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REVIEW OF AVAILABLE METHODS FOR EVALUATION OF SOIL SENSITIVITY FOR SEISMIC DESIGN

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ABSTRACT

Sensitivity describes the effect of soil disturbance/remoulding on shear strength. Cyclic stresses during seismic events may lead to varying levels of disturbance and remoulding of brittle sensitive clays. The Canadian Foundation Engineering Manual (CFEM) recommends site-specific evaluation of the seismic hazard, including site response analysis, for sites that have quick or highly sensitive clays. Different levels of soil sensitivity have been shown in different versions of CFEM and their errata. The current manual CFEM (2006) classifies clay as highly sensitive if its sensitivity is greater than 40 (classified as Class F soil). However, there is considerable variation within the literature with respect to descriptions of sensitivity and more importantly, the related seismic risks that different soil states represent. This can have a significant impact on determination of the appropriate seismic forces on supported structures according to the seismic provisions of the current National Building Code of Canada, NBCC (2005). This paper reviews the different methods used to evaluate soil sensitivity and the sensitivity classifications in the literature. Based on this review, suggestions are provided for improvements of this approach to seismic design.

INTRODUCTION

Sensitivity of soil is an indication of the reduction in shear strength of soil when it is subjected to any disturbance, e.g. when it is remoulded or when it is subjected to monotonic or cyclic loading. Soil sensitivity is defined as the ratio of the undrained shear strength of undisturbed soil to the undrained shear strength of remoulded soil at the same water content, i.e.

$$St = \frac{S_u \ \text{Undrained shear strength (undisturbed)}}{S_{ur} \ \text{Undrained shear strength (remoulded)}} \qquad (1)$$

The ratio of peak undisturbed strength to remoulded strength, as determined by the unconfined compression test, was used initially by Terzaghi (1944) as a quantitative measure of sensitivity. However, the remoulded strength of some clays is so low, that unconfined compression test specimens cannot be used. Therefore, the vane shear test (either in the laboratory or in the field) and the Swedish fall cone test are often used.

Soil sensitivity is an important measure of the loss of strength and structure in the soil body under the effect of static or seismic loading. Several scales (or ranges) are used in the literature to classify sensitive clays according to their sensitivity level, from low sensitivity to extra quick. The sensitivity values of soil were initially classified in the 3rd and 4th editions of the Canadian Foundation Engineering Manual, CFEM (1992) and CFEM (2006), as given in Table 1 below; these were later changed in the Errata, given by Table 2.

The National Building Code of Canada, NBCC 2005 specifies the seismic hazard in spectral format considering the soil class and using the probability of a 2% occurrence in 50 years. NBCC requires site-specific seismic hazard assessment for Class F soils, which includes *"Liquefiable soils, quick and highly sensitive clays"*. If the sensitivity value is determined with Table 1 (i.e. $S_t > 40$ is considered "high" or susceptible), then only a few sites in Quebec and Eastern Ontario will need site specific seismic evaluations. However, if the sensitivity values given in Table 2 (i.e. $S_t > 8$ is considered "high") are used, then most sites underlain by non-weathered Champlain Sea clay will require site specific seismic evaluations. Thus, the sensitivity value can have a significant impact on design in Canada. Despite the significance of these classifications, there is considerable variation within the literature with respect to descriptions of sensitivity and the related risks for different sensitive soil states.

This paper presents a summary of the methods that can be used to determine the sensitivity of soil and their relationships based on several databases. It also presents the sensitivity scales available in the literature. Suggestions for seismic design are also proposed for engineering structures in areas of sensitive soils.

Table 1. Sensitivity classifications in CFEM (2006).

Classification	S_t
Low sensitivity	< 10
Medium sensitivity	10 – 40
High sensitivity	> 40

Table 2. Sensitivity classifications in CFEM (2006) Errata.

Classification	S_t
Low sensitivity	< 2
Medium sensitivity	2 – 4
Extra (High) sensitivity	4 – 8
Quick	> 16

SCALES OF SOIL SENSITIVITY

Sensitive soils are classified according to the value of soil sensitivity, S_t. Skempton et al. (1952) showed that most clays, except for heavily over-consolidated and boulder clays, lose some of their strength when remoulded, and proposed the sensitivity classifications shown in Table 3. Sensitivity of 2 to 4 is common among normally consolidated clays, but 4 to 8 is also frequently encountered.

