# One-Dimensional Nonlocal Model for Gyratory Compaction of Asphalt Mixtures

Tianhao Yan, Jia-Liang Le, Mihai Marasteanu, Mugurel Turos
yan00004@umn.edu

University of Minnesota
Department of Civil, Environmental, and Geo- Engineering

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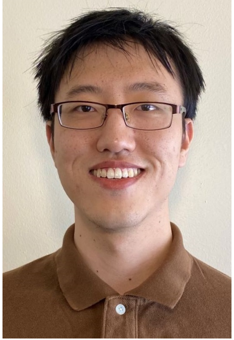
# About the authors



Tianhao Yan

Jia-Liang Le

Mihai Marasteanu

Mugurel Turos

# Research Background

- Importance of compaction
  - Compaction → field density → durability.
- Current situation
  - Low field density is a prevalent issue: Superpave designs mixtures to 4% air voids, while the in-place air voids are typically 7∼8 % in the field.
- Limited understanding on compaction
  - Complexity of the material: multiscale and multiphase
  - Although many research efforts have been devoted to high-fidelity numerical simulations (FEM and DEM) of compaction, some basic questions still remain unanswered.

# Macroscopic Phenomena of Gyratory Compaction

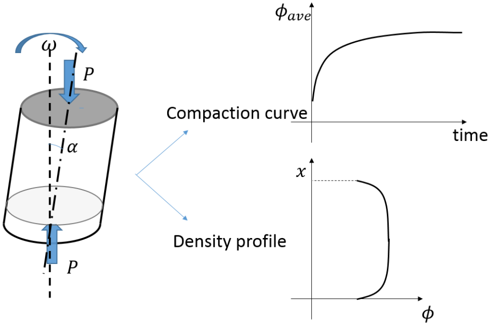


Figure: Gyratory compaction and results ( $\phi_{ave}$ represents the average $\%\mathrm{G}_{\mathrm{mm}}$ of the specimen, $\phi$ represents the local $\%\mathrm{G}_{\mathrm{mm}}$ )

- Rate of densification decreases with time.
- Rate of densification increases with the amplitude of gyratory shear.
- Density profile in the vertical direction has a bathtub shape.

# Macroscopic Phenomena of Gyratory Compaction

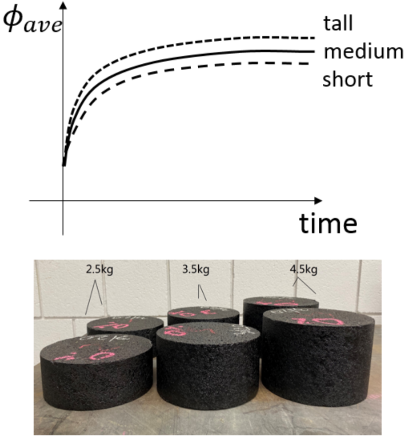


Figure: Size effect

Size effect:

- taller specimens are easier to compact than shorter ones.

How to physically explain these phenomena?

# Objectives

- Explain the aforementioned phenomena of compaction by physical mechanism at the **mesoscale**.
- Develop an **analytical model** for gyratory compaction considering the mesoscale mechanism.

