Modeling sampler plugging in gravels using the Distinct Element Method (DEM)

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ABSTRACT
A numerical modeling research program was undertaken to investigate the causes and effects of sampler plugging in gravels. The research utilized two-dimensional Distinct Element Method (DEM) software to simulate the penetration of samplers into assemblages of particles with various mean grain sizes. Plugging occurred when the ratio of sampler to mean particle size decreased, and was associated with a relative decrease in penetration energy. It is postulated that "efficient plugging" may explain the empirical observation of lower than expected Standard Penetration Test (SPT) blow counts in gravels.

RÉSUMÉ
Un programme de recherche en modélisation numérique a été entrepris afin d'étudier la relation de causes à effets de l'obturation du carrotier dans les graviers. Un logiciel bidimensionnel employant la Méthode d'Éléments Distincts (MED) a été utilisée pour simuler la pénétration du carrotier dans des groupements de particules formés de grains ayant différentes grosseurs moyennes. L'obturation est observée lorsque le ratio de la grosseur du carrotier par rapport à la grosseur du grain diminue et est alors associé à une réduction relative de l'énergie de pénétration. Il est stipulé que l'obturation efficace pourrait expliquer le nombre de coups observés inférieur à celui escompté lors d'essais de pénétration standard du carrotier.

1 INTRODUCTION

There is a growing body of evidence suggesting that gravel deposits can liquefy during earthquake loading. This is a concern in the geotechnical engineering community due to the lack of a reliable approach to assessing the liquefaction susceptibility of gravels. The liquefaction susceptibility of sands is typically assessed using Standard Penetration Test (SPT) blow counts (N), but large soil grains are known to affect SPT (N) values. One approach to overcoming grain size effects in gravels has been to use scaled-up versions of the SPT, including over-sized samplers. This type of test was first referred to as a "Large Penetration Test" (LPT) by Kaito et al. (1971), and studies using several different types of LPT have since been described in the literature. LPT blow counts are typically converted to equivalent SPT blow counts using an SPT-LPT correlation factor. The equivalent SPT blow counts are then used with existing SPT-based liquefaction assessment procedures. Daniel et al., (2003a) proposed a generic procedure for predicting SPT-LPT correlation factors that is based on details of the LPT, including hammer energy and sampler dimensions.

The LPT approach to overcoming grain size effects is limited by the practical range of sampler sizes, which is small relative to the range of grain sizes that are classified as sands and gravels. Based on this observation, and following on Tokimatsu (1988), Daniel et al. (2003b, 2004) suggested that both SPT and LPT blow counts should be expected to vary with grain size, and that the variation of both types of blow count should be taken into account when interpreting data of the type shown in Figure 1, which illustrates the variation of empirical SPT-LPT correlation factors with mean grain size (D_{50}). The SPT-LPT correlation factors shown in Figure 1 initially increase with mean grain, size but begin to decrease as (D_{50}) becomes larger than about 1.0 mm, creating a concave-down trend. This trend indicates that SPT blow counts decrease *relative* to LPT blow counts in coarser soils, but additional interpretation is required to determine what the actual SPT and LPT trends are.

SPT grain size effects in gravels are often assumed to be related to the occurrence of sampler plugging. It is commonly assumed that the SPT sampler will become plugged by gravel particles, causing it to become a closed-ended, full-displacement penetrometer, rather than an open-ended sampler. The increased bearing area is assumed to cause a relative increase of the measured blow count in the absence of any change in state or engineering properties. The use of LPT in gravels is an attempt to ensure that penetration testing is carried out using an open-ended sampler. LPT with sampler outer diameters ranging from 73 to 140 mm, compared to 51 mm for the SPT, have been used to date. Considering this relatively small range of available LPT sampler sizes and the known variation of SPT blow counts with grain size throughout the sand and gravel range of grain sizes (e.g. Skempton, 1986; Kulhawy and Mayne, 1990), this interpretation of grain size effects seems overly simplistic.

