Thermal Shakedown In Granular Materials

Shuai Zhou, Graduate Student and T. Matthew Evans, Associate Professor
Oregon State University School of Civil and Construction Engineering

Background and Motivation

Deeper than approximately 6 m below ground surface, soil temperature remains relatively constant. It is possible to exploit this property as either a heat source in the winter or a heat sink in the summer to offset climate control costs in buildings. An emerging technology for this is energy piles which serve both as a heat exchanger and a foundation to support the structure. Previous research (e.g., Suryatriyastuti et al, 2012) has sought to elucidate the thermally-induced mechanical behavior change of energy piles. According to Kalantidou et al (2012), *in-situ* tests conducted have shown that the strains induced during heating/cooling are reversible and their impact on performance is negligible. However, this work neglected the effects of repeated thermal cycling over the design life of the structure.

In the current work, we seek to use a particulate model, specifically the discrete element method (DEM), to study the effects of thermal shakedown in granular materials. Changes in specimen macrostate (e.g., porosity) and microstructure (e.g., fabric tensor) are observed with the long-term goal of extrapolating them to predict the response of field-scale performance of energy piles over many thermal cycles.

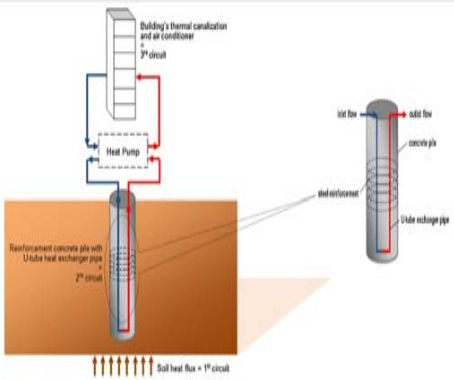

Figure 1. Diagram of energy pile by Suryatriyastuti et al (2012)

Discrete Element Method Simulations

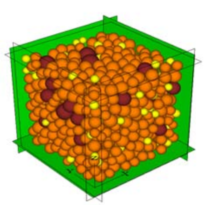

Figure 2. Sphere arrangement before 100 thermal cycling test

The current model is comprised of 902 spheres contained by a box comprised of six rigid walls. The assembly is consolidated to a porosity of 0.426 at an isotropic stress of 100 kPa. The assembly is thermally cycled 100 times while mechanical rearrangement is monitored. Thermal cycling is accomplished by changing the sizes of the particles according to the coefficient of volumetric thermal expansion for pure silica ($\alpha_v = 10^{-6}\ K^{-1}$ at 20 °C). Thus, on heating, each particle radius is increased by an increment *Δr*. Mass conservation requires that particle density must simultaneously decrease by some increment $\Delta\rho_s$:

$$\Delta\rho_s = \rho_o - \rho_{new}$$

$$\rho_{new} = \frac{\rho_o \cdot \frac{4}{3}\cdot\pi\cdot r_o^3}{\frac{4}{3}\pi\cdot(r_{new})^3}$$

$$r_{new} = r_o\cdot(1+\Delta T\cdot\alpha)^{\frac{1}{3}}$$

ρ_o is original density of spheres; r_o is original spherical radius;
ρ_{new} is new density of spheres after volumetric thermal expansion;
r_{new} is new sphere radius after thermal expansion;
ΔT is the temperature difference between heating and cooling;

Preliminary Results

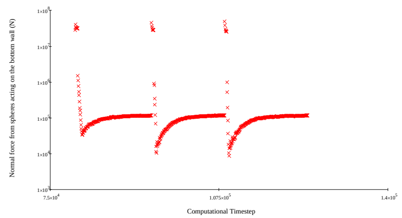

Figure 3. Normal Force from spheres acting on the bottom wall versus time steps

This is a detailed development of wall force with thermal cycles. In this plot, there are four thermal cycles. A thermal cycle, begins with volume expansion of the spheres corresponding to heating. This increase in volume causes an increase in normal force acting on the confining walls and a departure from static equilibrium as the particles rearrange in response to their increased volume. Once the system is back in equilibrium, particle radii are decremented, leading to a decrease in the force acting on the wall and another departure from static equilibrium.