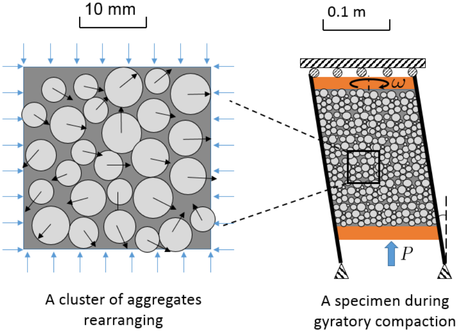


Figure: Different length scales of the compaction of asphalt mixtures

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# Aggregate Rearrangement

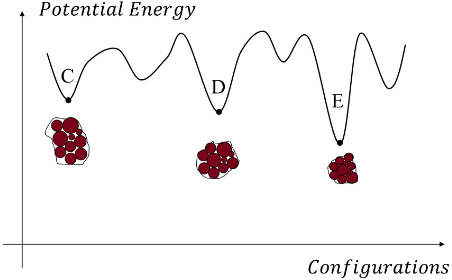
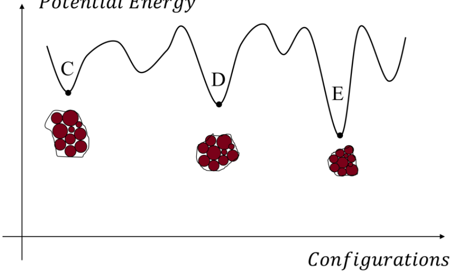


Figure: Energy landscape of aggregate rearrangements

- Static compression along leads to very limited compaction, because aggregates jam to a stable packing state (jammed state), represented by a local minimum (metastable state) in the energy landscape.
- Shear or vibration excitation provides the aggregates with kinematic energy to jump out of the energy well and evolve to denser packing states with lower potential energy.

# Aggregate Rearrangement



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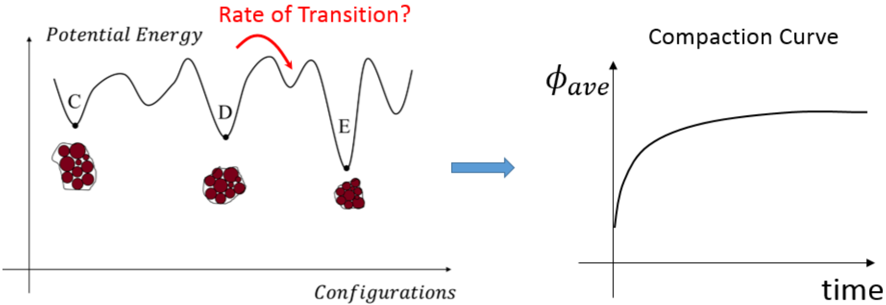
# General Idea for Compaction Modeling



The rate of transition between adjacent metastable states can be estimated by transition rate theory:

$$f = f_0 \exp(-U_b/E_s)$$

where $U_b$ is the energy barrier, $E_s$ is the kinematic energy of the random motion of aggregates.

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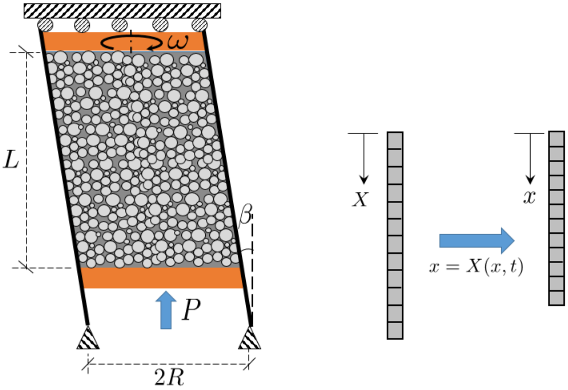
# Reduce the Problem to 1D



a) b)

Each material point represents a cross-section of the specimen

# Conservation of Mass

- Conservation of mass written in the reference configuration.

$$\frac{\mathrm{d}}{\mathrm{d}t}\left\{\phi(x,t)\frac{\partial x(X,t)}{\partial X}\right\}=0 \tag{1}$$

where $\phi$ is the compaction ratio, i.e., a non-dimensional density $\phi=\rho/\rho_m$

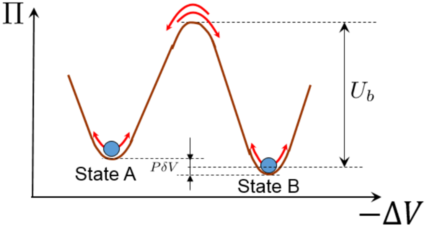
- Assume the initial density profile is uniformly distributed:

$$\phi(X,0)=\phi_0 \tag{2}$$

- Thus:

$$\phi(x,t)\frac{\partial x(X,t)}{\partial X}=\phi_0 \tag{3}$$

# Densification Rate Model



- Kramers equation (transition rate theory):

$$f = f_0 \exp(-U_b/E_s) \tag{4}$$

- Densification rate:

$$\dot{\epsilon}_V = -f_V \delta V/V_0 = -f_0 \epsilon_0^2 \frac{PV_0}{E_s} \exp(-U_b/E_s) \tag{5}$$