It is apparent that an improved understanding of SPT and LPT grain size effects is required if the results of either test are to be used for assessing the potential for gravel liquefaction during earthquake loading. This paper presents some results of a basic numerical study of sampler plugging in coarse soils. The study utilized Distinct Element Method (DEM) software that considers the interaction of individual soil particles and linear boundary elements.

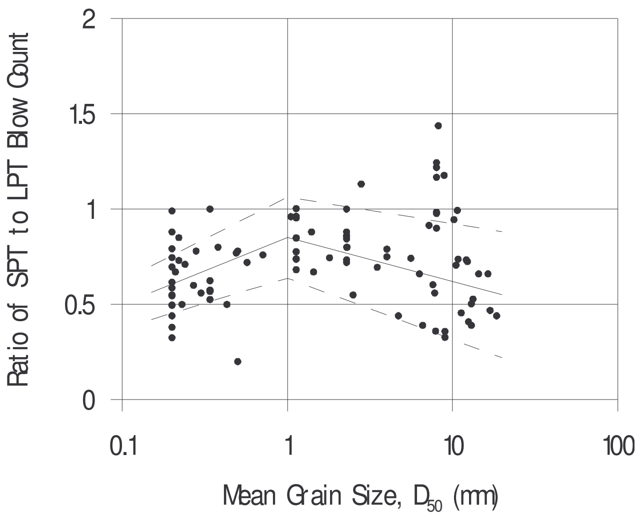

Figure 1. Field data illustrating grain size effects observed in SPT-LPT blow count ratios. LPT blow counts corrected to those of a “reference LPT” to allow for direct comparison.

2 DISTINCT ELEMENT METHOD (DEM)

Finite Element (FE) numerical simulations are widely used to study geotechnical problems by both practising engineers and those involved in research. The basic unit used to represent the soil is a deformable element that is connected to adjacent elements at shared nodes (Figure 2a). Displacements must be continuous both within elements and between adjacent elements. Because the deformation of granular soils is ultimately accommodated by interparticle slip, however, the assumption of a continuous displacement field is only reasonable if the element is much larger than the soil grains. For the purpose of modeling sampler penetration in gravels, the soil grains become comparable in size to components of the sampler (e.g. the sampler diameter), and the continuity assumption required for the FE approach becomes unreasonable.

The study described herein used the Distinct Element Method (DEM) approach to numerical simulation of geomaterials. During DEM simulations, each element or particle is independent and unattached to adjacent elements (Figure 2b). The basis of the DEM approach is that a finite period of time is required for a force disturbance applied to one particle to propagate further than those particles that are in direct contact. In that case, the net force acting on any one particle can be determined by considering only the magnitude of any body forces and the contacts specific to that particle, provided a sufficiently short time step is considered. The sequence of calculations during each time step consists of:

1. Identification of all particle-particle and particle-boundary contacts;

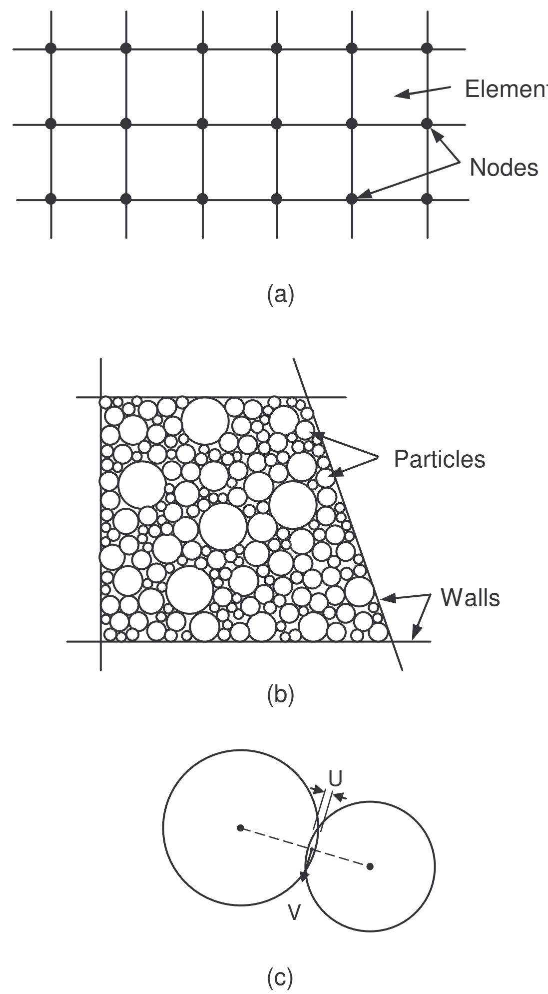

Figure 2. Comparison of (a) finite element mesh and (b) DEM particle assemblage. DEM inter-particle forces are related to particle overlap (U) and relative tangential velocity (V), as shown in plot (c).

2. Calculation of interparticle forces using a “soft-contact” approach for which the force is proportional to the particle overlap (Figure 2c);

3. Calculation of particle accelerations using Newton’s Second Law; and,

4. Calculation of new particle locations for use during the next time step.

The DEM software “Particle Flow Code in 2-Dimensions” (PFC2D, Itasca Consulting Group, Inc.) was selected for use during the study. PFC2D considers the interaction of circular particles and linear wall elements in two dimensions. Particles and walls have unit length in the third dimension.

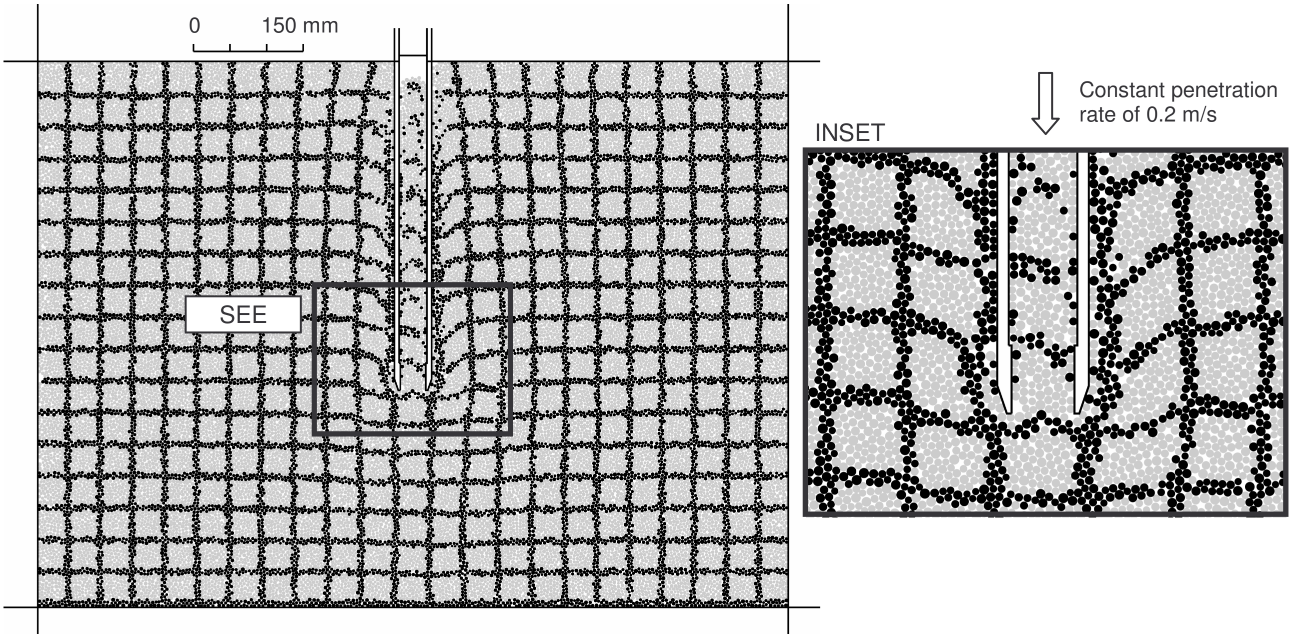

Figure 3. 1000 mm wide by 750 mm high sample containing 35,911 particles with mean diameter of 4.75 mm. Inset shows particle displacements around simulated sampler opening.