Table 3. Skempton et al. (1952) classification.

Classification	S_t
Insensitive clays	~ 1
Low sensitivity clays	1 – 2
Medium sensitivity clays	2 – 4
Sensitive clays	4 – 8
Extra-sensitive clays	> 8
Quick clays	> 16

Since most Norwegian quick-clays show sensitivity values higher than 16, which is the highest value at the Skempton et al. (1952) scale, Rosenquist (1953) extended the scale with the values shown in Table 4. Rankka et al. (2004) presented a scale of sensitivity for Swedish sensitive clays, given in Table 5.

Table 4. Rosenquist (1953) classification.

Classification	S_t
Insensitive clays	~ 1
Slightly sensitive clays	1 – 2
Medium sensitive clays	2 – 4
Very sensitive clays	4 – 8
Slightly quick clays	8 –16
Medium quick clays	16 – 32
Very quick clays	32 – 64
Extra quick clays	> 64

Table 5. Swedish classification (2004).

Classification	S_t
Low sensitivity	$S_t \leq 8$
Medium Sensitivity	$8 < S_t \leq 30$
High sensitivity[1]	$S_t > 30$

[1] To be called quick clay, the remoulded soil must be a fluid i.e. it has a remoulded shear strength < 0.5 kPa (Torrance 1983).

Holtz et al. (1981) compared the USA classification (where highly sensitive clays are rare) and the Swedish Classification (where highly sensitive clays are common), as shown in Table 6.

Table 6. Comparison of USA and Swedish classifications.

	S_t	
Classification	USA	Sweden
Low sensitivity	2 – 4	< 10
Medium sensitivity	4 – 8	10 – 30
High sensitivity	8 – 16	30 – 50
Quick	> 16	50 – 100
Extra quick		> 100

Bowles (1996) presented different classifications to show that soils with S_t less than 4 are insensitive, while S_t over 8 represents extra sensitive soil as shown in Table 7.

Table 7. Bowles (1996) classification.

Classification	S_t
Insensitive	$S_t \leq 4$
Sensitive	$4 < S_t \leq 8$
Extra sensitive	$S_t > 8$

From the above classifications of soil sensitivity, it can be noted that the CFEM (2006) follows the Swedish system, while its errata follows the USA system. The CFEM (2006) recommended using the Swedish fall cone in the laboratory and the vane test in the field to measure the sensitivity. Understandably, the wide difference between the sensitivity values in Tables 1 and 2 has led to some confusion and controversy within the geotechnical community.

METHODS OF SOIL SENSITIVITY EVALUATION

Different testing methods are available to evaluate the sensitivity of soil either in the field or in the laboratory. A brief summary of these methods is provided below.

Unconfined compression test (UCT)

In this test, a cylindrical specimen of undisturbed soil with height to diameter ratio between 2 and 2.5 is subjected to unconfined axial stress and the maximum stress it can sustain is used to determine the undisturbed shear strength of the soil. The same test procedure is used on the same specimen at the same water content after complete remoulding. Further details can be found in ASTM D 2166. The ratio of the two shear strength values gives the sensitivity of the soil, i.e.

$$S_{t(UC)} = \frac{S_{u(UC)} \text{ (undisturbed)}}{S_{ur(UC)} \text{ (remoulded)}} \tag{2}$$

This method is satisfactory for soil with low sensitivities, but for soils that have liquidity index close to 1, it is no longer possible to remould the soil sample to form a specimen that has enough strength to support itself for the unconfined compression test. Therefore, for highly sensitive soils, other tests should be used to measure the undrained shear strength of the soil.

Field vane test (FVT)

In this test, torque is applied to the soil through a cruciform bladed device (typically 2:1[height to width] aspect ratio) in the field at different depths. The undrained shear strength is calculated using the applied torque on the soil. The conversion of torque into undrained shear strength is found to be a function of the blade geometry and shape, and depends on the assumed stress distribution. For example, the undrained shear strength using a rectangular vane is,

$$S_{u(FV)} = \frac{6T_{max}}{7\pi D^3} \tag{3}$$

where T_{max} is the maximum measured torque corrected for apparatus and rod connection, and D is the vane diameter.

