Effect of Ballast Shoulder Cleaning on Fouling Particles Migration within Ballast Matrix

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ABSTRACT

Newly constructed or maintained ballasted track typically has clean, large, and uniformly graded ballast. With traffic accumulation, fine materials, such as degraded ballast aggregate, coal dust, clay, sand, and other small particles, will penetrate into the clean and uniformly graded ballast layer, leading to contamination, referred as fouling. Fouling is unfavorable to track performance due to the reduced drainage, causing formidable engineering challenges. For decades, researchers and practitioners have been focusing on developing feasible track maintenance solutions to restore track drainage. However, the effect of popular maintenance activities on track drainage restoration under different fouling conditions is not well understood. The lack of comprehensive understanding of fouling migration through the ballast layer gives rise to challenges in correlating fouling profile with track performance, and raises arguments regarding the benefits of maintenance activities. This paper presents the results from both a coupled Computational Fluid Dynamics (CFD) and Discrete Element Model (DEM) simulation of water transporting fouling material through a ballast section and a systematic full-scale laboratory study to quantify track drainage restoration from shoulder cleaning under different fouling conditions. A coupled CFD & DEM model is built to quantify the fines migration during rainfall events with varied initial fouling profiles. A full-scale track section is built in an innovative transparent ballast testing tank in the laboratory at the University of South Carolina to quantify particle migration before and after shoulder cleaning. Fouling particles are continuously tracked through high-resolution cameras to visualize the entire migration process of the fines. Preliminary results from this study indicate that shoulder cleaning restores ballast drainage capacity and enables the migration of accumulated fouling particles in the crib area by opening drainage paths toward the shoulders. These results from the simulation and the laboratory testing demonstrate the same fines migration phenomena.

Key words: Ballast drainage, shoulder cleaning, fouling, particle transport, visualization, full-scale test

INTRODUCTION

Ballasted track is the dominant track structure in freight railroad. Other than load bearing and transferring, vegetation prevention, and vibration reduction, the ballast layer needs to maintain proper drainage and material performance through roadbed maintenance. Through repeated train loading the ballast particles breaks and generate fines. Spilled material from wagons, wind blow material, and subgrade fines can also migrate into the ballast section further increasing the amount of fouling material in the track structure.

Fouling is unfavorable to railroad track performance due to the reduced drainage, causing formidable engineering challenges. For decades, researchers have been focusing on investigating the mechanical behavior of fouled ballast in terms of permanent deformation, bearing capacity, and resilient modulus. The behavior of fouled ballast with moisture has also been studied with specimens mixed with fouled ballast and water (*1-6*). Many studies have evaluated the fouled ballast behavior with mixtures of clean ballast aggregates and certain types of fine particles, such as coal dust, clay, and sand. The strength of the fouled ballast decreases when the fouling level or the moisture content increases (*1-5*). Some studies investigated the fouled ballast behavior with degraded ballast (*6*). The mechanical behaviors of the varying types of fouled ballast show some differences, although generally both types of fouled ballast behave very similarly.

Previous studies have greatly improved the understanding of the fouled ballast behavior. However, the fundamental mechanism that governs transport and accumulation of fine particles (fouling materials) in the ballast layer is not thoroughly analyzed. Earlier studies investigated the drainage behavior of the fouled ballast with or without a certain maintenance activity (*7-12*). For example, the transport paths of fines from the top of the ballast layer to certain locations within the layer or the transport paths of fines from the inner part of the ballast layer to outside remained unclear. The lack of fundamental understanding of fouling transport and accumulation in the ballast gives rise to challenges in correlating fouling profile with track performance, and raises arguments regarding the benefits of maintenance activities. To address the need for comprehensive understanding of the fouling transport mechanism, quantify the benefit of different maintenance activities, such as shoulder cleaning, and provide guidelines for maintenance optimization, this study built a full-scale track section to reveal the fouling profile changes before and after shoulder cleaning. The interface between the clean area and fouled area of the ballast was continuously tracked through high-resolution cameras to visualize the entire migration process of the fines. Preliminary results from this study indicate that shoulder ballast cleaning does restore ballast drainage capacity. From the visual evidence, fouling particles in the crib area migrate down through the ballast layer and out through shoulder once the drainage paths are opened after shoulder cleaning.

COUPLED CFD AND DEM ANALYSIS

A high-fidelity Computational Fluid Dynamics (CFD) model coupled with particles has been developed for selected ballast sections. Large ballast particles are simulated as the skeleton while the fines (fouling materials) are simulated as the moving particles under seepage. The flow field and drainage information were obtained by the developed model to investigate the fouling material migration. A preliminary model was developed based on the clean ballast test and the calibrated with results obtained from fouled ballast tests. Multiple analysis cases were run with varying amounts of fouling material, fouling profiles, and cohesive energy densities (CED) to quantify and understand the effects of modifying these variables. Initial simulations were run with water flowing through ballast without fouling material. Subsequent tests simulations coupled the fluid movement (water) with discrete element movement (fouling material) and demonstrated how fouling material moves through the ballast layer when carried by water.

LABORATORY EXPERIMENT SETUP

Ballast and Fouling Materials

The ballast materials used in this study were clean granite type 100% crushed aggregates. The fouling materials were different sizes of sands and silica flour. Both the ballast aggregates and fouling fines have no plasticity. Figure 2 shows grain size distributions of the clean ballast material and the fouled ballast. The clean ballast had a gradation that complied with the AREMA No. 4 requirements. The fouled ballast was a mixture of the same batch of clean ballast and the fouling materials. In other words, the fouling ballast in this study was the clean ballast plus extra sands added into the clean ballast. The fouling condition of the fouled ballast is quantified by the fouling index (FI), which is the summation of percentage of fines passing No.4 and No.200 sieves (*13*).

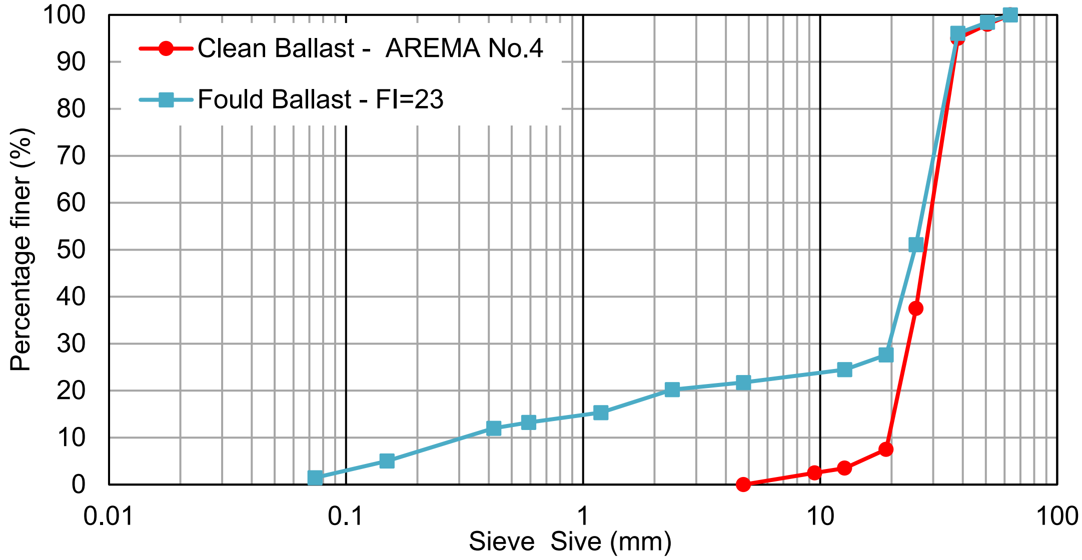


Figure 1. Grain size distribution of the clean and fouled ballast in this study

Ballast Flume Test Setup

In order to investigate the migration of fine materials within the ballast layer, a full-scale flume test setup was built at the University of South Carolina. Figure 2 gives a schematic drawing of the test setup. The flume has a length of 192 in., a width of 6 in., and a height of 24 in. Two acrylic glass panels are fixed by aluminum channels attached to an 8 in. x 8 in. x 192 in. wood base. The top of the acrylic glass panels is also fixed by aluminum channels attached to a 1 in. x 6 in. x192 in. wood top plate. Three irrigation hoses are attached to the top plate with drippers spaced every 6 in. on each hose. A flow meter, a pressure regulator, and a pressure gauge are installed between the water outlet and the irrigation hose to ensure consistent water flow condition for all tests. A full-scale ballast section is constructed within the flume. The top of the ballast is 126 in. wide, which is the length of a typical tie (102 in.) and 12 in. of shoulder on each side. The depth of ballast is 15 in. representing a 7 in. tall tie and an 8 in. ballast depth, and the length of the ballast bottom is 186 in., with a 2:1 slope on each side. Note that since this study only focuses on the fine particle migration within the ballast layer, the ballast layer was directly seated on the wood base and all joints in the flume were sealed and watertight.

For the clean ballast test, a total amount of 835 lbs. of clean aggregates are placed in the flume in

5-gallon buckets and hand tamped to achieve a void ratio of 0.67, which is consistent with the well compacted clean ballast (*14-15*). To protect the acrylic glasses from scratches, a thin layer of plastic film is attached to the inside of the acrylic glasses and replaced for each test. For the fouled ballast test, the clean ballast materials are carefully reclaimed from the flume. A total amount of 250 lbs. of sands and silica flour are added into the clean ballast to achieve the fouling index (FI) of 23%. During the preparation, the clean aggregates and the fines are mixed in small batches to make sure the fouled ballast layer is consistent without segregation. The fouled ballast materials are carefully hand tamped to fit into the same sections as the clean ballast. Because the fouling index for the fouled ballast in this study is 23%, which is a moderate fouling condition, not all the voids between the ballast aggregates will be occupied by the fines. It is expected that some fines settle to the bottom during compaction and the appearance of the fouled ballast may not be homogeneous throughout the entire layer.

To simulate the fine particle migration in the field, an irrigation hose with drippers is used to mimic the raining scenario. In the field, the fines may migrate from the center part to the toe area of the ballast layer in years. It is also possible new fines would be generated due to aggregate degradation or particle intrusion with traffic accumulation. To simplify the laboratory experiment, the “rainfall” is kept being a constant rate of 32 gallon per hour and the experiment is ended in six hours. Spread across the surface area of the test setup this water application rate correlates to 38 inches of rainfall per year.

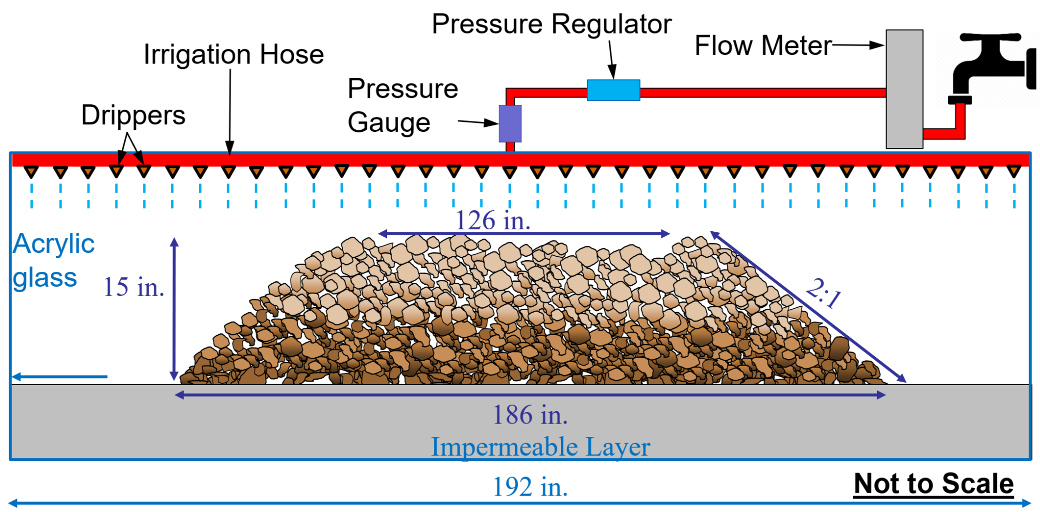
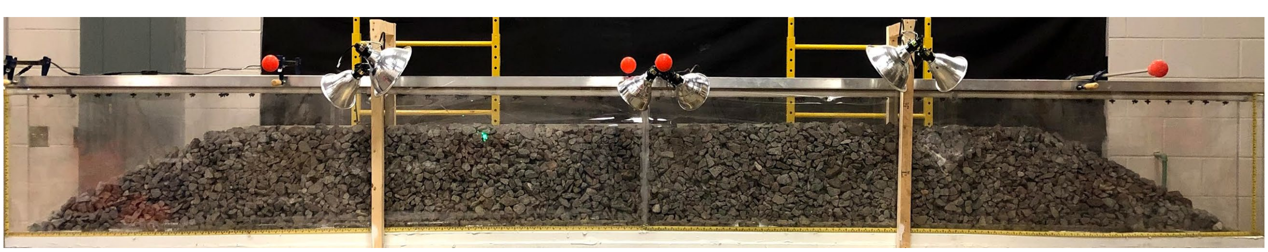


