Influence of grain size on the compressibility of Venice Lagoon soils

Influence de la taille des grains sur la compressibilité des sols de la Lagune de Venise

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ABSTRACT: The soils of Venice Lagoon are characterized by very erratic depositional patterns, resulting in an extremely heterogeneous stratigraphy. Identification of stratigraphic units is difficult because the layers are not continuous. The mineralogical composition of these soils, on the other hand, is quite uniform. The sediments were either originated in the basin of either the rivers Po and Adige, or the rivers Brenta, Piave e Sile and these common sources explain the similarity of composition. It is believed that mechanical action is the main agent determining grain size distribution. Since these soils are characterized by varying contents of coarse and fine-grained particles it is possible to examine what factors affect the transition from one material type to another. In particular, the compressive behavior of the soils will be considered with attention to the proportion of coarse-grained to clay content of the tested specimens and the relative importance of mechanical and physico-chemical factors.

RÉSUMÉ: Les sols de la Lagune de Venise sont caractérisé par de modes des deposition très erratiques entraînant une stratigraphie extrêmement hétérogène. L'identification des unités stratigraphiques est difficile car les couches ne sont pas continues. En revanche, la composition minéralogique de ces sols est assez uniforme. Les sédiments proviennent soit des basins des fleuves Po et Adige, soit des basins des fleuves Brenta, Piave et Sile et ces sont les sources communes qui expliquent la composition similaire des sols. On s'accorde à penser que l'action mécanique est le principal agent influençant la distibution de la taille des grains. Etant donné que les sols sont caractérisés par la présence des grains de petite et grand taille en quantités variables, il est possible d'examiner quel facteurs influencent la transition d'un mileu à un autre. En particulier, le comportament en compressions des ces sols sera étudié en prétant attention aux proportions de sable par rapport aux argilles dans les specimens analysés et à l'importance relative des facteurs méchaniques et physico-chimiques.

1 INTRODUCTION

The Venice Lagoon is suffering an overall rapid deterioration, including dramatic changes in the water and sediment balance in the basin with the corresponding environmental damage. Following an accelerated rate in land subsidence between 1946 and 1970, the city of Venice has observed an increase in the frequency of flooding with a record tidal level of nearly 2 m measured in November of 1966. Since then, numerous engineering solutions have been proposed, including the use of movable gates located at the three Lagoon inlets (i.e., Malamocco, Lido and Chioggia) to control water levels within the lagoon (Harleman et al., 2000). An extensive study on the characterization of these soils has been undertaken for the design of these submersible mobile barriers (Ricceri, 1997) and only a brief summary is presented here.

The subsurface soils of the Venice Lagoon down to 90-100m is characterized by a complex system of interbedded sands, silts and silty clays deposited during the last glacial period of Pleistocene (Wurm) when the rivers transported fluvial material from the Alpine ice fields. The Holocene is only responsible for the shallowest lagoon deposits, about 10-15m thick. Excluding the upper crust of highly overconsolidated oxidized silty clay (commonly referred to as *caranto*) and some thin deeper layers, the cohesive soils are generally slightly overconsolidated with overconsolidation ratios not exceeding 4-5. The depositional patterns of these sediments are rather complex due to the combined effects of geological history and human action, which modified significantly the morphology of the lagoon, inlets and channels over the centuries.

For classification purposes the soil types in the whole lagoon area have been reduced to three: medium to fine sand (SP-SM), silt (ML) and very silty clay (CL) according to Unified Soil Classification System. Their typical grain size distributions are reported in Figure 1. Subsurface profiles are characterized by irregular alternation of the three soil types, with a few thin layers of compacted peat.

Despite the highly heterogeneous soil conditions, the basic material properties may vary over a relatively narrow range due to the common mineralogical origin and depositional environment (Cola & Simonini, 2000). Typical grain size distribution and mineralogical composition of the soils at Malamocco are compared in figure 2. Sand composition is mostly carbonatic and siliceous, with a predominance of calcite and dolomite crystals, especially at higher depths. When the carbonate and quart-feldspar fractions decrease the clay minerals increase, although they never exceed the 20% level in any sample. Silt and clay particles were generally formed by mechanical crushing in a continental environment and are