3 METHODOLOGY

The study methodology consisted of creating 1.0 m wide by 0.75 m high DEM samples with known particle size distributions and boundary stresses, and penetrating pairs of "platens" into the samples at a constant rate of 0.2 m/s (Figure 3). The platen geometry is based on the cross-section of a standard SPT split-spoon sampler, with the internal liner omitted. The platens were simultaneously penetrated a total of 457 mm (18"), equivalent to the specified sampler penetration during an SPT.

Simulations were conducted using five samples with mean particle sizes ranging from 4.75 to 19.0 mm (Table 1), and with platens at five different spacings, corresponding to simulated sampler outer diameters of 25, 51, 76, 102 and 127 mm (1, 2, 3, 4 and 5 inches). An isotropic boundary stress of 100 kPa was applied and maintained during all simulations by automatically adjusting the upper and side boundary velocities during each time step using an automated "servo" subroutine. The grid pattern shown in Figure 3 was created by changing the colour of particles within selected vertical and horizontal bands at the beginning of the simulation. The distribution of particles can be plotted at any time during the simulation. This visual output is useful for assessing the manner in which platen penetration is accommodated by the particle assemblage.

Numerical output from the simulations included end bearing, frictional forces and soil plug height. Typical profiles of total resistance and internal friction are shown in Figure 4. Also shown is a profile of the cumulative penetration energy (E_p), determined by integrating the total resistance as a function of platen penetration. Small fluctuations in the calculated energy profile corresponding to those visible in the total resistance profile are not visible at the scale of the plot. The energy required to penetrate the platens from 152 to 457 mm (6 to 18"), identified as (ΔE_p), is roughly analogous to an SPT or LPT blow count.

Table 1. DEM Sample Details.

Mean Particle Size (mm)	Range of Particle Sizes (mm)	Number of Particles
4.75	4.00 to 5.60	35,911
6.30	5.60 to 6.70	20,642
8.00	6.70 to 9.50	12,681
13.2	12.5 to 16.0	4,290
19.0	16.0 to 22.4	2,246

Sampler plugging is traditionally discussed in terms of the "plug length ratio" (PLR), defined by the equation:

$$\mathrm{PLR} = \frac{\text{Plug Length}}{\text{Samper Penetration}} \cdot 100\% \qquad [1]$$

but has also been discussed in terms of the incremental filling ratio (IFR), defined graphically in Figure 4, which considers the plugging behaviour over an increment of sampler penetration (e.g. Brucy et al., 1991). An IFR profile is included in Figure 4 to demonstrate the onset of plugging behaviour during a simulation. An IFR of 100% corresponds to fully coring penetration, while a value of zero corresponds to fully plugged penetration.

It should be recognized that the interaction between particles and simulated samplers in the two-dimensional DEM environment will not be directly comparable to the interaction of real-world soils and samplers, which possess curvature in the third dimension. Despite this