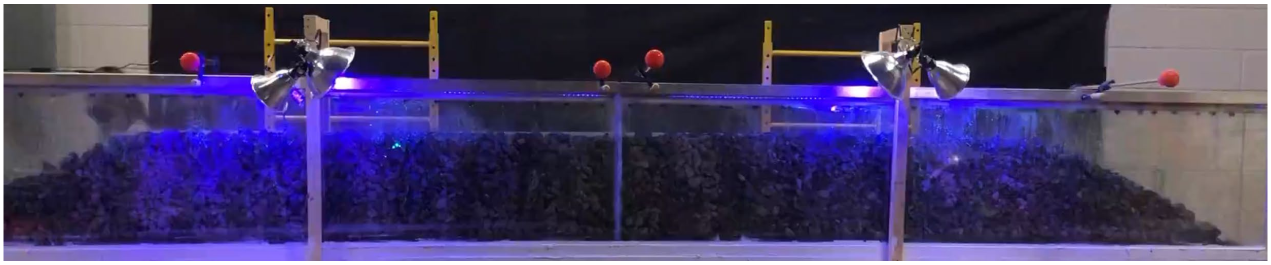
Figure 2. Schematic drawing of flume used for ballast testing

RESULTS AND DISCUSSION

Figure 3 presents the front view of the clean ballast at the beginning and after the rainfall for six hours. The water is dyed with green color and several UV lights are used to help visualize water accumulation. In Figure 3 (b), some moisture within the ballast layer can be identified under the UV lights. The reasons of the challenges in visualizing of the moisture are 1) the water accumulation is not significant and 2) the amount of moisture between the acrylic glass and the ballast particles is limited.



(a) At the beginning of the test



(b) After Six Hours of testing

Figure 3. Overview of the clean ballast layer before and during the test

Figure 4 shows close views from the side. There is no obvious water accumulation because the clean ballast has high permeability and water can easily drain from the ballast layer. The clean ballast reaches a stable state quickly, but the test is kept running for six hours to ensure the flow reaches an equilibrium state. Also, the amount of water that comes out of both sides are similar after multiple checks at different times, indicating the test setup is symmetric. The clean ballast test validates the flume test setup and proves symmetric between each side. For the fouled ballast test, the flume is divided into two equal parts by adding a wood plate at the middle.

(a) (b) (c)

Figure 4. Close view of the side of the flume during the test after six hours

As shown in Figure 5, one side of the flume is used for a normally fouled ballast section, while the other side of the flume is used to build a representative fouled ballast section after shoulder cleaning. The shoulder cleaned profile is provided by Loram Maintenance of Way, Inc. Note that the entire section from the shoulder area to the toe of the ballast in addition to triangular section which represents the shoulder ballast cleaner scarifier, is cleaned. The ballast section of the left side of Figure 5 is constructed by fouled ballast and clean ballast, respectively, to have the same profile of fouled ballast after shoulder cleaning. The fouled ballast used for both sides are the same fouled ballast with a fouling index of 23%. The gradations for the fouled and clean ballast sections still follow the gradations showing in Figure 1.

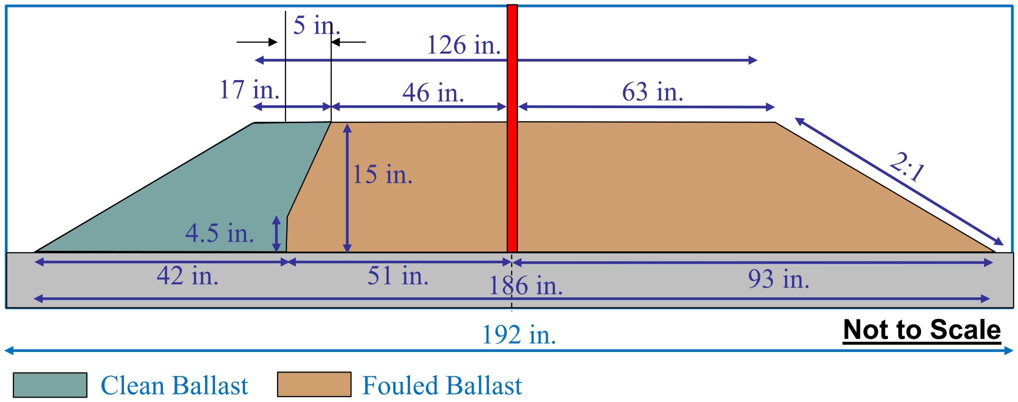
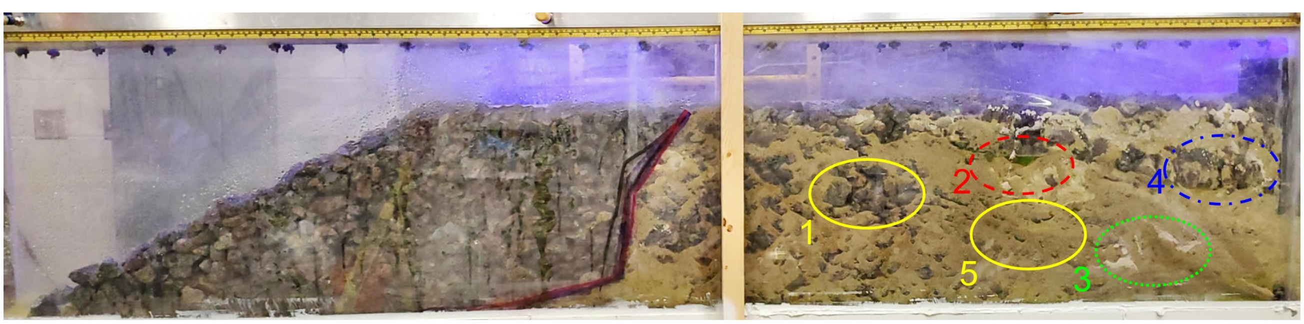


Figure 5. Schematic drawing of the fouled ballast test setup with and without shoulder cleaning

Figure 6 presents a view of fouled ballast with shoulder cleaning before and after six hours of testing. It is clear that the boundary between the clean ballast and the fouled ballast is progressively moving towards the crib along the depth except the bottom area. The boundaries are marked on the acrylic glass. For the bottom area, fines are moving towards the toe of the ballast layer. The changing of the boundaries between the clean ballast and the fouled ballast demonstrates the fines migrates from the crib to the shoulder and out of the ballast layer, carried by the flow of water.

(a) At the beginning of the test

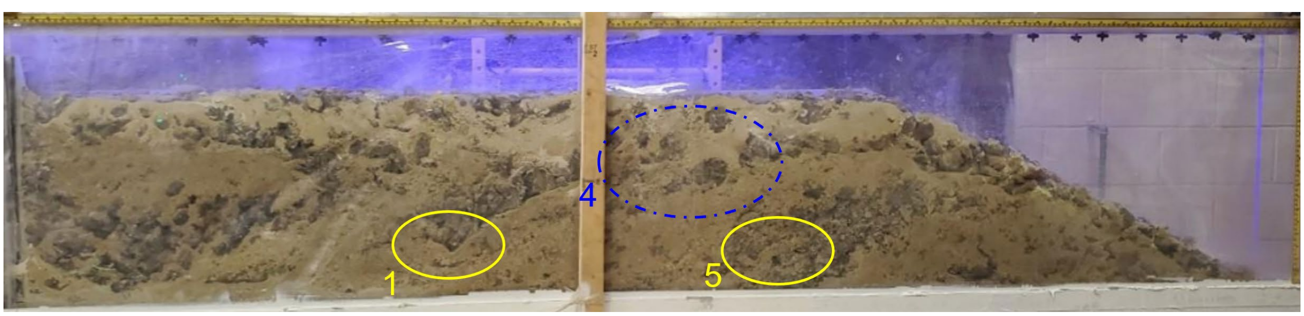


(b) After six hours of testing

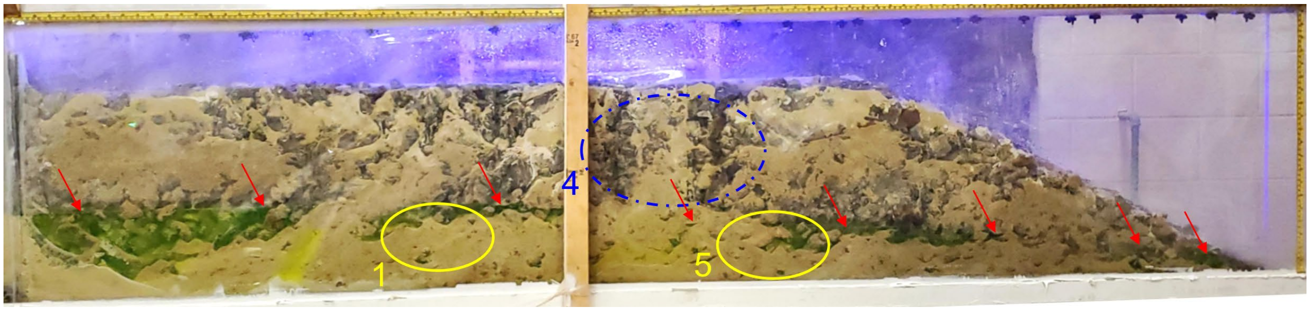
Figure 6. Overview of the fouled ballast with shoulder cleaning before and during the test

Figure 6 also tells other interesting stories. For example, there are fewer fines at the top of the ballast layer after testing. Portions of the fines from the top migrate to the side, while other portions of the fines migrate to the bottom. Looking at the highlighted Areas #1 and #5, circled by yellow solid lines, more fines can be observed after the test, indicating fines from the top have moved into these areas during the test. It is not showing that the migration trend of the fines is always consistent, though, and fines are not exclusively moving from the top to the bottom. There are less fines in Area #4, circled by blue dash dot line, indicating more fines have migrated away than accumulated in that area. The differences of increasing or decreasing of fines at certain areas depends on the particular porous structure of the aggregates and the flow path. This observation indicates that local fouling conditions are changing with the flow and migration of the fines. Therefore, using a single fouling index to represent the entire ballast layer may not be representative of the entire cross section. Area #3, circled by green dashed line, does not show any significant difference after the test. Looking at the color of fines at some locations within Area #3 identifies some are getting lighter in color than the surrounding area. This is because those locations are still dry, suggesting no moisture penetration into this area and the fouled ballast is not saturated at least to the depth of Area #3. The observation in Area #2 indicates that water accumulated in Area #2, circled by red dash line, is local water pocket. Local water pockets can form if the local permeability is very low, and the water table of the local water pockets cannot be interpreted as the saturation level of the entire ballast layer. In fact, no obvious water level can be observed for the fouled ballast with shoulder cleaning, similar as the clean ballast test. This demonstrates the effectiveness of shoulder ballast cleaning at restoring the drainage capability of the ballast section.

