can preconsolidate clay soils.

Conventionally, the results of one-dimensional consolidation tests are used to define the magnitude of the preconsolidation pressure or yield stress ($\sigma_p' = \sigma_{v\max}' = P_c'$), which separates the elastic from plastic behavioral domains (*8,9*). It is common to express the degree of preconsolidation in a normalized form termed the overconsolidation ratio (OCR), σ_p'/σ_{vo}', where σ_{vo}' is the current effective overburden stress (*10*). An alternative method of obtaining the magnitude of σ_p' or OCR from the results of laboratory strength tests is presented by Mayne (*11*). More recently, interest has focused on the possible use of in situ tests for profiling the OCR in clays (*10,12,13*).

AVAILABLE SAMPLING AND TESTING METHODS

For routine site investigations, methods of sampling and testing have been developed in geotechnical practice to characterize the engineering properties of stiff clays. Sampling and testing procedures and equipment have become standardized so that some degree of reliability and consistency of test results among different commercial laboratories, testing agencies, and research institutions can be ensured. In some instances, it has been necessary for consultants and testing agencies to adopt modified procedures or to develop specialized sampling and testing methods because of local anomalies and difficulties not considered by standard practice. For example, standard hydraulically pushed thin-walled (Shelby) tube sampling methods are inadequate for very hard Cretaceous clays. Specimens of these clays are more easily obtained by either drive or rotary coring methods. Additional examples include difficulties with the retrieval of high-quality samples of highly fissured clays, particularly those deposits responsible for shrink-swell damage to foundations and slope stability problems. The degree of fissuring affects the specimen quality during laboratory extrusion, trimming, and saturation. Consequently, swelling and softening often occur in fissured clays, which alter the engineering properties of the soil when subsequently measured in laboratory testing.

A variety of sampling and testing methods has been developed for determining the engineering properties of soil, primarily the shear strength and compressibility characteristics. Unfortunately, strength is difficult to quantify properly because of the inherently variable nature of these soil materials and the effects of disturbance caused by sampling, in situ testing, or both. Because a detailed discussion of sampling procedures and effects is beyond the scope of this paper, the reader is directed to the classic reference by Hvorslev (*14*) and the brief review of common sampling techniques in ASTM

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Standard D-4700 (*15*). Sampling disturbance effects on shear strength have been discussed in detail by Ladd and Lambe (*16*) among others.

The complex facets of soil behavior include the effects of anisotropy, nonlinearity, stress rotation, drainage, creep, strain rate, temperature, and rheological factors within a three-dimensional formulation of its stress-strain-strength time response to loading (*10,17*). Consequently, each particular test used to measure strength, for instance, gives a different interpreted value depending on the specific boundary conditions, initial stress state, rate and direction of loading, and induced failure pattern. Figure 1 illustrates some of the laboratory and in situ tests used for measuring and assessing the engineering properties of soil. The applicability of the various laboratory methods for stiff clays is discussed in more detail by Simpson et al. (*18*), whereas Robertson (*19*) and Lunne et al. (*20*) provide details on the in situ testing methods. For strength testing of clays under undrained loading, a wide assortment of laboratory devices is available, ranging from simple index tests (e.g., the fall cone) and routine unconfined compression to sophisticated cubical-type triaxial tests. In the field, undrained strengths can be determined from the simple vane shear and penetrometer devices or complex self-boring pressuremeters. Each of these tests may be used to evaluate the strength of a particular clay, but each device results in a different value because the loading direction, boundary constraints, rates of loading, and disturbance effects are all different (*21*).

Because drainage conditions markedly affect the behavior of clay soils, it is paramount to distinguish between the undrained shear strength (designated τ_f, s_u, or c_u) and the drained shear strength (represented by the effective strength parameters c' and ϕ). For overconsolidated clays, it is not always clear to the engineer whether undrained parameters or drained properties are appropriate for a given problem. In addition, if very large strains are likely to be mobilized, the shear strength of clays is reduced to a frictional response related to a mineralogical phenomenon (*22*) and is most appropriately reported in terms of residual effective strength parameters (c_r' and ϕ_r').