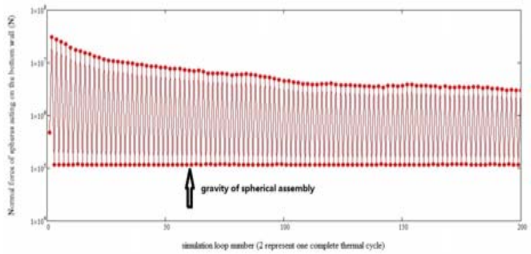

Figure 4. change of normal force from spheres acting on the bottom wall versus simulation loops (totally 200 loops or 100 thermal cycles)

The total weight of the assembly corresponds to the steady line at the lower position of this plot. There is a clear declining trend of wall force on expansion with an increasing number of thermal cycles. This declining trend is indicative of shakedown in the assembly – i.e., decreasing effects of repeated thermal cycling.

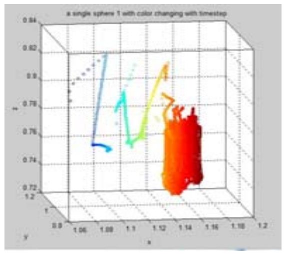

Figure 5. The displacement of one single sphere Versus time(the color changing from blue to red indicates change in time)

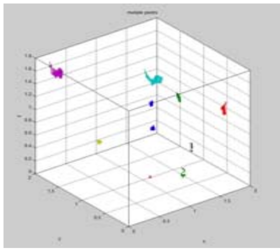

Figure 6. The displacements of ten spheres versus time (10 spheres have 10 different colors)

Figure5 and Figure 6 illustrate the motion of random particles over the course of 100 expansion-contraction cycles. There is clearly significant displacement during early stages, but individual particle motion asymptotes as the number of cycle increases. The current hypothesis is that this motion begins as Brownian but becomes constrained as shakedown occurs. Efforts to quantify and better understand this behavior is ongoing.

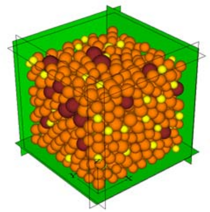

Figure 7. Sphere arrangement after 100 thermal cycling test

Figures 2 and Figure 7 are tests of before and after 200 thermal cycles, respectively, with gravity. By visually inspecting, it shows that the locations of the small spheres (yellow) moves downward slightly while the large spheres almost remain at their original locations. It does not have the drastic change as we might think of all the small spheres moving to the bottom after many thermal cycles. However, particle reorientation does occur. To quantify this finding is the research of our next step.

If this is true, I think that it is a significant insight – nice work in considering it. However, it is not visually obvious from comparison of these two figures. You need to quantify this in some more robust way of you want to include it on the poster.

Conclusions

It is expected that particles in an assembly will seek a more efficient arrangement when subjected to repeated perturbations. Thermal cycling offers an opportunity to seek a new equilibrium by providing room for particle displacement. Some amount of frictional resistance within the soil matrix is released and boundary tractions decrease as a result (assuming constant volume conditions). Based on these preliminary findings, it seems clear that skin friction and toe bearing of an energy pile will vary along the design life of the structure. Understanding how this affects pile's mechanical behavior is the subject of ongoing work.

Reference:
Cundall, P., & Strack, O. (1979). A discrete numerical model for granular assemblies. *Geotechnique*, *29*(No.1), 47-65.

Suryatriyastuti, M., Mroueh, H., & Burlon, S. (2012). Understanding the temperature-induced mechanical behaviour of energy pile foundations. *Renewable and Sustainable Energy Reviews*, *16*, 3344-3354.

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