Figure 7 presents the view of the fouled ballast without shoulder cleaning before and after the test. The greatest difference can be identified by comparing the fouled ballast without and with shoulder cleaning is the clear water line in the fouled ballast without shoulder cleaning. This is largely due to lack of an easy path for the water to flow towards the toe, thus the raindrops have to penetrate down into the fouled ballast layer and accumulate within the ballast layer, causing the bottom portion to be saturated. The saturation depth increases until the water pressure breaks the resistance of the fouled ballast to create a flow path(s) or until surface flow carries water over the top of the ballast section. In other words, the fines accumulated in the shoulder area act like a dam preventing the water draining out. The top of the water lines (red arrows in Figure 7b) decreases as it approaches the toe of the ballast layer. In terms of fine particles migration, similar phenomenon can be observed as that from the fouled ballast with shoulder cleaning. At the highlighted Area #1 and #5, circled by yellow solid lines, more fines can be observed after the test, indicating fines from the top have settled into these areas. For Area 4, circled by blue dash dot line, more fines have migrated away than accumulated. This observation again indicates the local fouling conditions are changing with the flow and the migration of the fines.



(a) At the beginning of the test

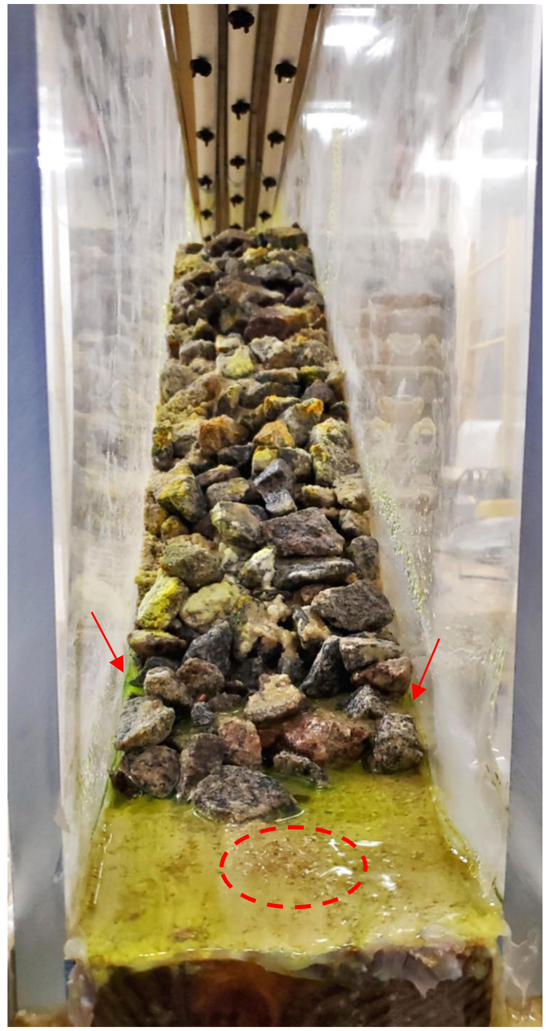


(b) After Six Hours of testing

Figure 7. Overview of the fouled ballast without shoulder cleaning before and during the test

Figure 8 presents the side view of the fouled ballast with and without shoulder cleaning after testing. Fines can be observed from both sections, confirming fine particles migrates out of the ballast layer. However, the total amount of fines coming out of the ballast layer cannot be used as the criteria to judge the capability of particle migration because most of the fines migrate out from the fouled ballast after shoulder cleaning would migrate into the cleaned area, not necessarily come out from the ballast layer. The numerical simulation is needed to reveal the local fouling changes at different areas in the ballast section. Figure 8 (b) shows the water table for the fouled ballast without shoulder cleaning (red arrows) as well as the surface flow that occurred over the top of the ballast section. No clear water table or surface flow can be observed for the fouled ballast with shoulder cleaning.

(a) With shoulder cleaning



(b) Without shoulder cleaning

Figure 8. Side view of the toe area of the fouled ballast

Figure 9 shows results of the coupled CFD/DEM analysis. Ballast particles are represented by the gray circles and fouling particles by the white dots. Simulations were run in 25 second increments to correlate to the 6-hour laboratory tests. Each analysis run took several days depending on the number of fines particles. The before/after graphs show the migration of fines both down into lower portions of the ballast and out towards the toe of the ballast. These results correlate well with the images presented in figure 6 from the laboratory tests. The fouling migration in the cross section was quantified in 2 in. x 2 in. sections with the change in local fouling index shown pictorially. The blue sections (top of the ballast layer) show a reduction in fouling and the darker green sections show an increase in fouling. This also represents the lab test data well with varying changes to fouling index (increases and decreases) in the ballast layer with an increase in originally clean shoulder section.

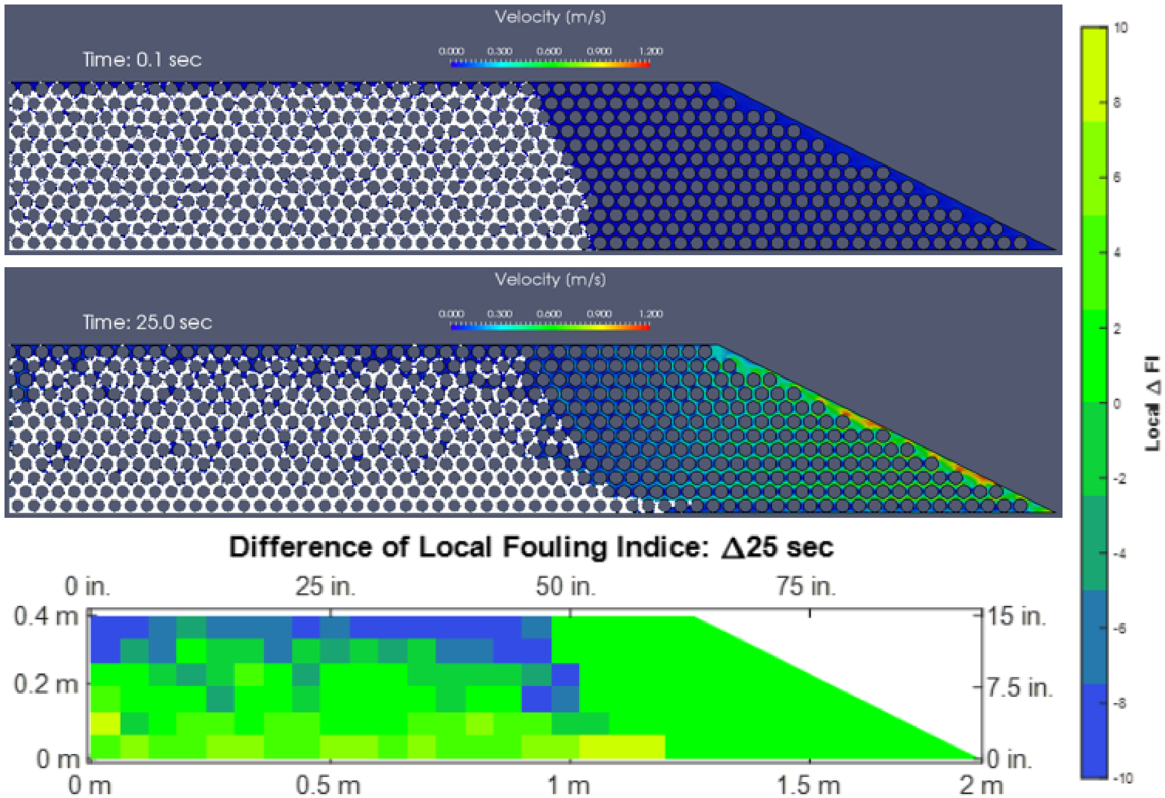


Figure 9. Side view of the toe area of the fouled ballast

CONCLUDING REMARKS

Full-scale laboratory experiments of railroad track ballast were conducted in this study utilizing a ballast drainage flume developed at the University of South Carolina. Both clean ballast, fouled ballast with shoulder cleaning, and fouled ballast without shoulder cleaning, were tested under the same raining conditions. Fine particle migration trend within the ballast layer under raining condition was observed through acrylic glasses. Numerical simulation of the same cases was done using a coupled CFD/DEM model. Based on the results from the experiments performed so far, the following conclusion can be drawn:

The developed ballast flume is a good setup to visualize the fine particle migration trend within the ballast layer and can be used to quantify potential benefits of different track maintenance activities. Preliminary results were obtained from comparing the cases with and without shoulder cleaning. No obvious water accumulation was observed for both clean ballast and fouled ballast with shoulder cleaning. Water accumulation and surface flow was observed for fouled ballast without shoulder cleaning and the water table decreased towards the ballast toe area. Shoulder ballast cleaning opens the critical drainage paths at the shoulder area and water can easily flow out of the ballast layer. Without shoulder cleaning, fouled ballast acts as a dam, preventing water drainage. Fine particle migration was observed for both fouled ballast sections with and without shoulder cleaning. Generally, fines migrate towards the bottom and the toe areas of the ballast layer. However, the local fouling index at different locations may increase or decrease depending on the interactions between the ballast, fines, and water. It is also possible to see local water pockets at certain locations which also depends on the permeability and flow rate at individual locations. Using local fouling index values instead of a single fouling index to represent the entire ballast layer can better illustrate the localized ballast fouling condition. The numerical simulation demonstrated the similar results as the laboratory testing. As both the model is further refined and calibrated it will be useful for testing different drainages improvement strategies in a cost-efficient manner. Future study will investigate the effects of different fouling materials, fouling index, rainfall intensities, and maintenance activities to correlate fouling condition to drainage behavior of ballast and identify the optimal maintenance strategy.

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List of Figures

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Presentation Outline

- Introduction & Research Motivation
- Laboratory Setup and Numerical Simulation
- Preliminary Results
- Concluding Remarks

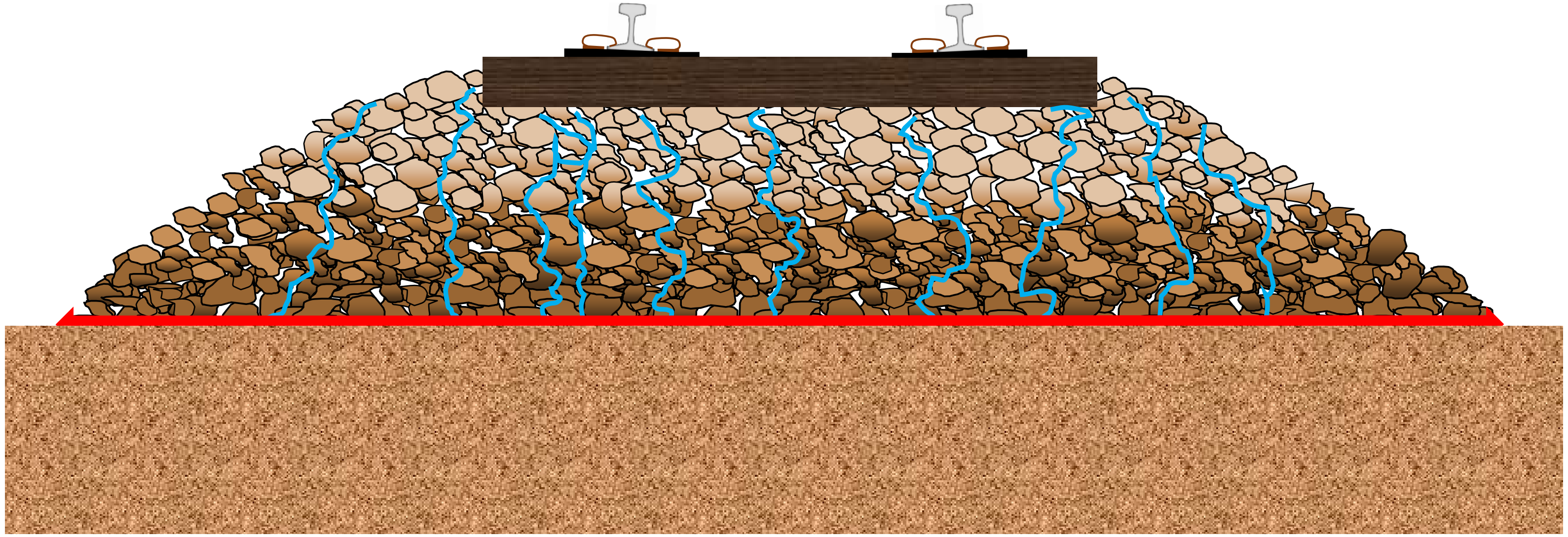
Function of the ballast layer

AREMA Virtual 2021 CONFERENCE

Ballast would get fouled

(Courtesy of Australian Transport Safety Bureau)