Following the determination of the peak torque, rotation of the vane rapidly through a further five to ten revolutions is used to determine the remoulded undrained shear strength. The determination of the remoulded strength shall be started immediately after completion of the rapid rotation. The ratio between the two strength values gives the soil sensitivity (Eq. 4). Again further details can be found in the relevant ASTM D 2573.

$$S_{t(FV)} = \frac{S_{u(FV)} \text{ (undisturbed)}}{S_{ur(FV)} \text{ (remoulded)}} \tag{4}$$

Andresen and Bjerrum (1956) reported that the sensitivity values obtained with the field vane test are often found to be less than those measured in the laboratory.

Laboratory vane test (LVT)

The laboratory vane test follows the same principle as that of the field vane test (see ASTM D 4648 for test details). A four bladed vane is inserted into the soil specimen, and the torque necessary to rotate the vane is measured and is related to the undrained shear strength. It is used on both undisturbed and remoulded soil samples to measure the soil sensitivity, i.e.

$$S_{t(LV)} = \frac{S_{u(LV)} \text{ (undisturbed)}}{S_{ur(LV)} \text{ (remoulded)}} \tag{5}$$

When the remoulded strength becomes extremely small, it is difficult to measure torque to give reliable sensitivity values.

Fall cone test (FCT)

In this test, a cone of known weight and dimensions is brought into contact with surface of the soil sample. It is released for 5 sec interval and allowed to penetrate the soil under its own weight. The penetration is then measured and related to shear strength as suggested by Hansbo (1957):

$$S_s = \frac{(kQ)}{H^2} \tag{6}$$

where S_s is shear strength, Q is the weight of the cone, H is the penetration, and k is cone constant. The test can be done on both undisturbed and remoulded soil samples. The sensitivity then can be defined by:

$$S_t = \frac{(H^2 \text{ remoulded})}{(H^2 \text{ undisturbed})} \text{ or} \tag{7}$$

$$S_t = \frac{(\text{H remoulded})}{(\text{H undisturbed})} \tag{8}$$

The cone is useful over a limited range of sensitivity. For the undisturbed test, the penetration should be at least 5 mm to be reliable, and if the remoulded strength is very low, the cone penetrates too far into the soil.

Cone Penetration Test (CPT)

The sensitivity of soil can also be estimated using the friction ratio (R_f %) obtained from CPT test results using

$$S_t = \frac{N_s}{R_f\,(\%)} \tag{9}$$

Schmertmann (1978) suggested a value of N_s = 15, whilst Robertson and Campanella (1983) suggested N_s = 10. Lunne et al. (1997) recommend using N_s = 7.5. However, it is recommended that local correlations should be also developed.

COMPARING SENSITIVITY VALUES FROM THE DIFFERENT TESTING METHODS

Eden and Kubota (1961) compared the sensitivity values considering different testing methods applied to Leda clay specimens from field testing at four borings in the Ottawa area. Five different approaches were used to compute sensitivity, and are numbered 1 to 5 as follows:

$$\text{No.1}\ \ S_t = \frac{\text{half the unconfined compressive strength } (q_u/2)}{\text{remoulded laboratory vane strength}} \tag{10}$$

$$\text{No.2}\ \ S_t = \frac{\text{undisturbed laboratory vane strength}}{\text{remoulded laboratory vane strength}} \tag{11}$$

$$\text{No.3}\ \ S_t = \frac{(\text{penteration of fall cone on remoulded soil})^2}{(\text{penteration of fall cone on undisturbed soil})^2} \tag{12}$$

$$\text{No.4}\ \ S_t = \frac{\text{undisturbed field vane strength}}{\text{remoulded field vane strength}} \tag{13}$$

$$\text{No. 5}\ \ S_t = \frac{\text{penteration of fall cone on remoulded soil}}{\text{penteration of fall cone on undisturbed soil}} \tag{14}$$

Eden and Kubota (1961) compared their results (in terms of sensitivity values from the above five methods) with a correlation proposed by Bjerrum (1954). Figure 1 shows the comparison, along with the individual observations for method No. 1. All of the data show a trend of increasing sensitivity with increasing liquidity index LI. Bjerrum's relationship can be expressed in the form:

$$S_t = \exp(\alpha.\,\text{LI}) \tag{15}$$

where $\alpha \approx 2$ and is thought to be related to mineralogy and post-depositional geological history. Also plotted on Figure 1are the lines for sensitive soils with α = 1 to α = 3, which appear to bracket most soils (Wood, 1990).