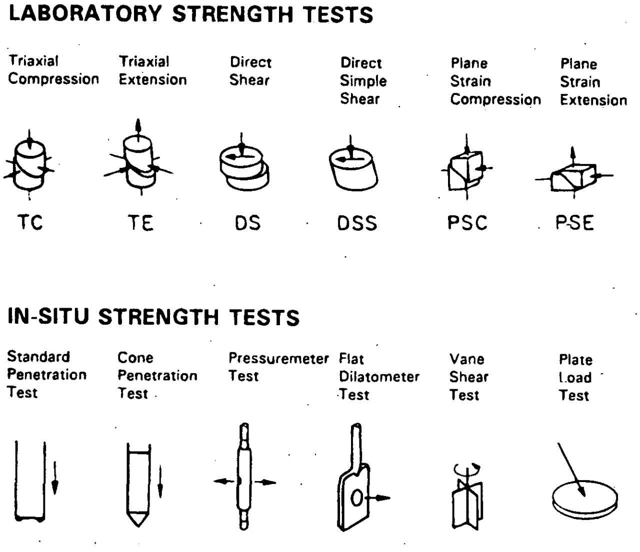

FIGURE 1 Types of laboratory and in situ strength tests.

SURVEY OF THE PRACTICE

To obtain an understanding of the current state of the practice in the sampling and testing of overconsolidated clays, two series of questionnaires were sent out by the Transportation Research Board Committee on Soil and Rock Properties in 1989 and 1992 to representative members of the geotechnical community. A total of 48 replies was received. Figure 2 shows the geographic locations of respondents, indicating that the results are generally representative of the U.S. practice. The West Coast, East Coast, southeastern, and midwestern states appear to be adequately represented, whereas the Mountain States and the Southwest may be slightly underrepresented. This also may reflect the paucity of overconsolidated clay deposits in those regions of the country.

The source categories of the survey respondents are given in Figure 3. Approximately 83 percent of the responses were from practitioners, including both geotechnical consulting firms (48 percent) and state highway departments (35 percent). A few additional replies were returned by academic institutions (12 percent) and representatives of FHWA (4 percent).

Figure 4 summarizes the typical problems encountered in characterization, analysis, and construction in overconsolidated clays. Almost 50 percent of the respondents reported that slope stability was paramount. The construction of spread footings, slabs, and pavements on expansive clays was a common problem 35 percent of the time, and apparent difficulties with the analysis and construction of deep foundations in overconsolidated, fissured clays, or both were reported by about 20 percent of the community.

The geotechnical profession uses a variety of different techniques for sampling, laboratory testing, and field measurements to assist in the evaluation of stiff to hard clay deposits. Figure 5 shows that across 90 percent of the country, both hydraulically pushed thin-walled tube and driven split-barrel (split-spoon) sampling methods are commonly used in these materials. Rotary techniques including both Denison and Osterberg samplers are used at about 47 percent of the locations. Once samples have been retrieved and transported to the laboratory, the consolidated-undrained (CU) triaxial compression test is the most often chosen method as a regular test (70 percent) to determine the shear strength of overconsolidated clays (Figure 6). The CU triaxial test is probably chosen because it provides the stress-strain response and assessments of both undrained strength ($\tau_f = s_u$) and the effective stress strength parameters (c' and ϕ') if pore pressure measurements are taken.

Approximately 45 percent of all the respondents use unconfined compression (UC) and unconsolidated-undrained (UU) triaxial compression tests for assessing τ_f. However, neither test provides effective confinement to clay specimens before shearing to failure. Therefore, the UC and UU tests do not simulate the geostatic stress state of the deposit. Ladd (*23*) discourages the common practice of using UC and UU testing because of the uncontrolled effects caused by sampling disturbance, high strain rates, and lack of appropriate effective confining stresses.

A significant number (40 percent) of laboratories use drained direct shear box (DS) tests on clay specimens to determine effective stress strength parameters (c' and ϕ'). A few laboratories also use repeated DS tests for evaluating residual parameters (c_r' and ϕ_r'), although the fully mobilized residual strength is probably not realized unless a ring shear apparatus is used (which apparently none of the respondents regularly use).