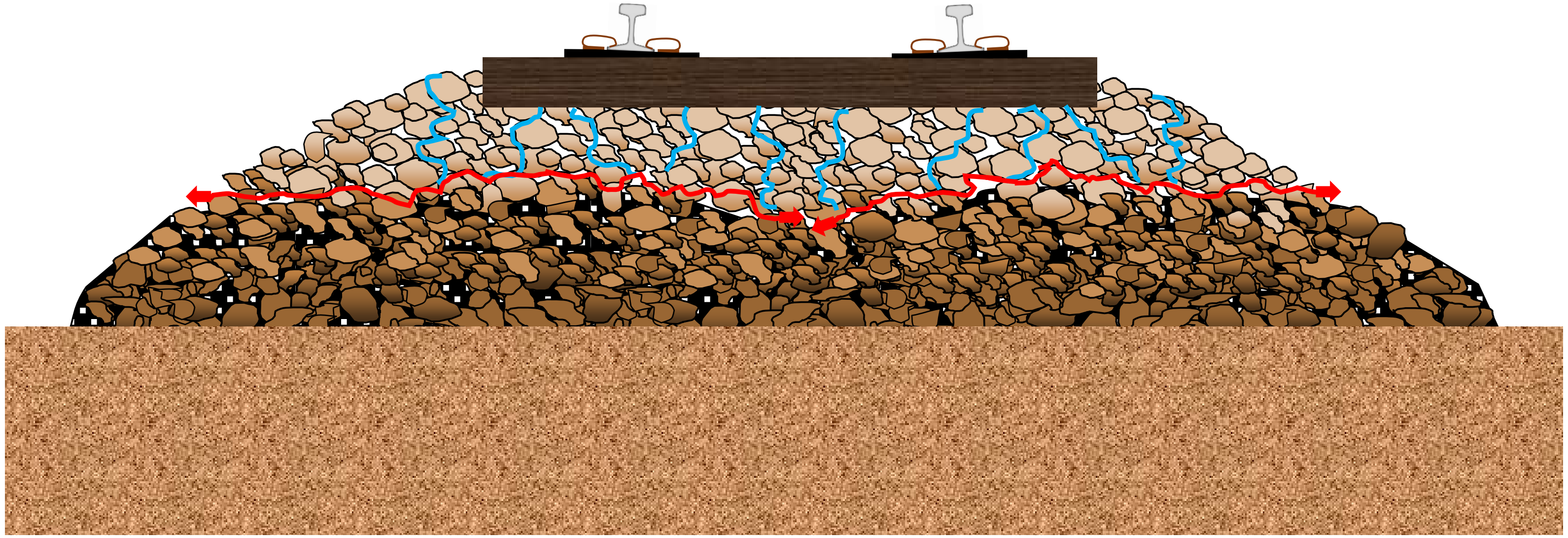
How do the water and fines migrate?



Newly constructed track drainage path

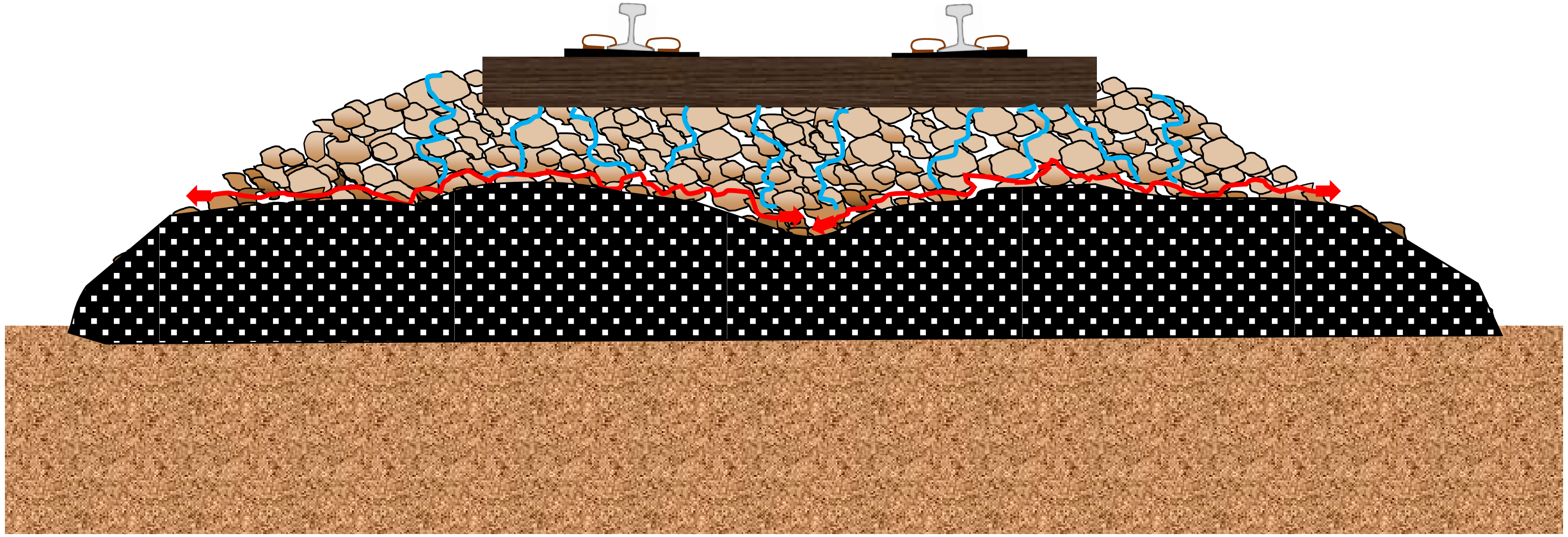
Without fouling materials, ballast layer have high drainage ability (free drain)

How do the water and fines migrate?



Hypothetical **Fouled track drainage path-1**

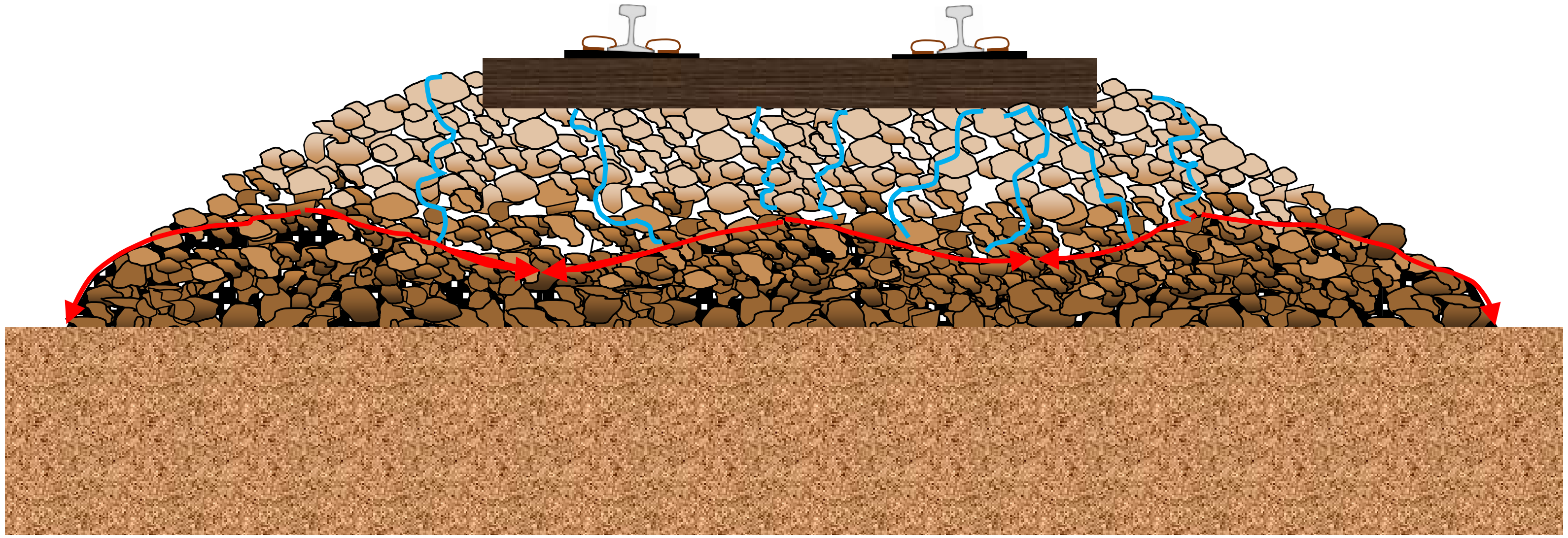
How do the water and fines migrate?



Hypothetical **Fouled track drainage path-1**
(fouling material highlighted)
With fouling materials accumulation, fouled ballast portion have low drainage ability

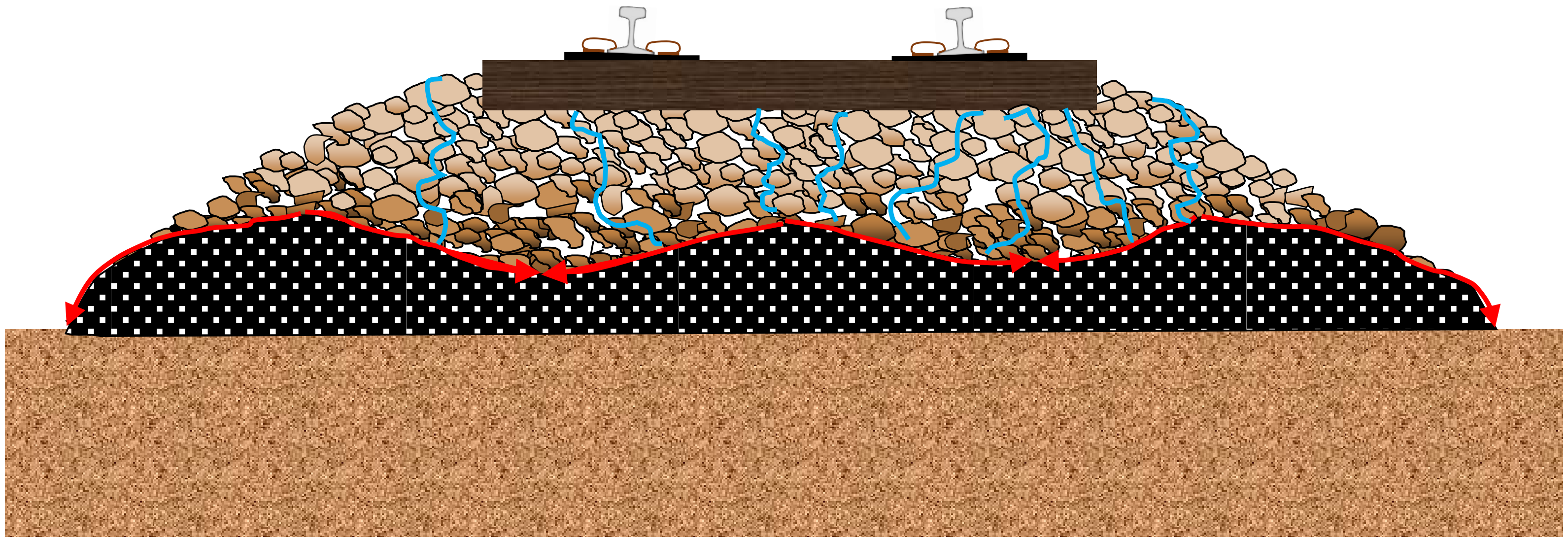
(Is it the real fouling material profile? Is this drainage path true?)

How do the water and fines migrate?