It is noted from Figure 1 that the laboratory vane and unconfined compression testing methods (methods No.1 and 2) agree reasonably with Bjerrum (1954) correlation. The field vane method (method No. 4) gives lower sensitivity when LI is less than 1.5 but higher values at greater LI. The fall cone method gives higher sensitivity for all LI values when using the square of the penetrations ratio (method 3) but lower estimates of the sensitivity when the penetration ratio is used (method No. 5). In general, the fall cone methods represent upper and lower bounds for all of the testing methods.

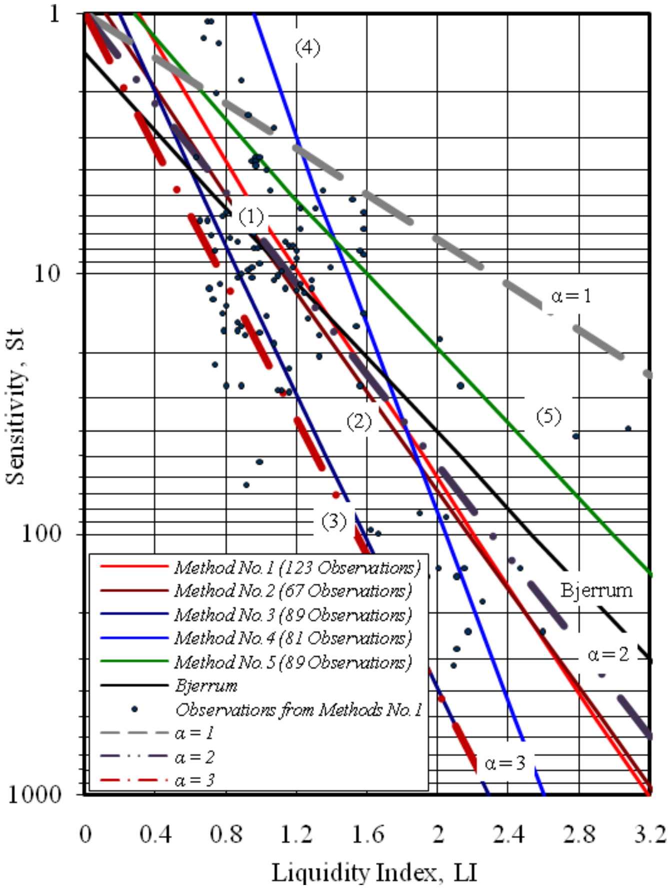

Fig. 1. Relation between LI and S_t for five methods. (Reproduced after Eden and Kubota 1961)

As shown in Figure 1, the data points for method 1 display a wide scatter. The data points for the other methods also display a similar scatter, but are not shown in Figure 1. Even though all laboratory specimens were assumed to be remoulded thoroughly using a mechanical mixer, some of this variation is certainly due to the assessment of the remoulded strength and the state of the soil, especially when the sensitivity is high. Given the common mineralogy and geological history of the samples, α would be expected to be approximately constant and can be assumed to play little effect in the data.

Data collected from 21 different references for sensitive clays, (mostly in Canada, but also from other parts of the world), are plotted in Figure 2. The straight lines representing methods 1-5 (from Fig. 1) are also plotted in Fig. 2

For comparative purposes, a correlation between these different test methods could be established to correct for the difference between the sensitivity values that each test provides. However, the additional effect of soil type and state (i.e. α) is difficult to remove from this data set, and whilst there is potential for this approach further work is required to link α to basic soil properties and the relationships between S_t estimated by each method.