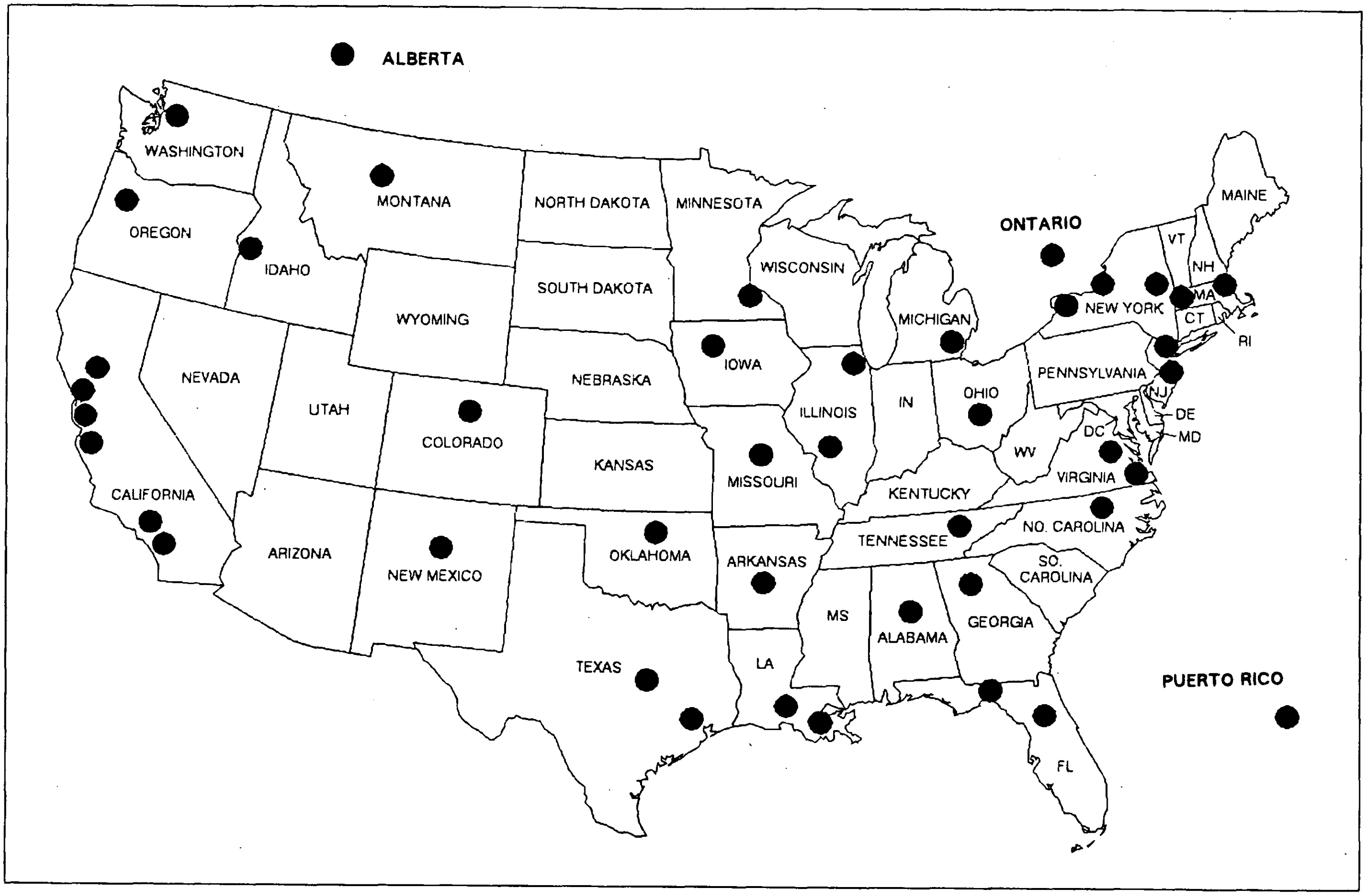

FIGURE 2 Location of survey questionnaire respondents.