Hypothetical **Fouled track drainage path-2**

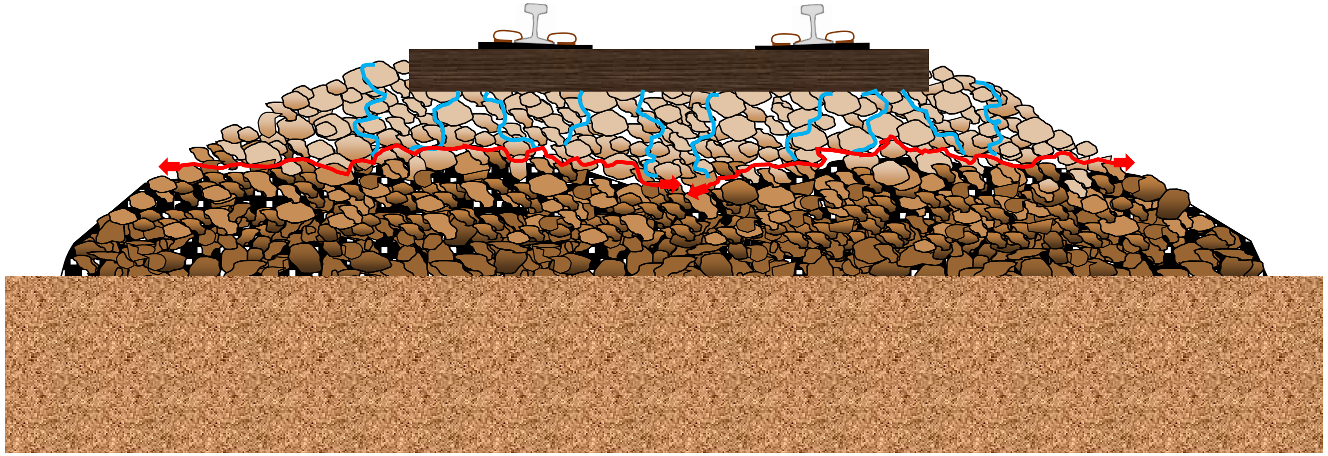
How do the water and fines migrate?



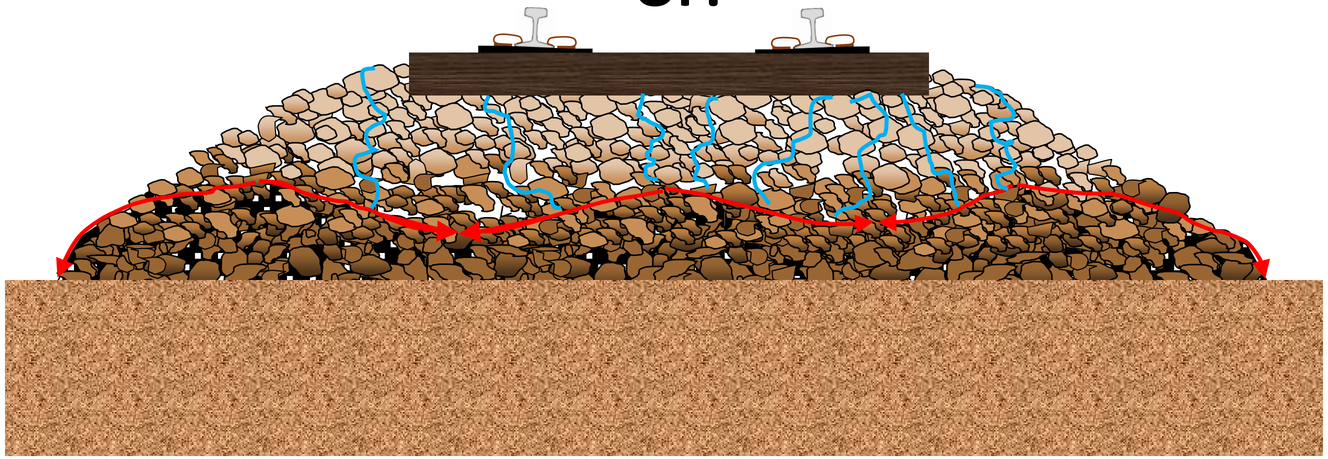
Hypothetical **Fouled track drainage path-2**
(fouling material highlighted)
With fouling materials accumulation, fouled ballast portion have low drainage ability

(Is it the real fouling material profile? Is this drainage path true?)

How do the water and fines migrate?



Or?



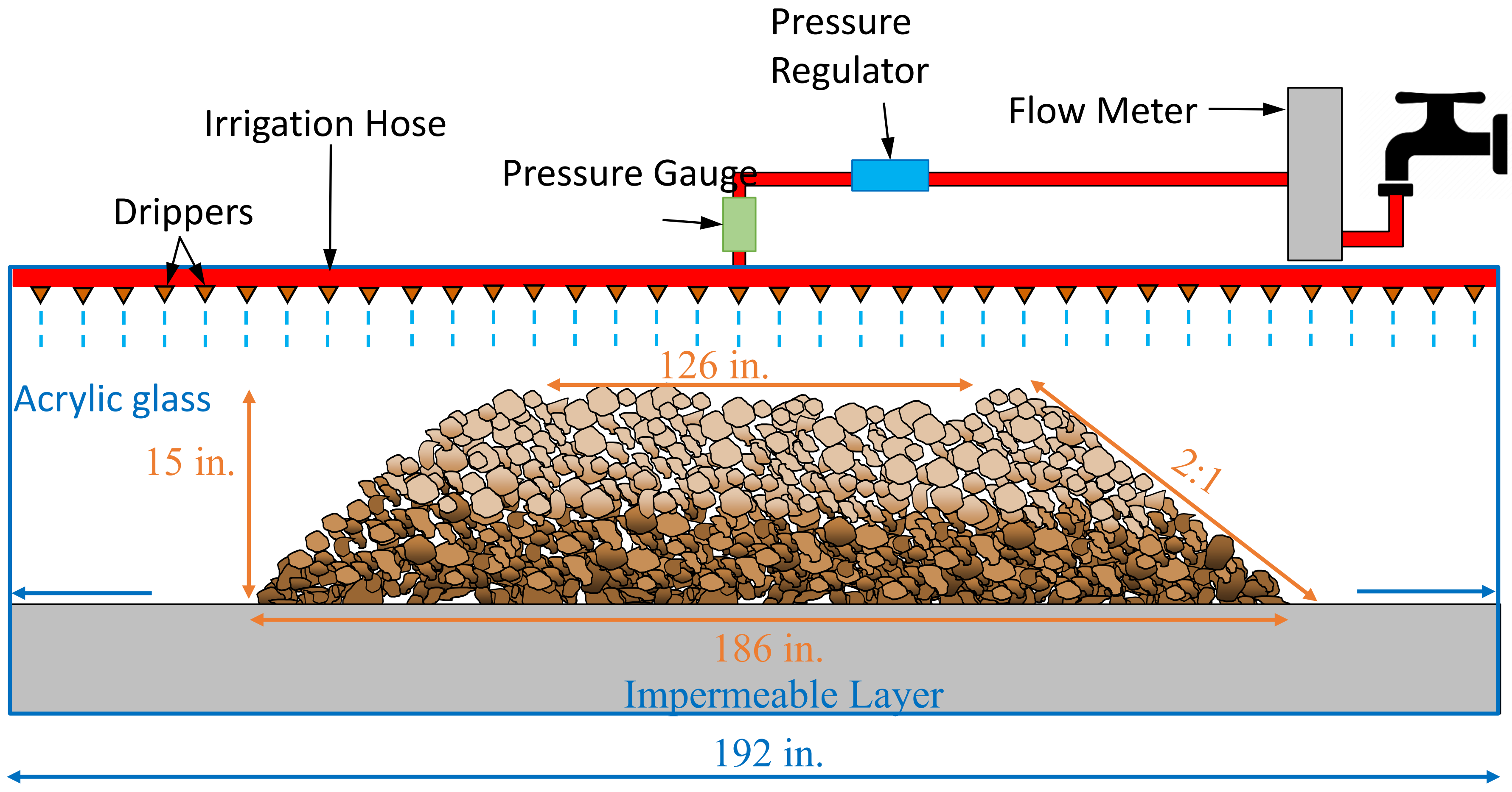
We do not know

How do the water and fines migrate after ballast maintenance?

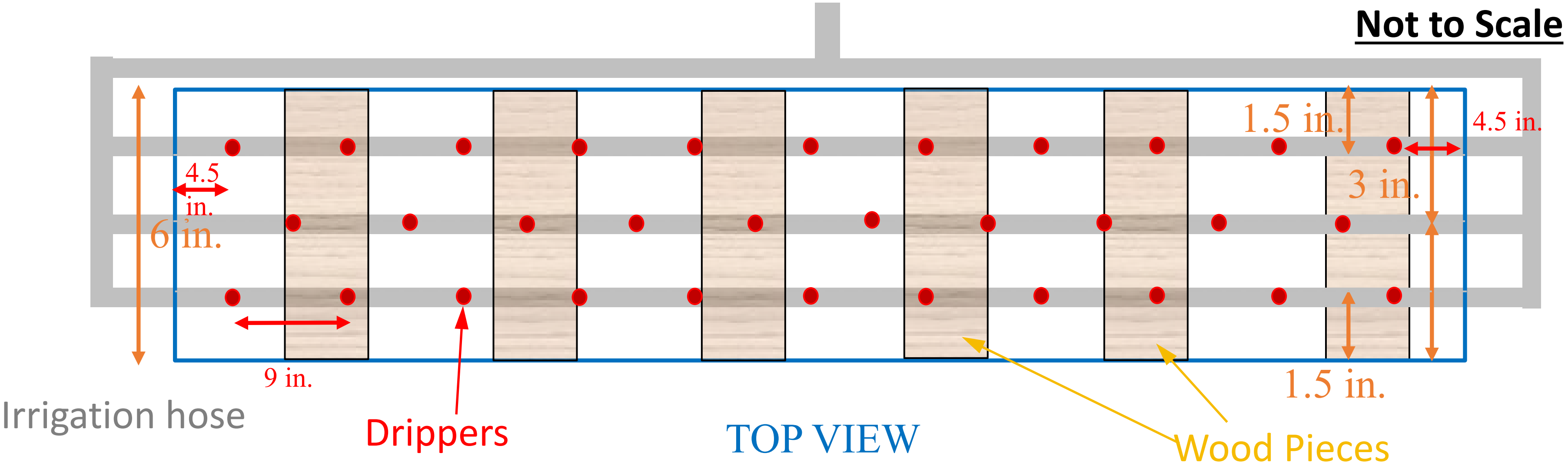
We know proper ballast maintenance will help

But how to quantify it?