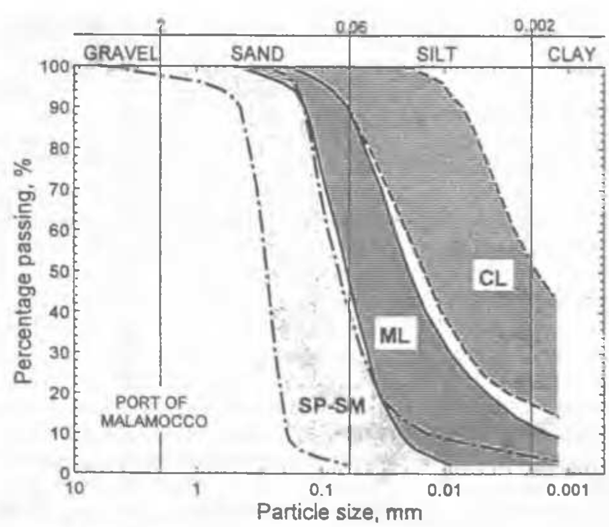

Figure 1. Grain-size distribution of Venetian soils.

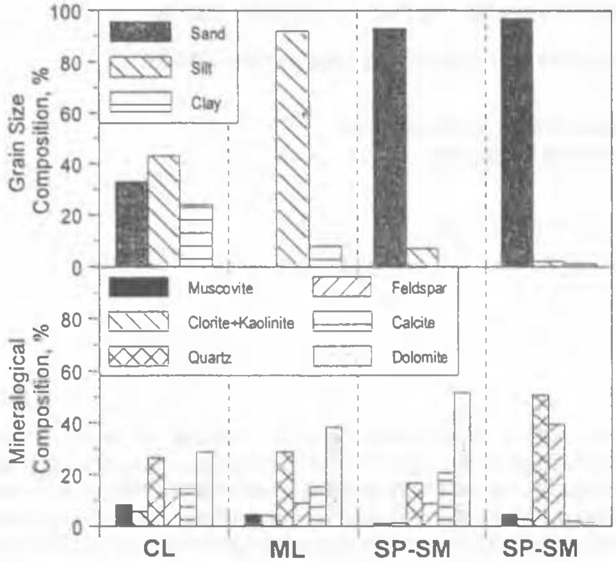

Figure 2. Comparison between grain size distribution and mineralogical composition of soils at Port of Malamocco test site.

aggregated in an irregular assemblage, characteristic of a predominant flocculated structure. Clay minerals are mainly composed of illite –prevalently 2M muscovite – with chlorite, kaolinite and smectite as secondary materials.

Similarly to the grain size distribution, the density and in-situ void ratio vary significantly within a sample. The relative density of the sandy layers lies in the range of 40% to 80%, with no particular trend with depth. Excluding the organic layers, the void ratio is between 0.6 and 0.9, the lowest value being measured in the overconsolidated crust of *caranto* and in the deepest sands.

2 SOIL COMPRESSIBILITY

In order to evaluate the compressibility characteristics of these soils a series of oedometer tests were performed on high quality specimens of the three soil types. The samples were obtained from three borings carried out at the Malamocco Test Site at one of the inlets to Venice Lagoon and identified throughout the paper as MSM10, MSgM1 and MSgM2. Particularly, in the first phase, the research program considered tests only on the cohesive soils from MSM10 and MSgM1. In a second time, additional tests on soils of ML and SM-SP classes from MSgM2 were planned to investigate the 1-D compressibility of sandy material.

Figure 3 shows the profile of water content, liquid limit and plastic limit as a function of depth for the specimens for the three borings with specimen numbers shown in the graph. In the case of MSgM2, the water content profile was only reported because the soils tested were all granular.

A summary of one-dimensional compression tests is presented in figure 4, where all the curves are plotted for each boring. For reference, the estimated current vertical effective stress in situ is also shown on each curve. The preconsolidation pressure cannot be obtained with the Casagrande construction within an acceptable degree of accuracy because it is difficult to select the point of maximum curvature on the rounded curves that characterize these silty soils.

The one-dimensional compression curves in figure 4 seem to break at about the same range of vertical stress, independently of the initial void ratio or the compression index (C_c). This would suggest that the soil has experienced approximately the same value of maximum vertical stress, independent of the depth of the material, which ranges from 13m and 94m. Although this is possible for very large loads, such as ice during a glaciation, it appears that it is not the case here.