The recent increase in the use of in situ testing methods is evident from the survey results. Figure 7 indicates that although the standard penetration test (SPT) still dominates U.S. practice, the cone penetration test (CPT) and pressuremeter test (PMT) appear to be gaining acceptance by practicing engineers. The dilatometer test (DMT) is also being increasingly used in practice as well. The use of in situ devices for evaluating clay properties on actual engineering projects has been frequently documented (*3,5,6*).

RECOMMENDATIONS FOR STRENGTH MODE SELECTION

For use in geotechnical practice, the following guidelines are suggested for selecting intact (undrained versus drained) versus residual strengths of clays in stability analyses. The short-term undrained shear strength ($\tau_f = s_u$) is the critical mode for designs involving soft clays in which the overconsolidation ratio ($OCR = \sigma_p'/\sigma_{vo}'$) is gen-

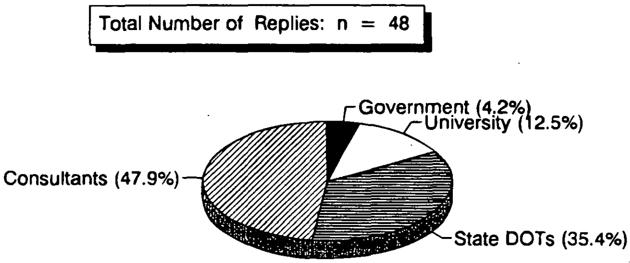

FIGURE 3 Occupational category grouping of survey respondents.

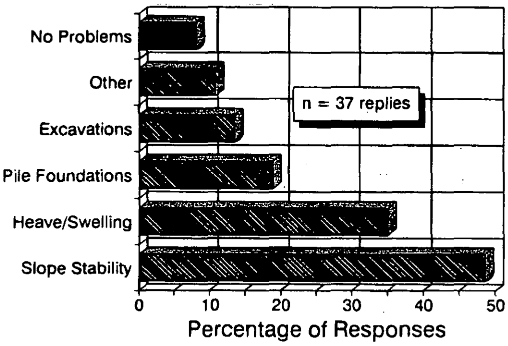

FIGURE 4 Problems facing practicing geotechnical engineers in overconsolidated clays.

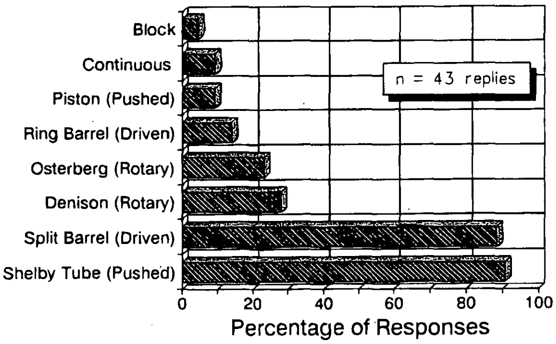

FIGURE 5 Sampling methods used in overconsolidated clays.

erally less than 4. For axisymmetric loading conditions, it is best determined as the average of undrained triaxial compression, direct simple shear, and triaxial extension tests measured on high-quality specimens (*24*). For long embankments, retaining walls, or continuous footings, plane strain tests are more appropriate. Unfortunately, these types of laboratory testing are normally beyond the ability or budget of the commercial or state laboratory. The use of only routine triaxial compression tests is unconservative because vertical loading is the strongest (*23*). In fact, the direct simple shear appears to give a reasonable average strength (*25*). Therefore, for nonorganic clays, undrained strengths may be best evaluated using the interpreted OCRs from conventional oedometer tests via (*10,17,23,25*)

$$(s_u/\sigma'_{vo})_{\mathrm{DSS}} = (0.23 \pm 0.04)\ OCR^{0.8}$$

where s_u/σ_{vo}' is the normalized undrained strength ratio. For OCRs generally greater than 4, the long-term drained strength is usually the most critical condition for slope stability analyses. If uncertainty exists as to which mode (undrained or drained) is critical, both analyses should be investigated.