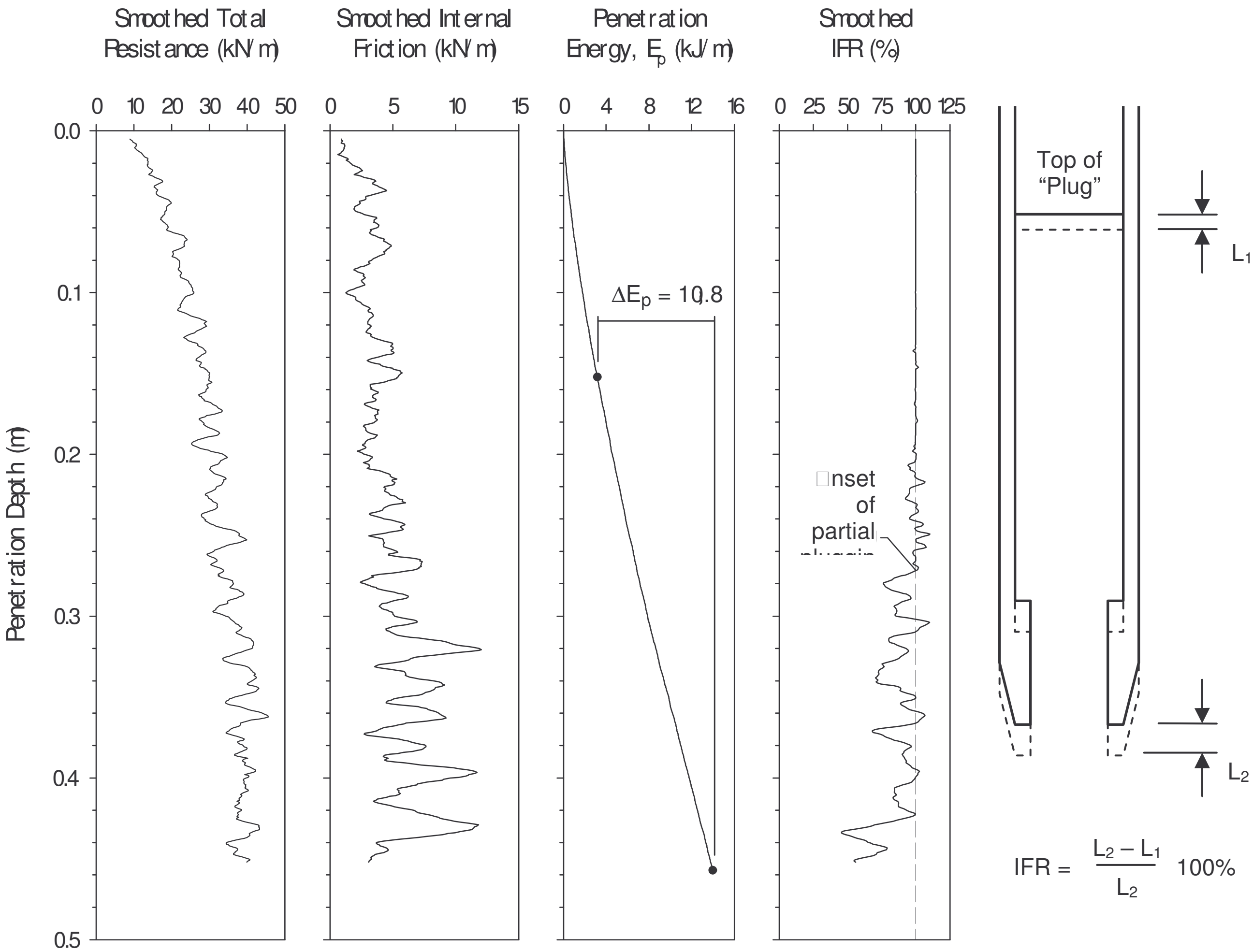

Figure 4. Typical platen penetration simulation results, and a graphical definition of "Incremental Filling Ratio" (IFR). Total resistance, internal friction and IFR have been smoothed to clarify trends.

limitation, it is considered that some of the insight gained from the two dimensional simulations is applicable to real-world situations. This and other limitations are discussed at length by Daniel (2008), where a more thorough description of the methodology followed and additional results can also be found.