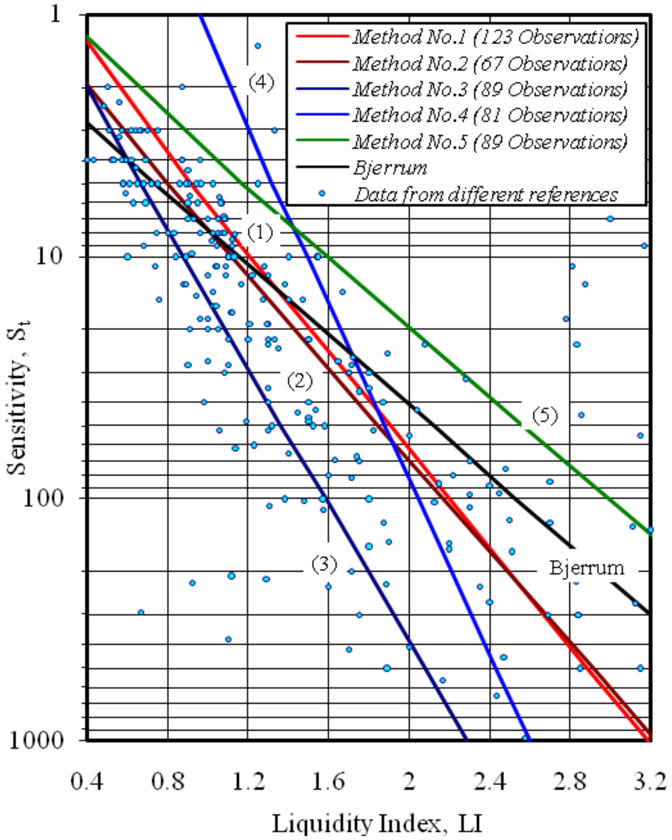

Fig. 2. Data collected from 21 references.

REMOLDING OF SOIL SAMPLE

Soil remoulding can be done by either by hand, mechanical mixer, vane or cyclic loading as described below.

<u>Hand remoulding</u>: according to ASTM D 2166, specimens may be prepared either from a failed undisturbed specimen or from a disturbed sample, providing it is representative of the failed specimen. Specimens can be prepared by wrapping the material in a thin rubber membrane and working the material thoroughly with the fingers to assure complete remoulding. It should avoid entrapping air in the specimen, and exercise care to obtain a uniform density, to remould to the same void ratio as the undisturbed specimen, and to preserve the natural water content of the soil.

<u>Mechanical mixer remoulding</u>: this is another way of remoulding soil samples in the laboratory. It is not mentioned in the ASTM, but it was used by many researchers to produce soil sensitivities for their research (e.g., Devenny, 1975).

<u>Vane remoulding:</u> The ASTM D 2573 and ASTM D 4648 state that to get the remoulded shear strength of soil, rotate the vane rapidly through a minimum of five to ten revolutions following the determination of the maximum torque. The determination of the remoulded strength shall be started immediately after completion of rapid rotation and never more than 1 minute after the remoulding process.

In many sensitive clayey soils, residual strength may be obtained within one to two revolutions or less. If such soils are being tested, it is recommended that several remoulded strengths be obtained using a standard five to ten revolutions for verification. If no major remoulded strength differences are noted, remoulded strengths may be obtained at less than the recommended five to ten revolutions. The vane remoulded strength is typically higher than the hand remoulded strength and, as a consequence, produces lower sensitivities. For the laboratory vane test, the remoulded samples are prepared in a container. For more sensitive soil, the remoulded clay is in a semi fluid or fluid state. Under this condition, a shear surface may not form in the clay slurry.

Devenny, (1975) studied the effect of the degree of soil remoulding on the value of soil sensitivity. Table 9 shows a summary of the tests performed on two types of sensitive clay. After each stage of remoulding, the shear strength was measured with a standard laboratory vane. Full remoulding took considerable energy for both soils. The Labrador clay was difficult to remould by hand and became warmer during mechanical mixing. A limiting value of sensitivity for mechanical mixing was 88 for both soils.