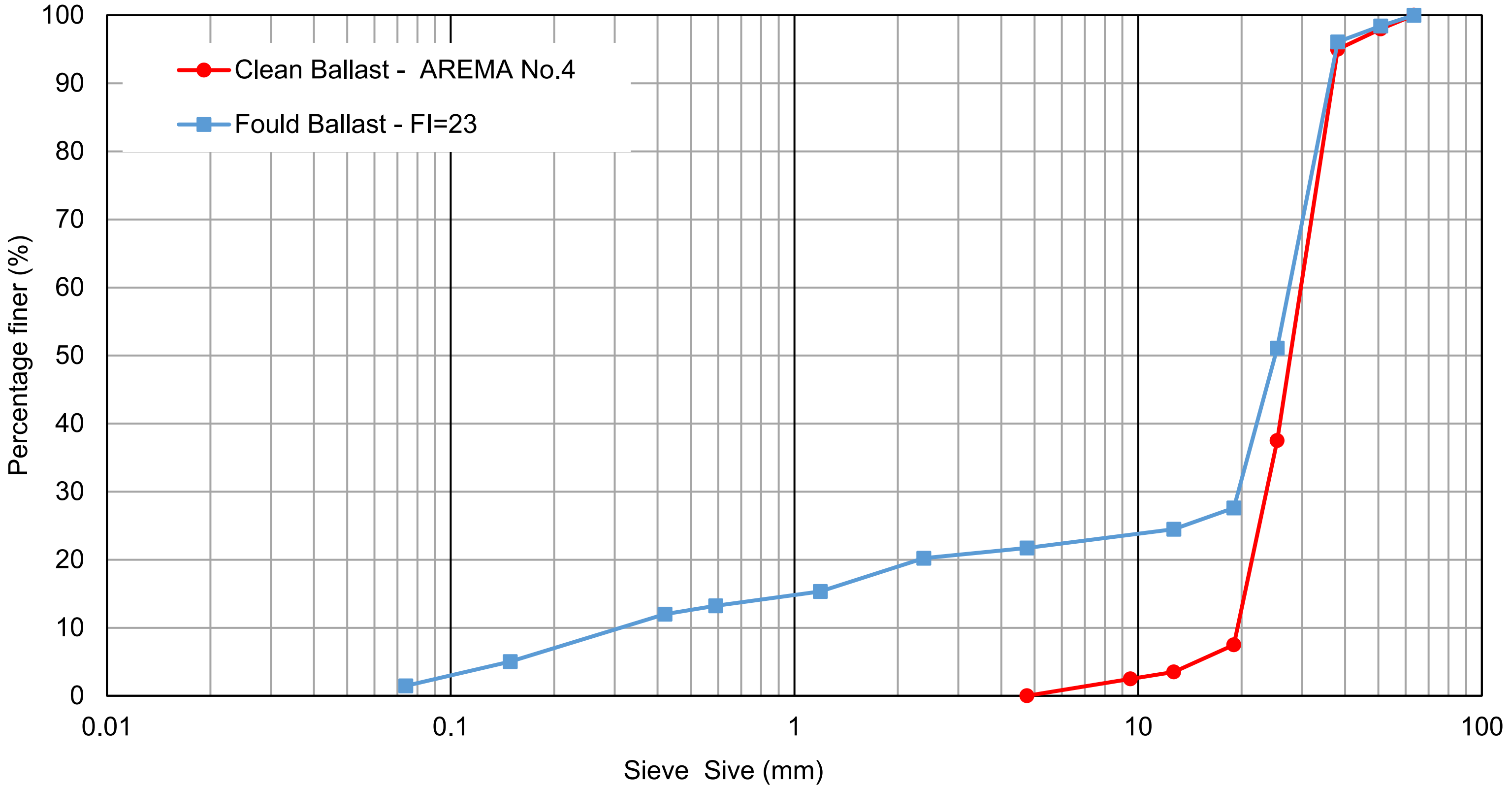
Laboratory Test Setup



Laboratory Test Setup

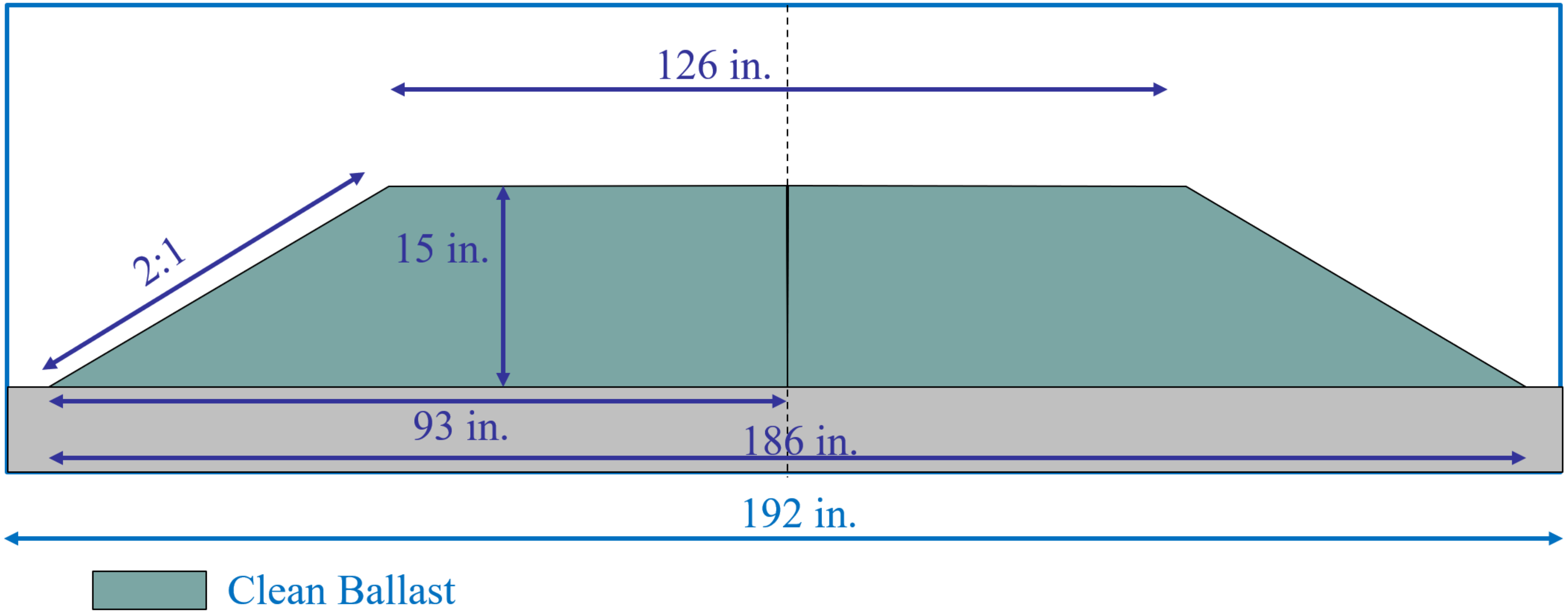


Laboratory Test Ballast Materials



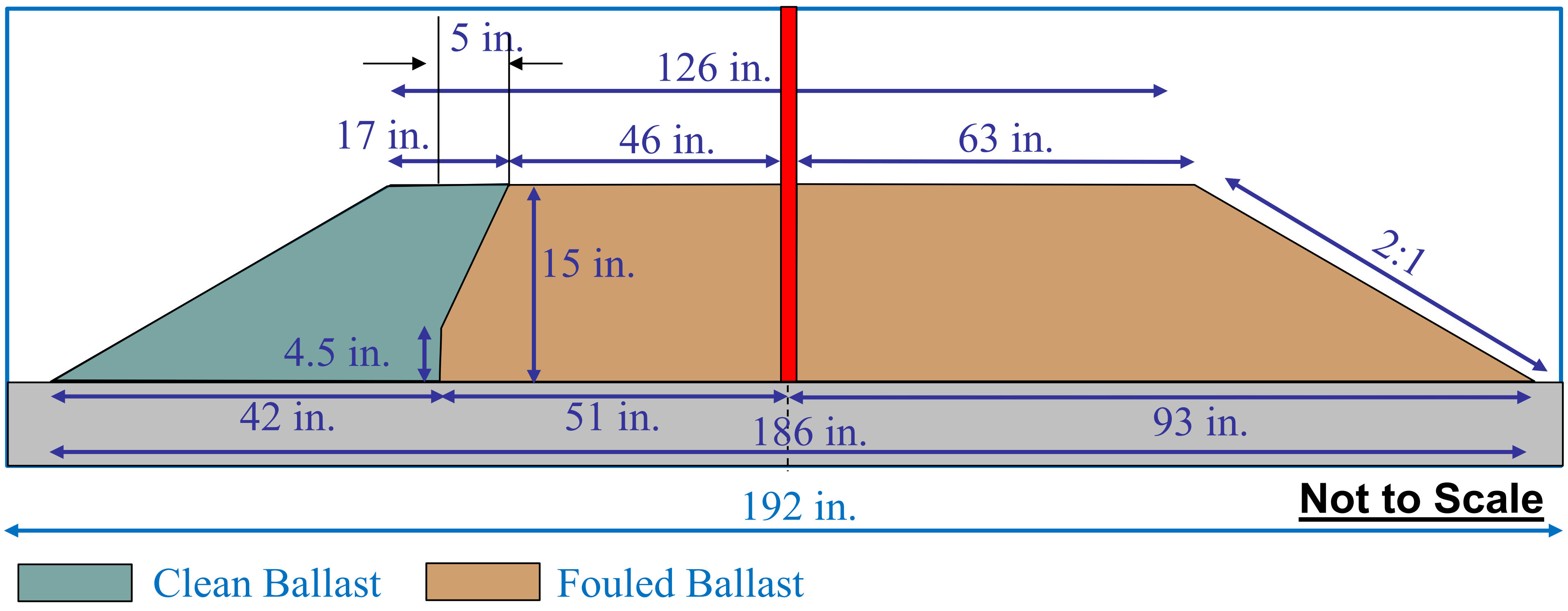
- The clean ballast material meets AREMA No. 4 Gradation
- The fouled ballast material is the mixture of clean ballast and sands at different sizes to reach a Fouling Index of 23 (a moderately fouled condition)

Laboratory Test with Clean Ballast



(shoulder cleaning profile is provided by Loram)

Laboratory Test with Fouled Ballast



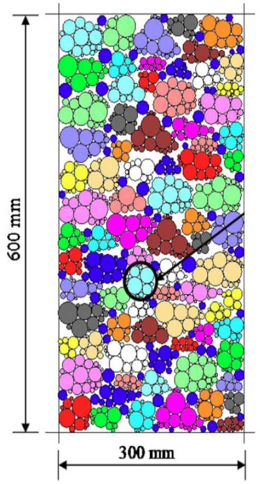
(shoulder cleaning profile is provided by Loram)

Traditional Ballast Simulation Approach

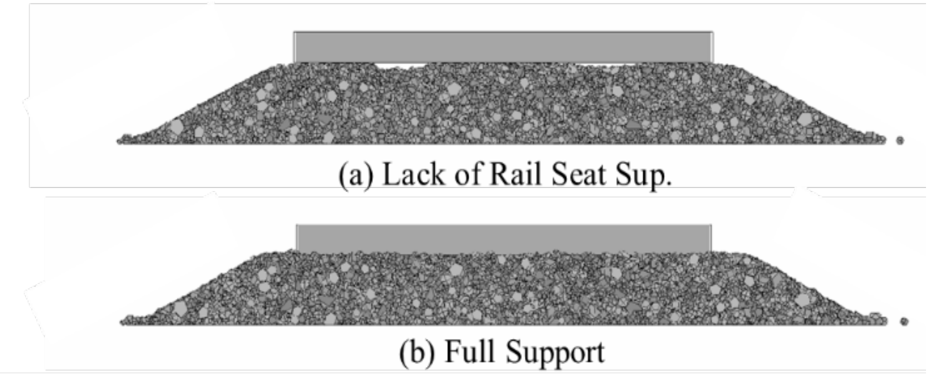
Traditional DEM simulation 1) does NOT consider water,

2) does NOT consider particles in the size range of fouling materials

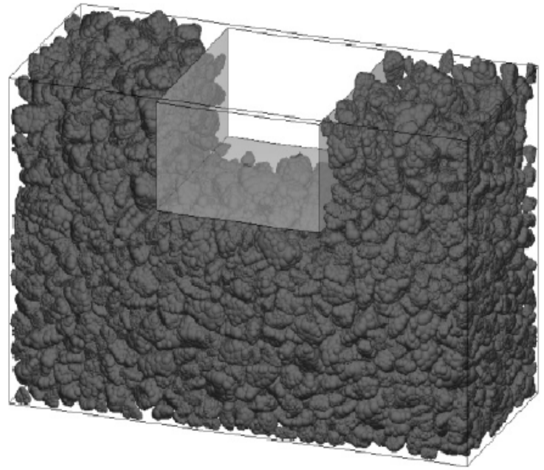
3) hundreds to thousands of particles



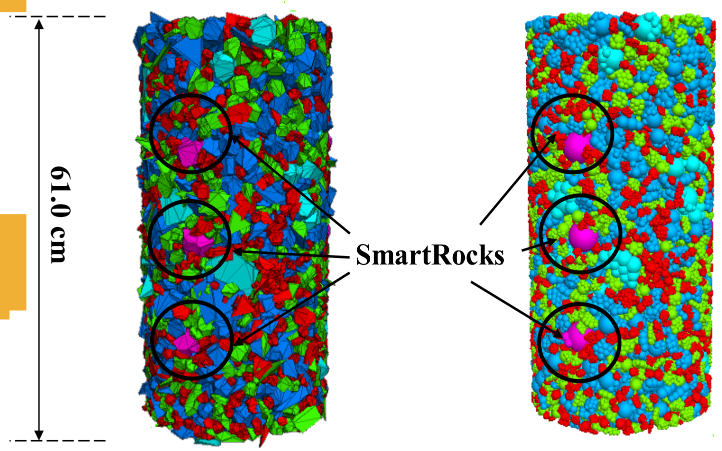
Indraratna et al. (2010)



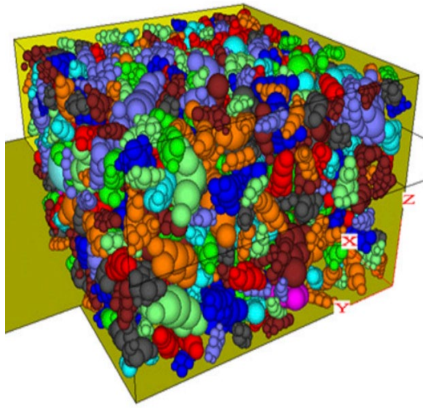
Feng and Hou (2017)