4 SIMULATION RESULTS

As demonstrated in Figure 3, the DEM is a powerful tool for visualizing the manner in which samplers penetrate coarse soils. In addition, the DEM approach is well suited to a study of sampler plugging, because plugging occurs whenever conditions within the model support it with no special coding required. Figure 5 shows end of simulation particle configurations for penetration of the five sampler sizes into the 8.0 mm mean particle size sample. The black lines in the plot represent particle-particle or particle-wall contacts and are proportional in thickness to the magnitude of the force. A natural progression of plugging behaviour is evident in the plot, with the final plug length ratio tending to decrease with decreasing platen spacing.

Trends similar to the trend demonstrated in Figure 5 were noted for the other four particle sizes considered (not shown). These trends are illustrated in Figure 6a, which is a plot of the final plug length ratio (at 457 mm penetration) against the ratio of the internal platen spacing to the mean particle size. Normalization of the platen spacing to the particle size is seen to reduce the data onto a single trend line. The plot demonstrates that some degree of plugging can be expected when the ratio of platen spacing to mean particle size decreased below about 5 to 8.

Figure 6b illustrates the corresponding trend between the required interval penetration energy (ΔE_p) and the ratio of platen spacing to mean particle size. In this plot, the interval penetration energy has been normalized to the equivalent large sampler penetration energy, determined by doubling the interval penetration energy required for a single platen. The "equivalent large sampler" energy should be roughly equal to the penetration energy for platens spaced at the sample

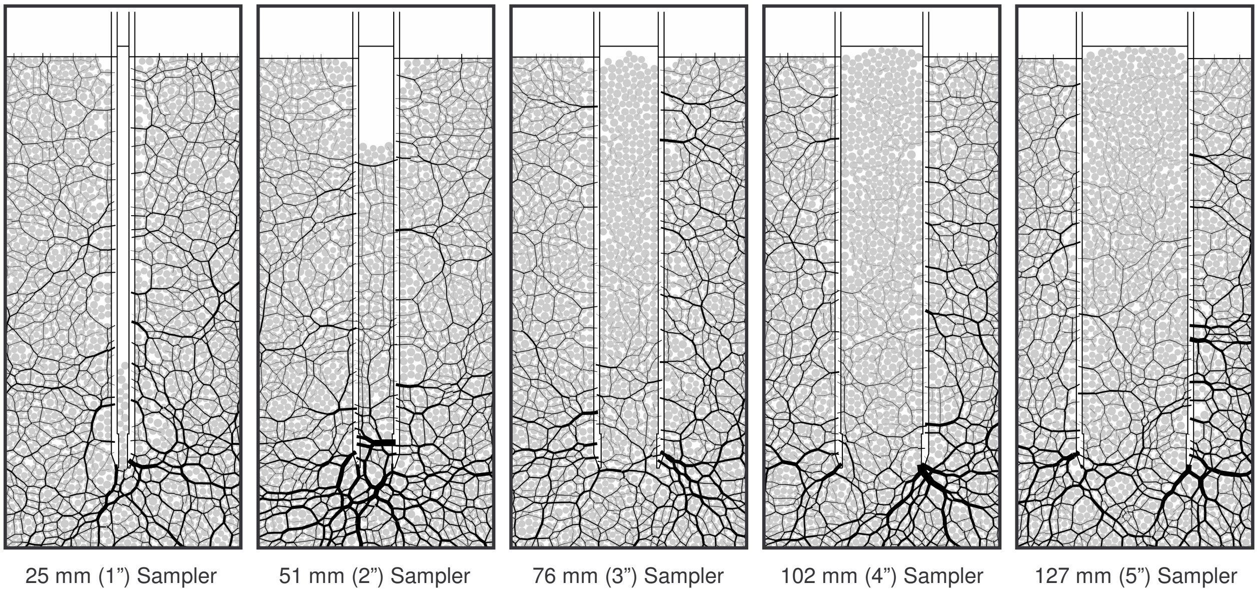

Figure 5. End of simulation particle distributions for five samplers in sample with mean particle size of 8.0 mm. Black lines are proportional in thickness to particle-particle and particle-wall contact forces.