3 PROPOSED MODEL FORMULATION

Pestana and Whittle (1995) proposed a new compression model for cohesionless soils in order to describe the non-linear compression response over wide ranges of confining stress and density. The model assumes that specimens compressed from different initial formation densities approach a unique response at high stress levels, referred to as the Limiting Compression Curve (LCC) which is linear in a double logarithmic void ratio-effective stress space. For one-dimensional compression the K_0-LCC is given by:

$$\log(e) = -\rho_c . \log(\sigma'_v / \sigma'_{vr}) \quad (1)$$

where σ'_{vr} is the reference vertical effective stress at a void ratio of one and ρ_c is the slope of the K_0-LCC line in the proposed space.

Alternatively, equation 1 can be rewritten as:

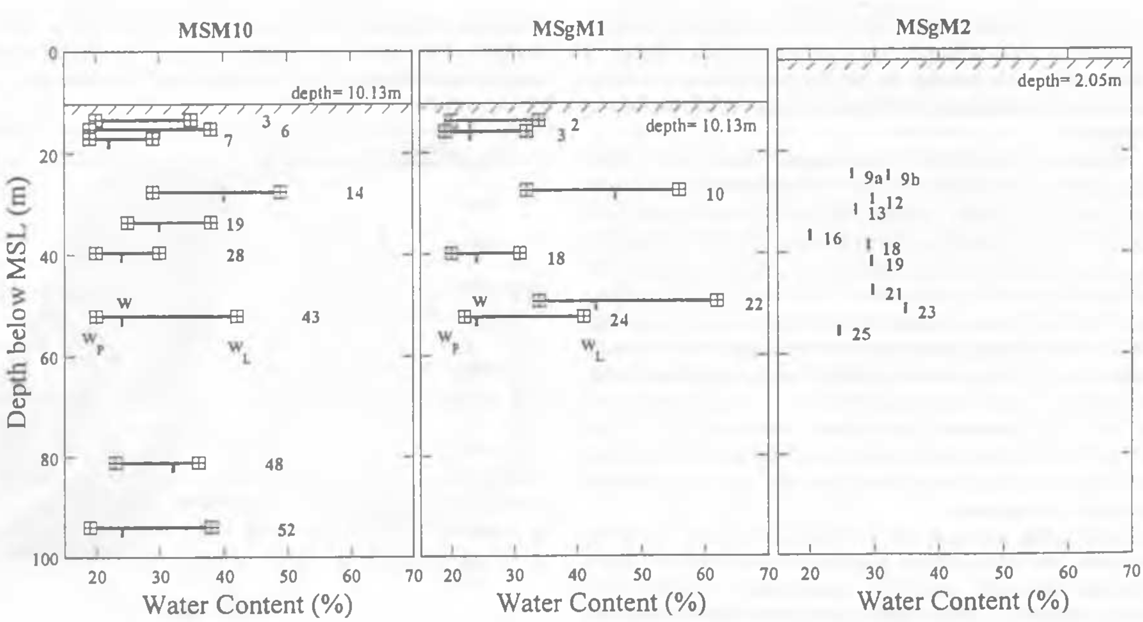

Figure 3. Profile of water content and index properties for soils at the Port of Malamocco test site.