Based on the observations shown in Table 9, Devenny, (1975) concluded that the currently accepted definitions of sensitivity are misleading because they do not consider the amount of energy required to remould the soil. Devenny, (1975) proposed the term “apparent sensitivity” and expressed it as:

$$\text{Apparent Sensitivity}, S_t = \frac{U}{A} \qquad (16)$$

where U is the sensitivity resulting from complete remoulding (20 min. in a mechanical mixer) and A is the sensitivity resulting from 15 revolutions of standard laboratory vane. For example, the sensitivity of Leda clay would be described as 88/13 while for Labrador clay 88/40.

Table 9. Effect of remoulding on strength and sensitivity (Devenny, 1975).

Soil	Degree of remoulding	S_u (Kg/cm^2)	S_t
Leda Clay	Undisturbed	0.3	1
	1 revolution of vane	0.067	4.5
	2 revolutions of vane	0.0415	7.2
	3 revolutions of vane	0.034	10.2
	4 revolutions of vane	0.0287	10.5
	5 revolutions of vane	0.0276	10.9
	10 revolutions of vane	0.0234	12.7
	15 revolutions of vane	0.0225	13.3
	5 minutes in mixer	0.0063	47.6
	20 minutes in mixer	0.0034	88
Labrador Clay	Undisturbed	1.4	1
	Hand remoulding	0.165	8.5
	15 revolutions of vane	0.035	40
	15 minutes in mixer	0.016	88

<u>Cyclic loading remoulding</u>: Yong et al. (1983) tried to develop a technique to address the energy required to achieve 100% remoulding and the condition that determines 100% remoulding. A continuous stress reversal (cyclic load) was applied on a sample of 1 cm thickness and 7.9 cm diameter in a direct simple shear test system to produce various states of remoulding. The results obtained from this test can be presented in the form of a stress-strain curve for each cycle and then the maximum shear strength obtained for each cycle is plotted against the number of cycles or alternatively, the remoulding energy, see Figure 3.The total input remoulding energy required to achieve various stages of soil remoulding was calculated based on the area under the stress-strain curve. From this approach, it can be seen that sensitive clay can lose strength under the effect of cyclic loading, which has obvious implications for seismic design. It also provides a good measure of the total required energy to remould the soil sample, which is an important factor in determining the soil sensitivity.

EFFECT OF CYCLIC LOADING ON SENSITIVE SOIL

Lee (1979) studied the cyclic strength of two undisturbed high sensitivity soil samples, with sensitivity of 380 and 35 respectively. Both samples had similar remoulded strengths and the peak strength of the two samples was 140 and 70 kPa. Even though the stronger clay reverted to a thin fluid and would pour readily from a beaker when thoroughly remoulded, the weaker soil would not quite pour when remoulded. Both clays were failed under cyclic loading along one or more thin well defined shear planes. The soil within these planes was thoroughly remoulded, but elsewhere the soil remained strong, firm and brittle. He concluded that critical zones in sensitive soils, where the initial horizontal stresses were high, e.g. for high embankments, natural slopes, and cuts in undisturbed clay may become unstable during strong seismic shaking and lead to progressive failure and flow slides as soil breaks up, remoulds and liquefies along sheared surfaces. He also presented a procedure to check the seismic stability of sensitive clay site by comparing the seismic shear stresses using the Seed and Idriss (1971) approach to the cyclic strength of soil profile.

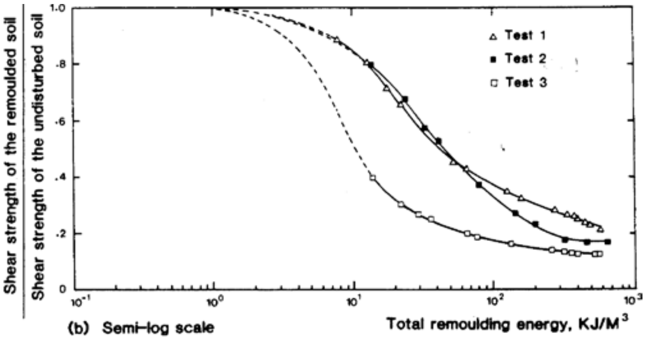

Fig. 3.Shear strength ratio in relation to total remoulding energy per unit volume (after Yong, 1983)

Robertson (2007) suggested that clay material may not suffer cyclic liquefaction if PI >12 (because the effective stress will not reach zero), but it may experience cyclic failure. When the cyclic stress ratio (CSR) is large relative to the undrained shear strength ratio (S_u/σ'_{vc}), cyclic deformations can develop. Boulanger and Idriss (2004) showed that the cyclic resistance ratio (CRR) for cyclic failure (deformations) in clay materials is controlled by the undrained shear strength ratio, which is a function of the stress history (OCR).