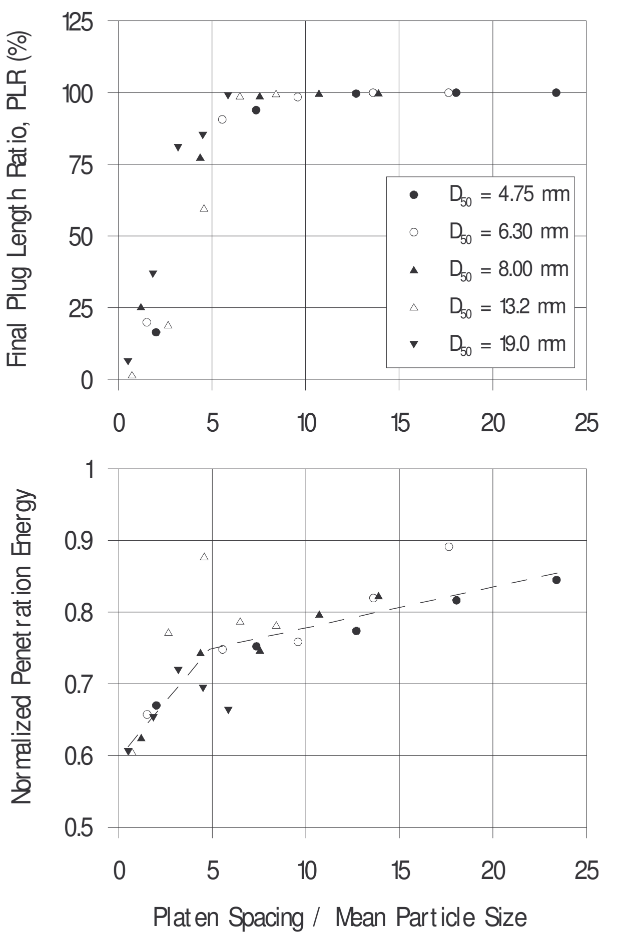

Figure 6. Effect of sampler to particle size ratio on final plug length and penetration energy.

width (1.0 m), and is a convenient method for addressing differences in penetration energy between samples that are not due to plugging effects.

A simple bi-linear trend line has been sketched on Figure 6b, and is defined by the following set of equations:

$$\text{Normalized Energy} = 0.6 + 0.03 \cdot \frac{ID}{D_{50}} \qquad [2a]$$

for (ID/D_{50}) less than 5 and:

$$\text{Normalized Energy} = 0.75 + 0.006 \cdot \frac{ID}{D_{50}} \qquad [2b]$$

for (ID/D_{50}) greater than or equal to 5, where (ID) is the internal platen spacing. The trend line suggests that the relative penetration energy generally decreases as the platen spacing to particle size ratio decreases. This trend is amplified when the sampler to particle size ratio becomes less than about five. It is postulated that this decrease in energy is correlated to the onset of plugging, which occurs at a similar ratio of platen spacing to mean particle size.

5 DISCUSSION

The observed trend of penetration energy decreasing following plugging in the DEM environment runs contrary to common opinion about sampler plugging in gravels, which holds that sampler plugging will cause an increase in penetration energy or blow count (e.g. Jamiolkowski and Lo Presti (2003). Real world sampler plugging is commonly envisioned as an inefficient process in which one or more oversized particles becoming wedged in the sampler opening. The results of the numerical study