Laryea et al. (2014)



Liu et al. (2019)



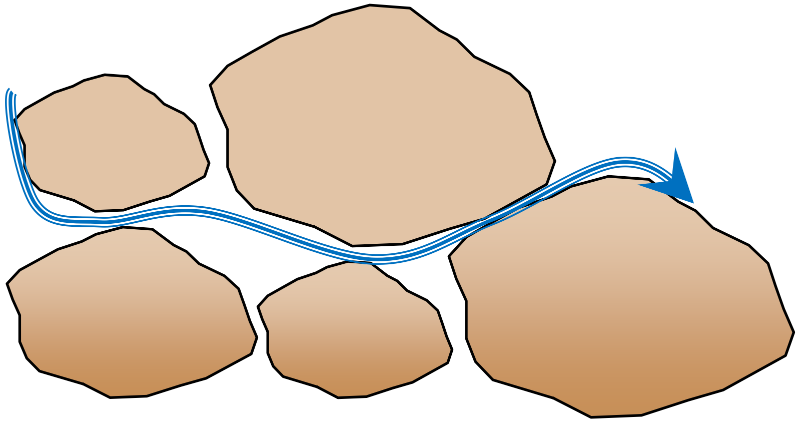
Indraratna et al. (2012)

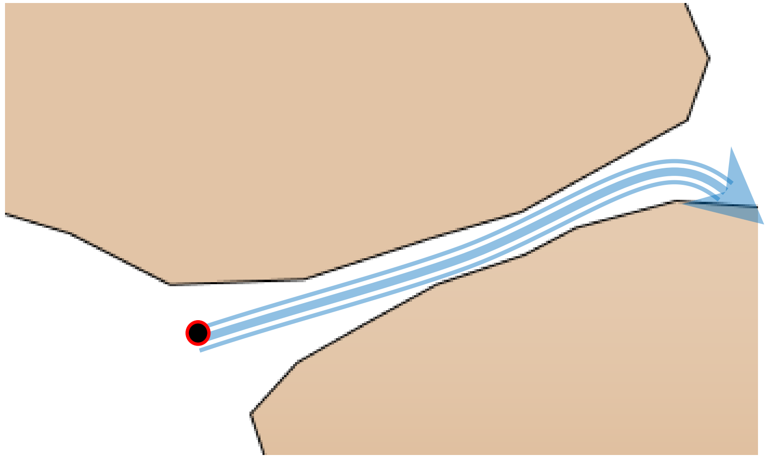
Our Simulation Approach

CFD+DEM

The two most notorious computational expensive numerical simulation method:
Computational fluid dynamics + discrete element method

Allow the interaction between fouling particles, ballast particles, and water





Fines carried by the flow and can settle within the ballast layer

Our Simulation Approach

CFD+DEM

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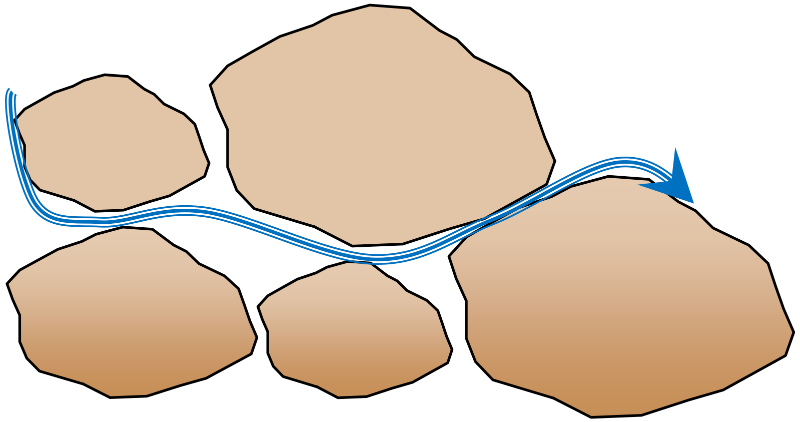
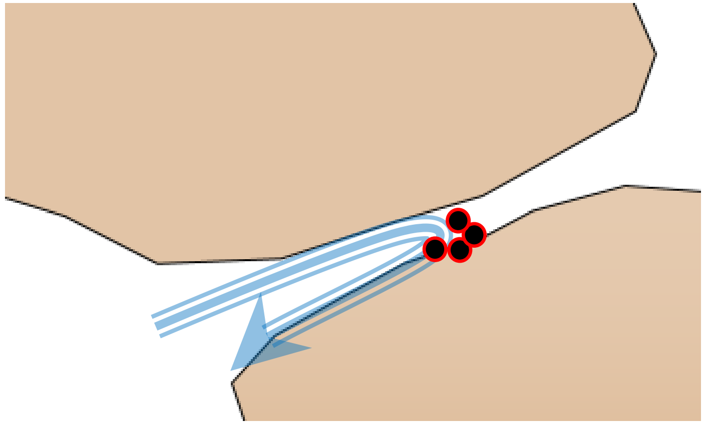


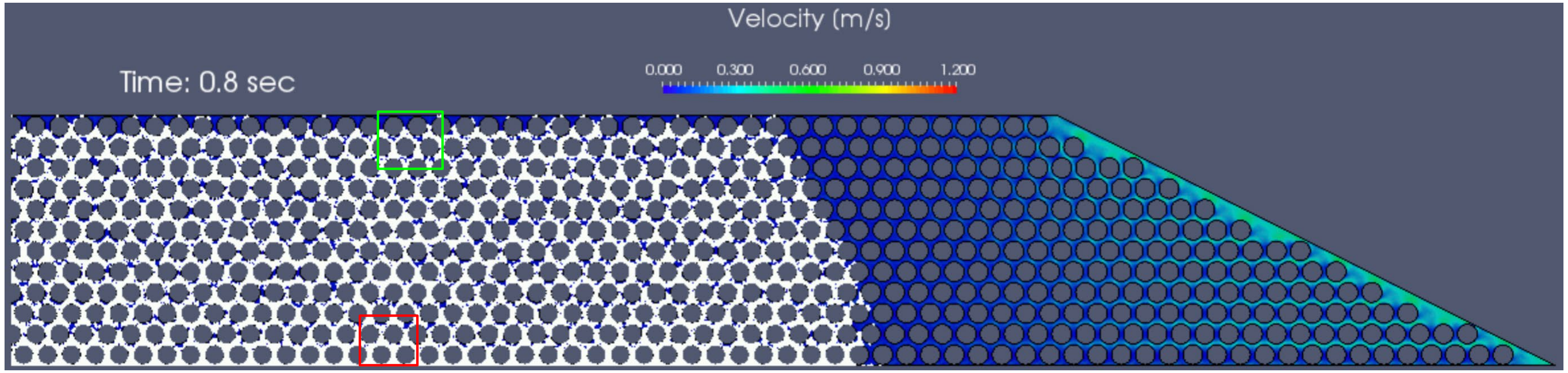


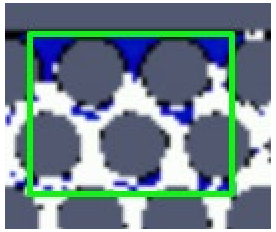
Settled fines can clog the water path and change the flow

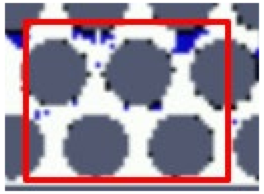
Our Simulation Approach

So far just the case w/ shoulder cleaning

Less fine particle, less computing time







Fouling Particle Size:1 mm
Fouling Particle Quantity: ~200,000 (FI=23)
Two-way coupled simulation: water-particle interactions
Total injected water:

Simulation Time t=25 Sec
Injected Rain = 20 Inches
(approximately total precipitation for 2 years in Nevada, or 0.5 years in South Carolina)

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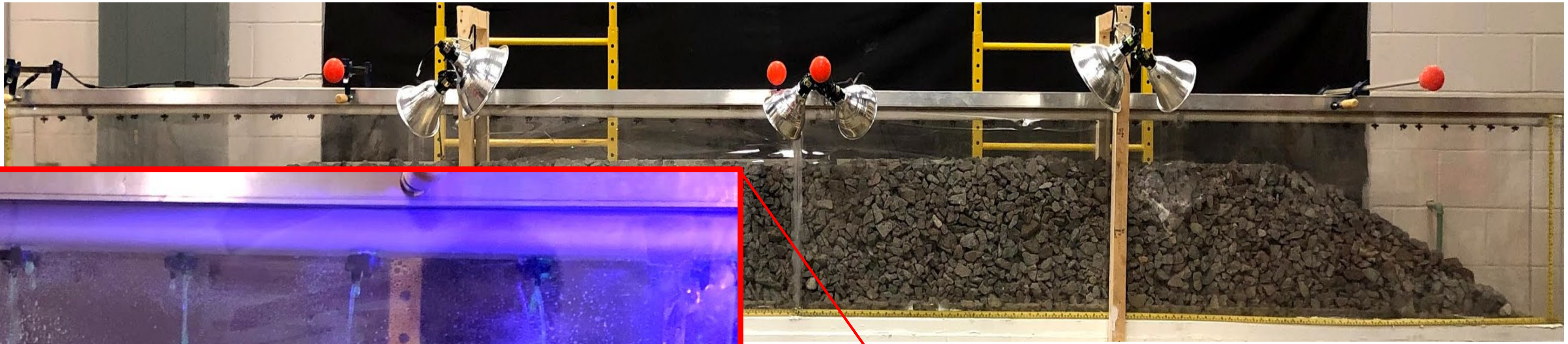
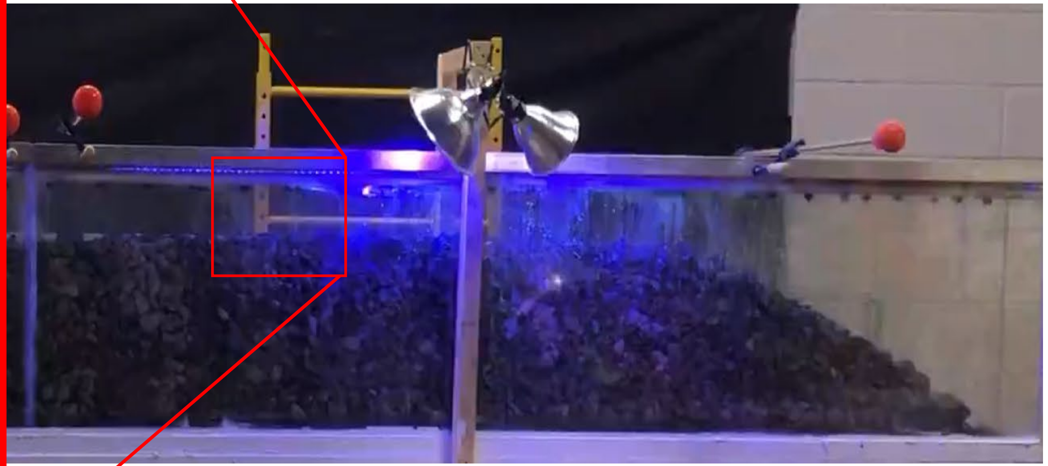
Laboratory Test Results with Clean Ballast