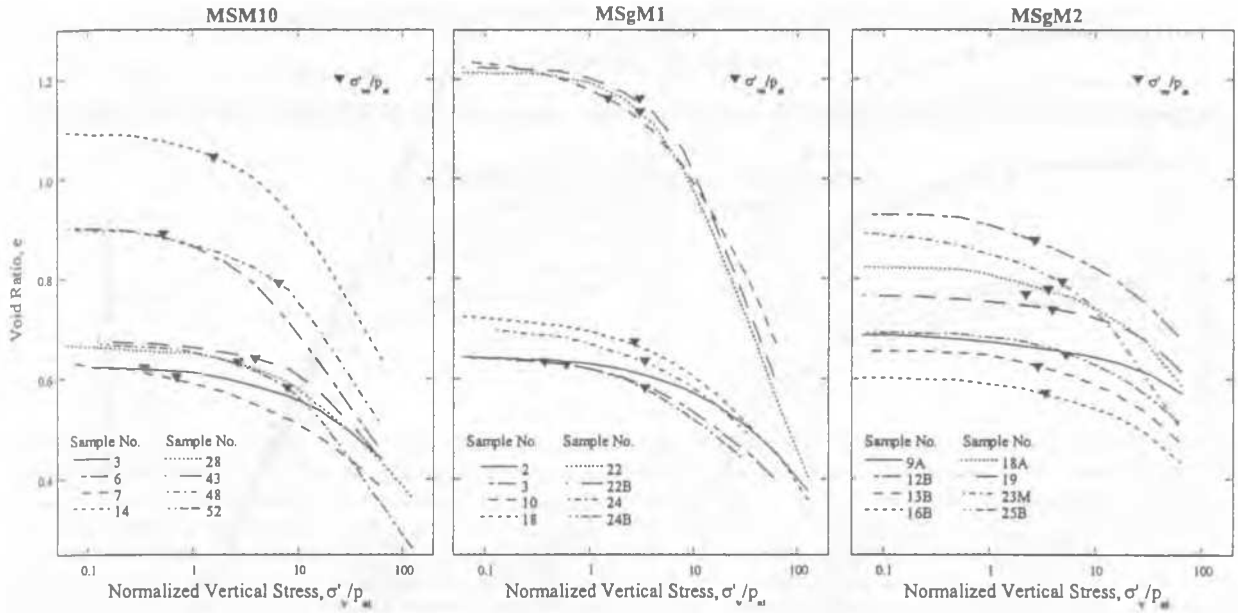

Figure 4. Oedometer compression curves for the soils at the Port of Malamocco test site.

$$\log(e/e_1) = -\rho_c.\log(\sigma'_v/p_{at}) \quad (2)$$

where e_1 is the void ratio at $\sigma'_v/p_{at} = 1$ with $p_{at} = 1$ atm ~ 101.33 kPa. Pestana (1994) suggests that the 1-D compression of clays can be described, for numerical purposes, by the same K_0-LCC framework. For fully saturated clay-sand mixtures where the clay content is higher than 40 to 50%, the model predicts that the location of the curve is dependent on the clay fraction, but the slope is uniquely a function of the mineralogy of the clay matrix. Under the assumption that the grains behave as "rigid inclusions" in a clay-water phase, the model predicts that e_1 is proportional to the clay fraction. Figure 5 shows the proposed model for silty clay materials.

At small stresses, the compression of these soils is dependent on the value of current density as well as confining stress (similarly to sands) but the compression curves appear to converge to a unique curve at large stresses, which can be described by the LCC framework. Similarly to clays, the location of the LCC (i.e., e_1) appears to be controlled by the fines fraction. The compression behavior of these silty materials is nonlinear with the compressibility controlled by the ratio σ'_v/σ'_{vb} describing the proximity of the current stress level to the corresponding vertical stress at the LCC at the same void ratio. Pestana (1994) shows full details of the model formulation to describe the response in the transitional regime.