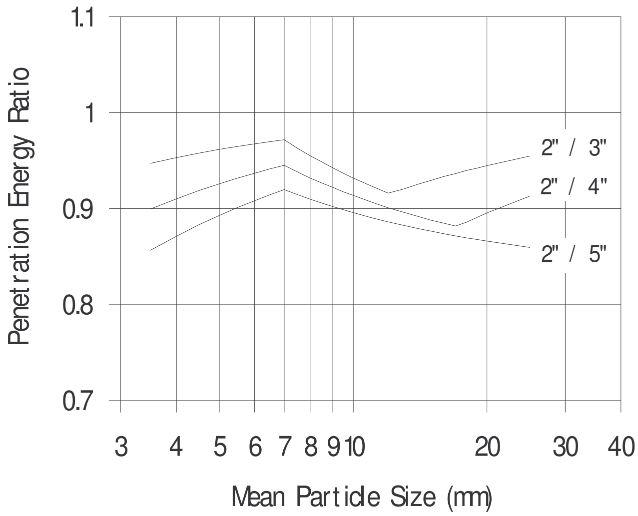

Figure 7. Effect of simulated sampler to particle size ratio on penetration energy ratio.

illustrate "efficient plugging", wherein plugged sampler penetration occurs because it is the most efficient mode of penetration.

As a first approximation, the trend line defined by Equation [2] can be used to predict the variation of the ratio of normalized penetration energies for two different platen spacings as follows:

$$\frac{(\text{Normalized Energy})_A}{(\text{Normalized Energy})_B} = \frac{0.75 \cdot D_{50} + 0.006 \cdot (\text{ID})_A}{0.75 \cdot D_{50} + 0.006 \cdot (\text{ID})_B} \quad [3]$$

where the subscripts (A) and (B) indicate two platen spacings. It has been assumed for Equation [3] that (ID/D_{50}) is greater than 5 for both simulated samplers. Slightly modified equations are easily developed using Equation [2b] to represent the case of one or both simulated samplers having (ID/D_{50}) less than or equal to 5. The relationships defined by sets of equations derived in this manner are plotted in Figure 7. In all cases, simulated sampler (A) was assumed to have an equivalent external diameter of 51 mm (2"), representing an SPT sampler, while three sizes of simulated sampler (B) were considered, including 76 mm (3"), 102 mm (4") and 127 mm (5'), representing three sizes of LPT sampler. For all three simulated LPT samplers, the predicted penetration energy ratio initially increases with mean particle size, then decreases above a mean particle size of 7 mm, corresponding to an (ID/D_{50}) value of 5 for the simulated SPT sampler. The penetration energy ratio then begins to increase again as the value of (ID/D_{50}) decreases below 5 for the simulated LPT sampler. The latter increase is not observed for the simulated 127 mm (5") LPT sampler due to the range of mean particle sizes shown in the plot.

The three trend lines shown in Figure 7 are analogous to the variation of SPT-LPT blow count ratios shown in Figure 1. The initial concave-down trend in Figure 7 is believed to reflect efficient plugging of the simulated SPT sampler. It is postulated that efficient plugging of SPT samplers may similarly be the cause of the concave-down trend seen in Figure 1. This is presented as an alternative to the inefficient plugging of both SPT and LPT samplers hypothesized by others.

Insufficient data regarding the actual plugging behaviour of SPT and LPT samplers in the field are available. The relative prevalence of efficient versus inefficient plugging during real world testing is unknown, and would clearly be related to the number of oversized particles present in the soil. Additional studies, preferably including direct measurement of IFR during SPT and LPT, are required to investigate this effect.

6 CONCLUSIONS

The DEM is a useful tool for studying micromechanical behaviour of soils. The study results presented herein demonstrated that plugging of simulated samplers was triggered when the ratio of the platen spacing to the mean particle size decreased below about 5 to 8. The plugging occurred in the DEM environment with no prompting from the user, and appears to be correlated with a relative decrease in the energy required to penetrate the simulated samplers over a set interval (Figure 6). The occurrence of efficient plugging was demonstrated to be a potential alternate explanation for the concave-down trend observed when SPT-LPT blow count ratios are plotted as a function of mean grain size (Figure 1). Further study of the nature of real world SPT and LPT sampler plugging is required to clarify which hypothesis is correct.

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