Lefebvre et al. (1989) defined the term “Stability Threshold” as the cyclic limit that corresponds to the maximum cyclic stress level at which the soil will not suffer failure, regardless of the number of applied cycles. They presented results based on one way cyclic triaxial test results. These data were for different soils and show extreme variation with the stability threshold ranging between 0.18 and 0.90. The higher values are for high plasticity soil and the lower values for lower plasticity soil such as sensitive clays. The trend of stability threshold is increases with plasticity. The value of the stability threshold reflects the effect of strain rate difference between static and cyclic tests. From their study, they concluded that for highly sensitive clay, the normalized stability threshold for both normally and over consolidated specimens is about 60 to 65% of the original undrained shear strength measured at the same strain rate.

Javed, (2002) performed a study on the strength of sensitive clay under cyclic loading, and concluded that the shear strength of sensitive clay decreases with:

1. Increase in the number of cycles,
2. Increase in the cyclic deviator stress,
3. Increase in pore water pressure, and axial strain,
4. Reduction in preconsolidation pressure,
5. Reduction in confining stress,
6. Increase in water content and liquid limit,
7. Decrease in plastic limit and plasticity index, and
8. Increase in initial degree of saturation.

DISCUSSION AND CONCLUSIONS

In the proceeding sections a number of significant issues have been identified that should be addressed before improvements in design approaches can be made. These can be summarized as follows:

1. There are significant variations between the different classification systems available;
2. There are significant variations in the estimates of sensitivity using the different laboratory and field tests available for soils at the same liquidity index;
3. The relationship between sensitivity and liquidity index is non-unique and appears to be a function of mineralogy and post-depositional geological processes;
4. It is currently unclear what the full effects of cyclic loading are on sensitive soils of different sensitivity and which soil loading states and geotechnical systems are particularly at risk for seismic loading.

To begin to address these issues and shortcomings a number of inter related steps are required. Firstly, more uniform classification systems are required to allow the full range of soil sensitivities to be described across different geological regions; whether this is possible in a unified global system is open to question, but certainly correlations between regional systems should exist. Secondly, these classification system(s) should be based on the minimum number of standardized laboratory and field tests. Indeed the very definition of the soil sensitivity needs to be clarified and defined; the reference soil state described as "remoulded" and the amount of energy required should be quantified more succinctly. Interestingly, whilst the mode of failure for each of the available tests is different and the measured undrained shear strength would be expected to be different, it is more surprising that the relative index between the intact and remoulded states (i.e. the sensitivity) is so different between the methods. As well as the amount of "remoulding energy" applied by each method of shearing, this may also be affected by different strain rates, drainage conditions, pre-test disturbance and other effects such as thixotropy. Certainly "remoulding energy" based definitions of sensitivity and the relative amounts of energy input into the soil specimen by different methods would useful and at the very least would allow rationale correlations between the methods and help to account for the effects of the aforementioned parameter (α) on the databases available.

Lastly, a more comprehensive investigation of the fundamental cyclic behaviour of a range of sensitive soils should be performed. There appears to be a less coherent framework for identifying soil states and sites that are at significant risk of failure during seismic events than is available for other soil types. Understanding of the performance of these soils subjected to cyclic loading and the appropriateness of element tests and scales physical model tests should be investigated more closely. This should then be distilled into more rationale improvements to dynamic response analyses embedded in software used for design.

Certainly the amount of research involved in these steps is significant and the authors have at this stage rarely identified a range of potential changes that are required. In the long term this approach will help to remove the confusion that currently exists in the geotechnical community related to this topic.

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