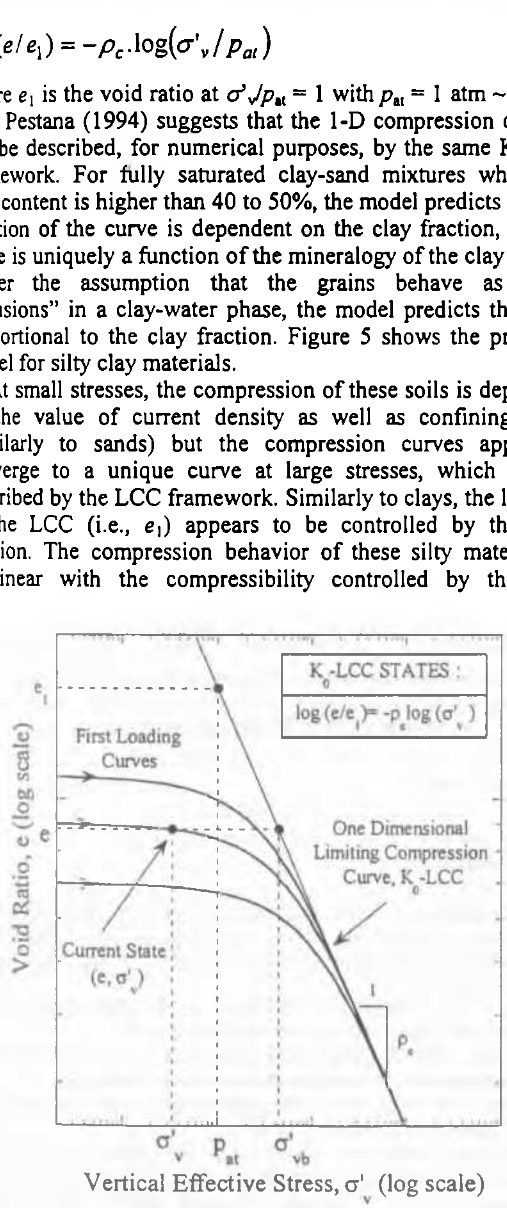

Figure 5. Idealized behavior of silty clays soils (modified from Pestana, 1994, Pestana & Whittle, 1995).

The compression curves shown on figure 4 were examined in the proposed framework and three different groups could be identified with very characteristic response in the LCC regime. For each group an average value of ρ_c was selected based on the LCC response in the range of vertical stress 10-100 atm (~1 to 10 MPa): 0.23 for group 1, 0.17 for group 2 and 0.4 for group 3.

Each curve was then normalized by the corresponding value of void ratio e_1 at 1 atm. Within each group all the one-dimensional compression curves appear to converge to the LCC. The normalized curves for group 1 are shown in figure 6. Heterogeneity for these materials appear to be controlled primarily by the amount of clay fines, which in turn determine the value of e_1.

Figure 7 shows the variation of the reference void ratio e_1 with the fines fraction (defined here as the percent smaller than 5 μm). For the silty clays of Malamocco, the value of 5μm appears to describe well the separation between fine and coarse grained materials. The correlation between the fine fraction and the normalized void ratio is extremely good for group 3, while the scatter is larger for group 1 and 2. This discrepancy is partially attributed to the fact that the gradation analyses were not performed on the material used for the compression experiments themselves but on soil material from the same boring at a close distance. Variable soil description within 10cm have been reported by Cola and Simonini (2000).

Figure 7 shows lines of equal reference void ratio of the fine fraction, e_{1C}, defined as the ratio of the volume of voids to the volume of the clay fraction. For cases in which the specific gravity of the clay and coarse-grained phase are similar, the void ratio of the clay fraction is approximated as: $e_c = e/FF$ (where FF is the fine fraction and e is the global void ratio). The graph shows that as the percent of fines increases the value of e_1 for the mix increases, while the void ratio of the fines remains constant. Any given clay (or 100% fines) will have a different value of $e_1 = e_{1C}$, so when the data points align on a straight line they indicate that their fine fraction mineralogical composition is the same. Lines of constant reference void ratio of the coarse grained fraction (defined as the ratio of the volume of the clay + voids to the volume of the coarse grained material) are also plotted in figure 7. These lines cut the constant e_{1C} lines at an angle, implying that the change in behavior takes place at different fine fractions for different soils.