Many commercially available computer stability packages adopt a Mohr-Coulomb failure criterion and thus

$$\tau = c' + \sigma'_v \tan\phi'$$

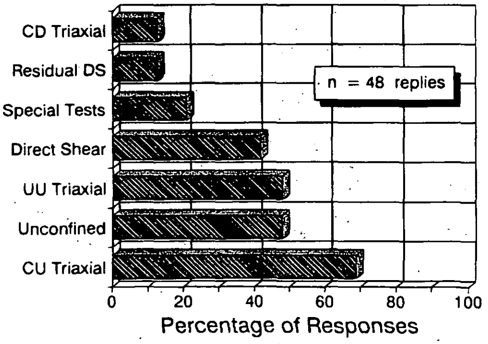

FIGURE 6 Laboratory strength test methods for stiff to hard clays.

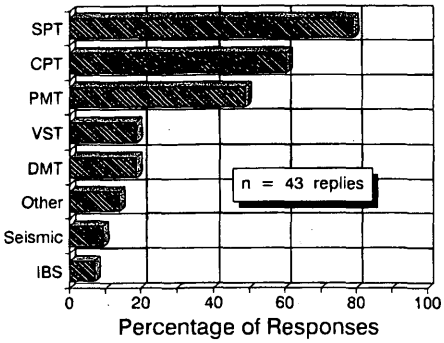

FIGURE 7 In situ testing practices in overconsolidated clays (SPT = standard penetration test, CPT = cone penetration test, PMT = pressuremeter test, VST = vane shear test, DMT = dilatometer test).

where c' and ϕ' are determined by consolidated-undrained triaxial (with pore pressures measured), consolidated-drained triaxial, or drained direct shear box tests over a range of effective confining stresses. Conservative results should apply to the selected value of c' because poor saturation procedures, excessive strain rates, and inadequate back pressures may cause unduly high c' parameters. The best recommended practice is to adopt $c' = 0$ for effective stress analysis (*26*). If necessary, however, a small but assumed value of $c' \approx 0.02\sigma'_p$ may be appropriate (neglecting stress level dependency) on the basis of the extensive review of back-analyzed slopes by Mesri and Abdel-Ghaffar (*27*). The effective friction angle (ϕ') of clay should not be estimated from plasticity charts alone. Measured ϕ' values of natural clays worldwide (*28*) fall within the range 17 degrees $\leq \phi' \leq$ 43 degrees, and values outside this range should be further tested and verified or considered suspect.

Clays that are very heavily overconsolidated ($OCR > 30+$) are also most often fissured, and therefore no longer behave as a continuum. Passive failure, resulting from K_o-values reaching K_p during extensive unloading or desiccation cracking, slickenside features, faulting, and additional factors have occurred in most deposits of highly overconsolidated clays. Residual strength parameters may be appropriate for analysis and design, although the use of such values will result in very flat slopes. Similarities with the famous fissured London clay (*29*) are found in overconsolidated clays and clay shales throughout the United States and Canada (*7,30*). The residual strength is basically a frictional characteristic of the clay mineralogy and, c'_r is usually very close to zero (*22,31*). Skempton (*32*) has discussed in detail the residual strength of cohesive soils and its relevance to landsliding and stability problems.

RECENT TRENDS

Developments in sampling, laboratory testing, and field measurement devices offer improved characterization of stiff natural clays. With regard to sampling issues, Holm and Holtz (*33*) and Lacasse et al. (*34*) discuss the use of larger tube, piston, and block sampling techniques for providing quality laboratory specimens. A sample disturbance will often result in e-log σ'_v curves that plot below the true field curve and consequently underestimate the yield stress (σ'_p) of clays in routine consolidation testing (*8*). To minimize swelling of stiff clays in the oedometer, the Norwegian Geotechnical Institute recommends the use of dry filter stones (*9*). The procedures in this regard recommended by ASTM D-2435 (*35*) for incremental consolidation tests are satisfactory.