- $E_s$ is related to the amplitude of gyratory shear and is assumed as a constant.
- How to estimate the energy barrier $U_b$?
  - $U_b$ should increase as the material getting denser.

# Densification Rate Model

- We propose a simple relation between the energy barrier and the **nonlocal density** (will be introduced in the next slide).

$$U_b = U_0 + U_1 \langle \bar{\phi} - \phi_t \rangle^k \tag{6}$$

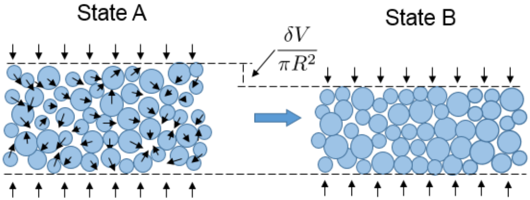
where $\langle x \rangle = \max(x, 0)$, and $U_0, U_1, k, \phi_t =$ constants.

- Substituting it to the Eq: $\dot{\epsilon}_V = -f_0 \epsilon_0^2 \frac{PV_0}{E_s} \exp(-U_b/E_s)$, we obtain:

$$\frac{\partial v(x,t)}{\partial x} = -C_1 P \exp\left[-C_2 \langle \bar{\phi}(x,t) - \phi_t \rangle^k\right] \tag{7}$$

Note: in 1D the volumetric strain rate $\dot{\epsilon}_V$ equals $\frac{\partial v(x,t)}{\partial x}$

# Why Nonlocal Density?



Aggregate rearrangement is a **nonlocal** process:

- A collective behavior of a **cluster** of aggregates.
- movement of one aggregate affects the rearrangement of the neighborhood aggregates
- A **material length scale** should be introduced to the model, i.e., the size of cluster.

# Nonlocal Density

- To characterize the interacting of the neighboring aggregates, we define a nonlocal density $\bar{\phi}$ as the weighted average of $\phi$:

$$\bar{\phi}(x,t) = \int_{-\infty}^{\infty} \alpha\left(x - x'\right) \phi\left(x', t\right) dx' \tag{8}$$

  where $\alpha(\cdot)$ is the Gaussian nonlocal weighting function $\alpha(x) = \frac{1}{l_a\sqrt{2\pi}} \exp(-\frac{x}{2l_a^2})$, where $l_a$ represents the length scale of aggregate rearrangement, and $l_a \propto$ **aggregate size**.

- An alternative way of solving Eq. 8, is by solving the following **implicit gradient model**:

$$\bar{\phi}(x,t) - \frac{{l_a}^2}{2}\frac{\partial^2\bar{\phi}(x,t)}{\partial x^2} = \phi(x,t) \tag{9}$$

# Summary of Governing Equations and Boundary Conditions

Governing equations:

$$\text{Conservation of mass:} \quad \phi(x,t)\frac{\partial x(X,t)}{\partial X} = \phi_0 \tag{10}$$

$$\text{Densification rate model:} \quad \frac{\partial v(x,t)}{\partial x} = -C_1 P \exp\left[-C_2 \langle \bar{\phi}(x,t) - \phi_t \rangle^k\right] \tag{11}$$

$$\text{Gradient model for nonlocal density:} \quad \bar{\phi}(x,t) - \frac{{l_a}^2}{2}\frac{\partial^2 \bar{\phi}(x,t)}{\partial x^2} = \phi(x,t) \tag{12}$$