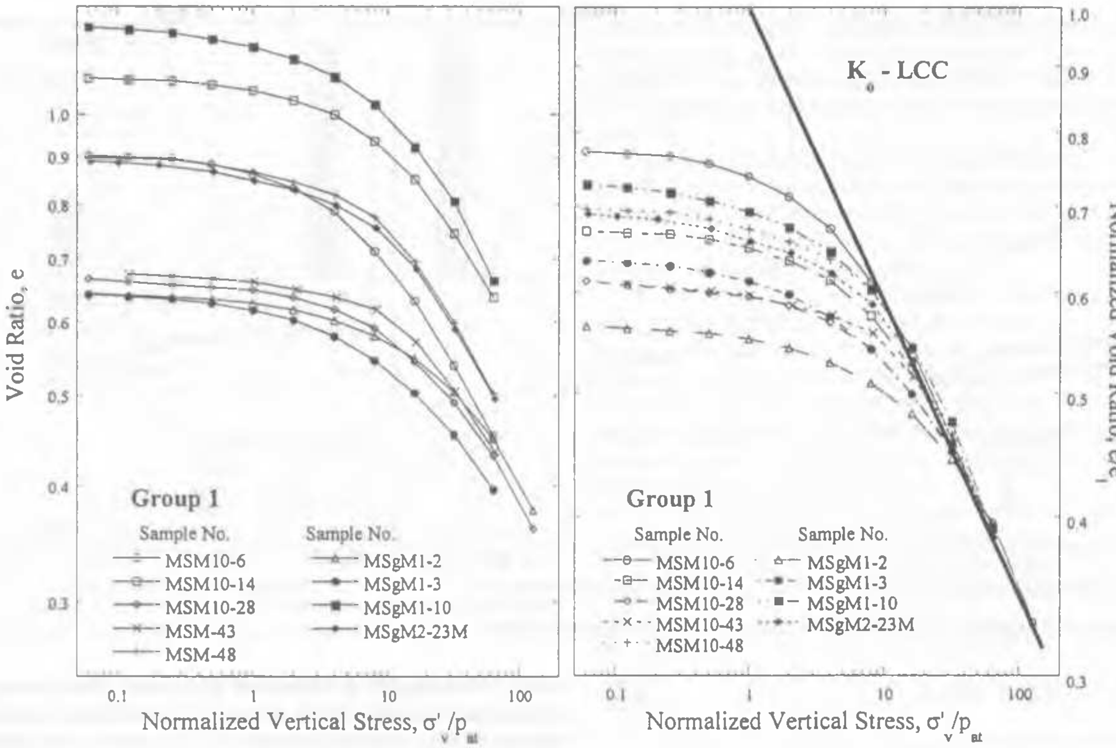

Figure 6: One dimensional compression curves and normalized response for silty clay materials.

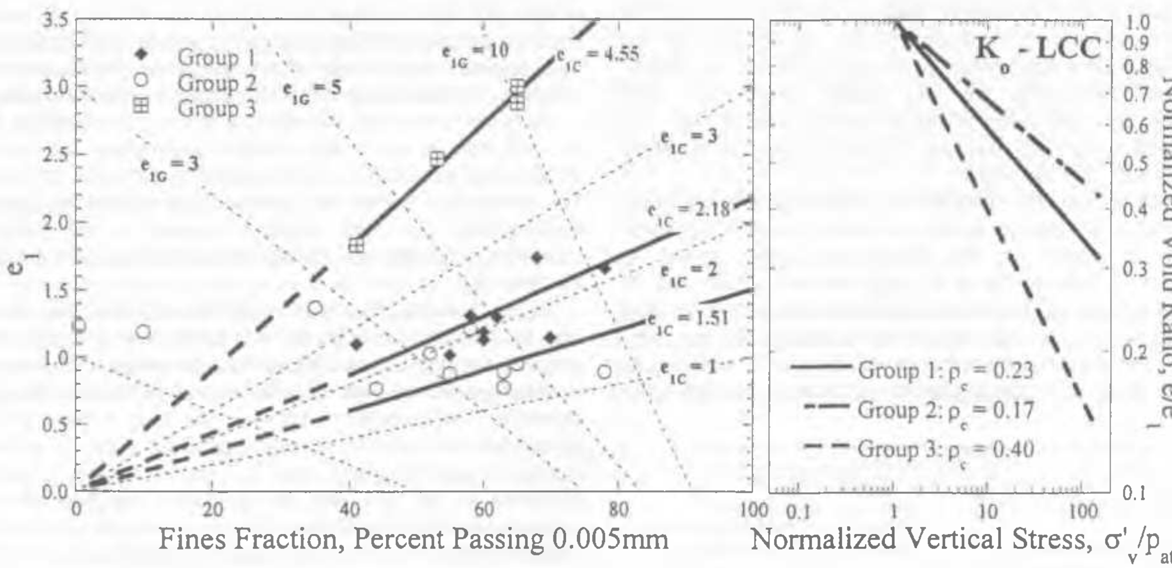

Figure 7: Compression parameters for silty clay materials as a function of clay fraction (<5μm).

4 CONCLUSIONS

The compressibility of natural silty clays of same mineralogical origin appears to be described by the same framework proposed for cohesionless soils provided that the location of the LCC is adjusted to account for the different clay fraction in the specimens. This implies that the slope of the LCC is nearly unique for most practical purposes while the location described by the reference void ratio, e_1 is controlled by the fine (i.e., clay) fraction (<5 μm). For clay contents exceeding 40% the granular phase acts as a rigid inclusion and the behavior of the soil is dominated by the fines fraction. In these cases, the reference void ratio is nearly proportional to the fine fraction. The trend in e_1 for fines fraction below 40% and toward zero is affected by the granular phase and requires a full description of the coarse grained-clay mixture.

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