Internal measurements of strain within the triaxial chamber are preferred so that the true nonlinearity of the stress-strain-strength curve can be fully appreciated (*36*). Measured soil stiffness from laboratory specimens now agrees more closely with observed field measurements and back-calculated equivalent moduli from full-scale performance data (*37*). However, internal strain measurements are possible only at research laboratories at the present, and most commercial and government laboratories will continue to measure deformations outside the triaxial cells.

A variety of different laboratory devices (a resonant column, bender elements, and internal strain measurements), as well as improved field measurements, have been used for the measurement of low-strain shear modulus ($G_{\max}$). This is an important and fundamental engineering property that can be useful in the characterization of all types of civil engineering materials (soil, rock, steel, concrete, etc.). Several commercial laboratories use resonant column testing for this purpose, and the growth of nondestructive testing using geophysical methods (cross hole, down hole, and spectral analysis of surface waves) permits an evaluation of $G_{\max}$ in the field.

Additional improvements in the laboratory assessment of clay behavior have been made through extensive stress path testing to define the full three-dimensional locus of yield surfaces (*13,17,21,28*). This test provides a complementary effective stress interrelationship between ϕ', c', s_u, K_o, σ_p', and stress state variables as a function of time. Complementary to these findings is a recent thorough study of more than 60 back-calculated slope stability failures, which quantifies the stress-dependency effects on the effective cohesion intercept (c') and illustrates that the magnitude of c' also depends significantly on stress history (*27*). This latter study showed that the normalized ratio of c'/σ_p' falls within the range of 0.02 to 0.10 and depends on the confining stress level.

A variety of field and in situ tests also have been introduced (*10,20,38*). Figure 8 shows the conceptual chronologic progress of evolution of the science of geotechnical engineering (*39*). The role of in situ testing has increased because of more detailed stratigraphy, better economy, and more immediate results provided by these new tools, especially the electric cone, piezocone, dilatometer, and geophysical techniques. Recent methods such as spectral analysis of surface waves for obtaining profiles of $G_{\max}$ are of interest because they are noninvasive and conducted at the ground surface. Improved means of interpreting the results of in situ tests also have been developed, and these tests now can be used to provide initial estimates of the degree of overconsolidation of a particular clay deposit (*12,13,20,38*). A theoretical assessment of the effective stress parameters (c' and ϕ') of clay deposits from piezocone test results has been proposed as well (*40*).

A number of hybrid devices also have emerged that optimize data collection and benefit from several techniques at the same time. Such devices include the come pressuremeter (*41*) and seismic piezocone (*42*), which provide independent measurements of failure stresses as well as soil stiffness at either low-strain $G_{\max}$ or intermediate-strain levels in the ground. Further research, validation, and applied technology programs may prove these to be the routine tools of the geotechnical engineer in the 21st century.

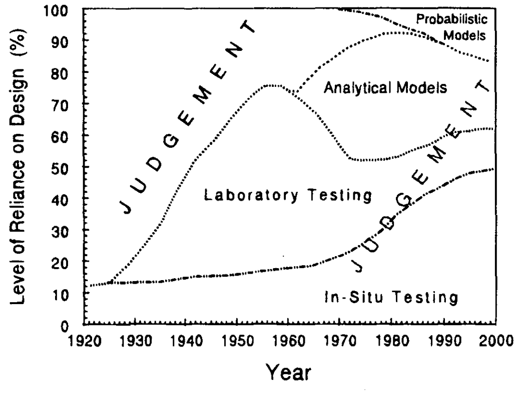

FIGURE 8 Evolution of selection of engineering design parameters for clays [modified after Lacasse (*39*)].

SUMMARY

Current means of sampling and testing stiff to hard natural clays in geotechnical practice are reviewed via the results of a survey questionnaire, with responses coming from all parts of the United States. Principal difficulties with civil engineering projects situated in overconsolidated clay occur in the proper characterization and evaluation of the material properties for analyses involving slope stability, expansive subgrades, and deep foundation systems. Observed trends in practice show increased use of more reliable laboratory tests (consolidated-undrained triaxial type and internal strain measurement systems), as well as the implementation of in situ tests (cone, piezocone, pressuremeter, and dilatometer) for assessing the strength and deformational characteristics of natural overconsolidated clays.

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