Boundary and initial conditions:

$$\text{Initial condition:} \quad x(X,0) = X \tag{13}$$

$$\text{Boundary conditions:} \quad v(0,t) = v_0(t) = 0, \ \text{for } t \geq 0 \tag{14}$$

$$x(0,t) = x_0(t) = 0, \ \text{for } t \geq 0 \tag{15}$$

$$\text{Nonlocal boundary conditions:} \quad \bar{\phi}(0,t) = \bar{\phi}(L,t) = 1, \ \text{for } t \geq 0 \tag{16}$$

# Simulation Results

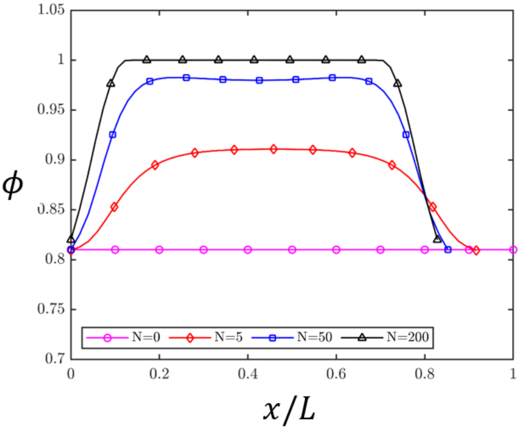


Figure: Simulated density profile

- The model can simulate the density profile which is consistent with experimental results, because the consideration of:
  - nonlocality
  - nonlocal boundary effect

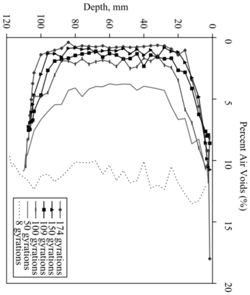


Figure: Tested density profile (Masad and Button, 2004)

# Experimental Validation

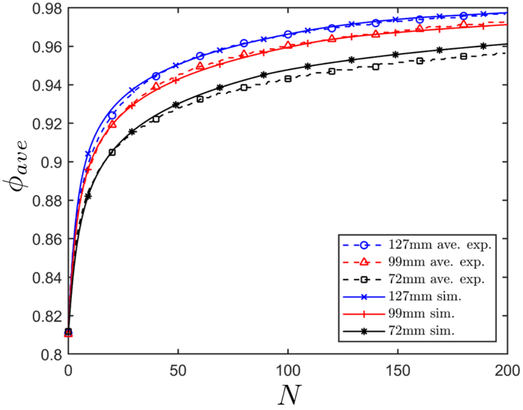


Figure: Compaction curves of different size specimens, comparison between simulation and experimental results

- Gyratory compaction tests of different specimen heights were performed to validate the model.
- The model can simulate the shape of compaction curves, because the consideration of:
  - compaction mechanism of aggregate rearrangement.
- The model can simulate the size effect observed in experiments, because the consideration of:
  - nonlocality.

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- Aggregate rearrangement is proposed as the main physical mechanism for compaction of asphalt mixtures, which explains many macroscopic phenomena in gyratory compaction.
- Based on the physical mechanism, a 1D nonlocal model is developed, which simulates the shape of overall compaction curve, the size effect, and shape of density profile.
- The model provides an effective means to characterize the compactability of asphalt mixtures.
- Since the model predicts the size effect in gyratory compaction, it also provides a qualitative explanation for the size effect in the field, i.e., the effects of lift thickness and aggregate size on the field compaction.

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# References

1 T. Yan, M. Marasteanu, and J.-L. Le. One-dimensional nonlocal model for gyratory compaction of hot asphalt mixtures.
*Journal of Engineering Mechanics*, 148(2):04021144, 2022.
`https://doi.org/10.1061/(ASCE)EM.1943-7889.0002073`

2 T. Yan, M. Marasteanu, and J.-L. Le. Mechanism-based evaluation of compactability of asphalt mixtures.
*Road Materials and Pavement Design*, 22(sup1):S482–S497, 2021.
`https://doi.org/10.1080/14680629.2021.1905697`

**Thank you!**

yan00004@umn.edu