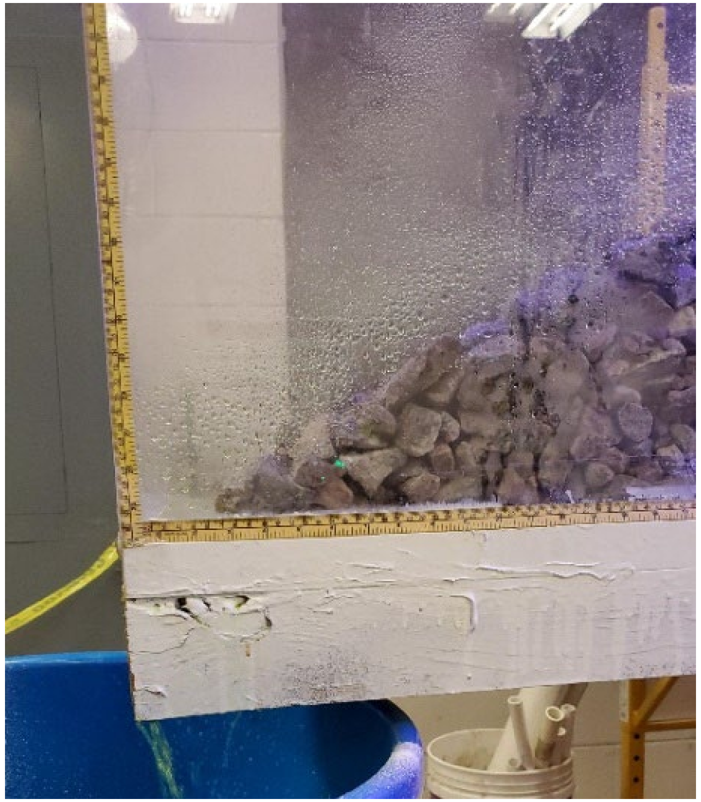


inning of the test



ours of testing

Laboratory Test Results with Clean Ballast



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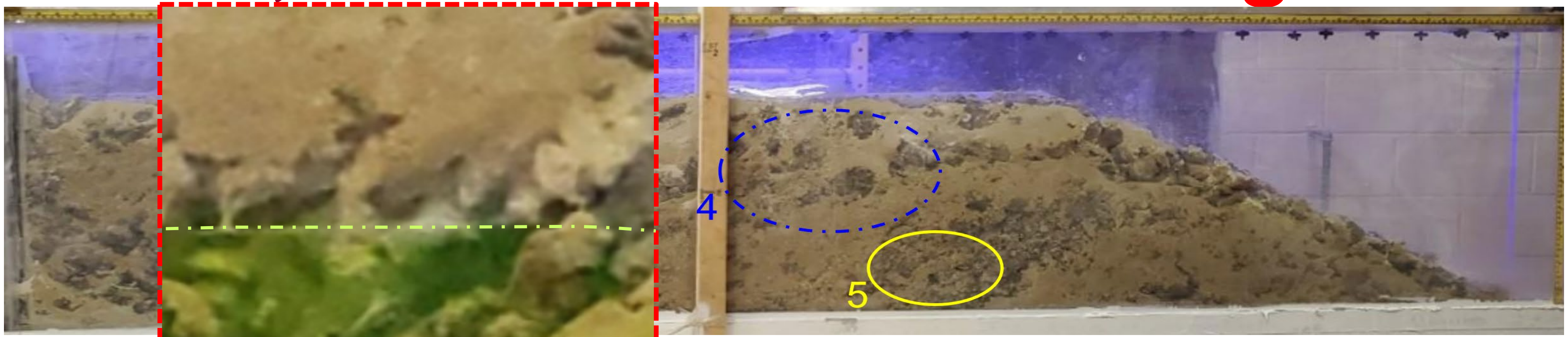
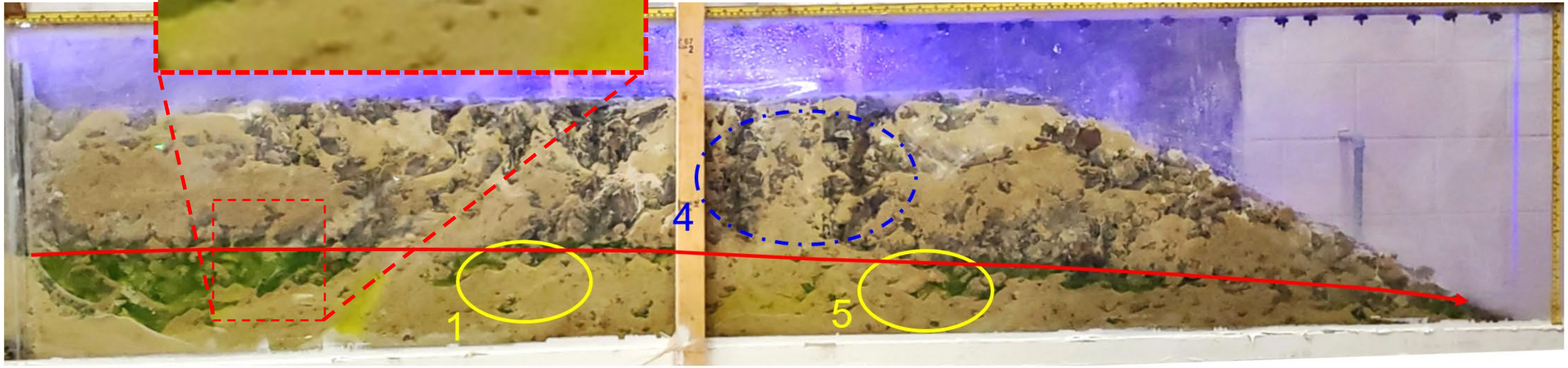
Laboratory Test Results with Fouled Ballast, *w/o shoulder cleaning*

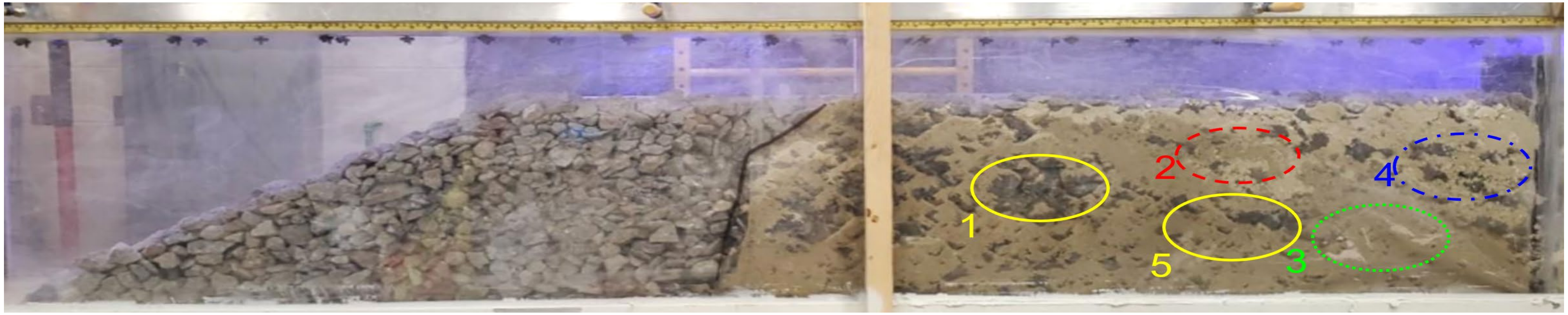


(a) At the beginning of the test

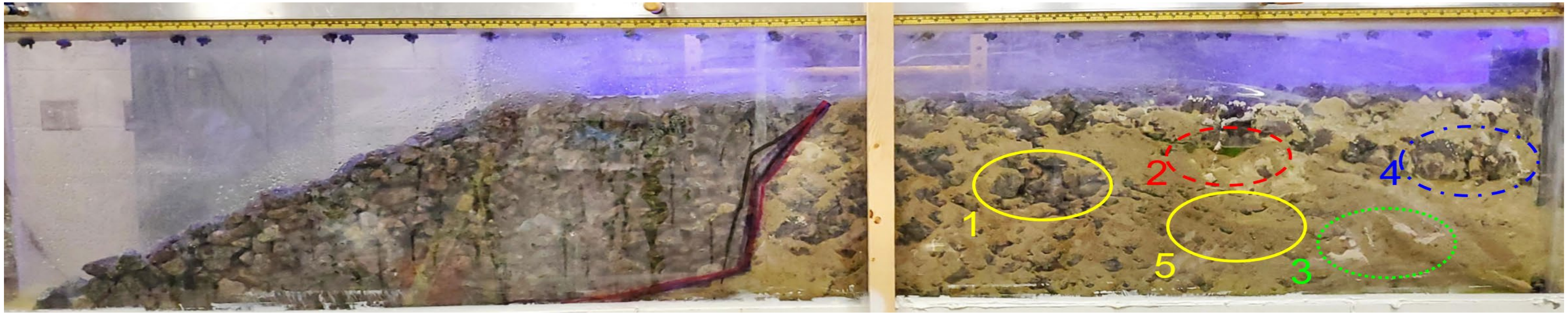


(b) After Six Hours of testing

Laboratory Test Results with Fouled Ballast, *w/ shoulder cleaning*



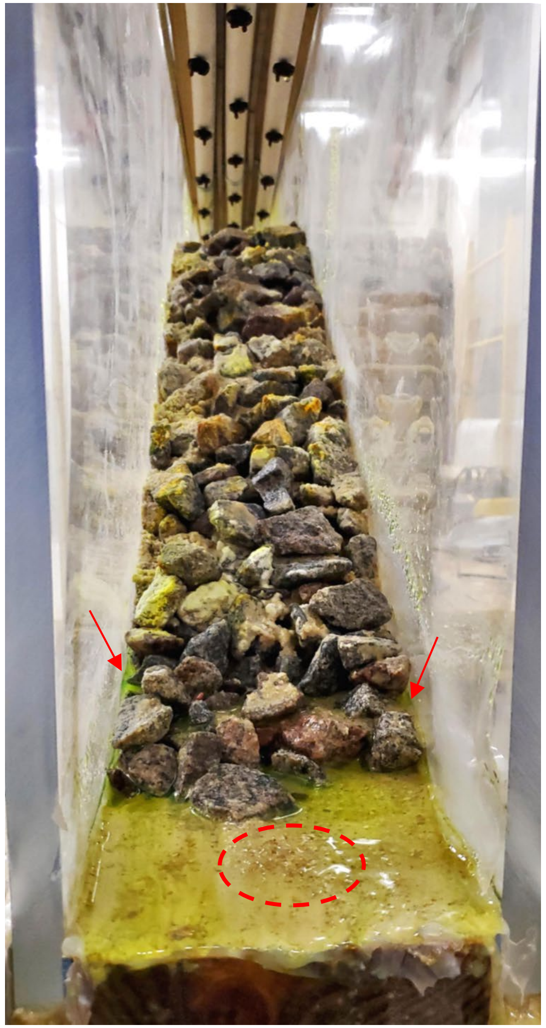
(a) At the beginning of the test



(b) After Six Hours of testing

Laboratory Test Results with Fouled Ballast

With shoulder cleaning

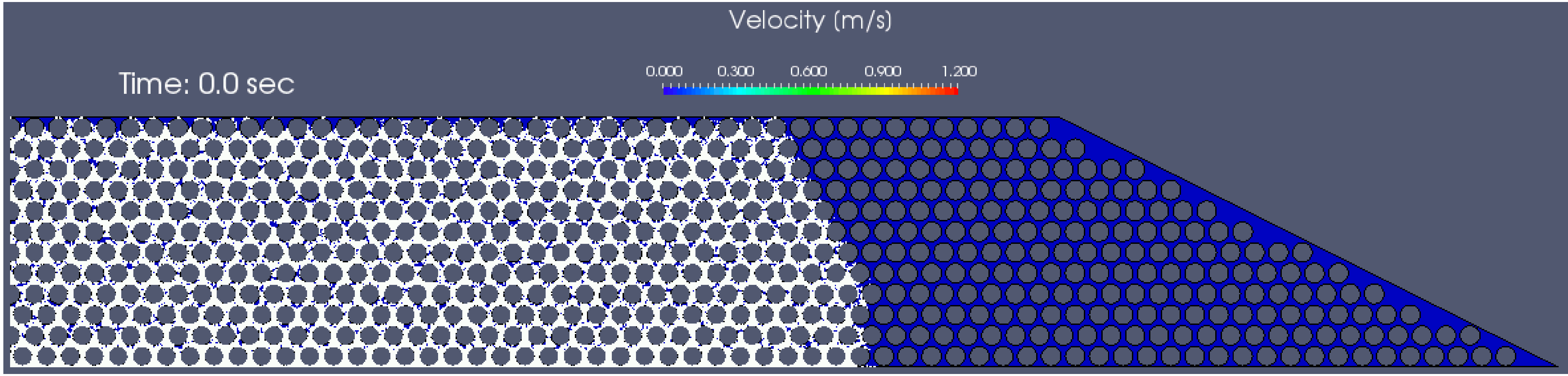


Without shoulder cleaning

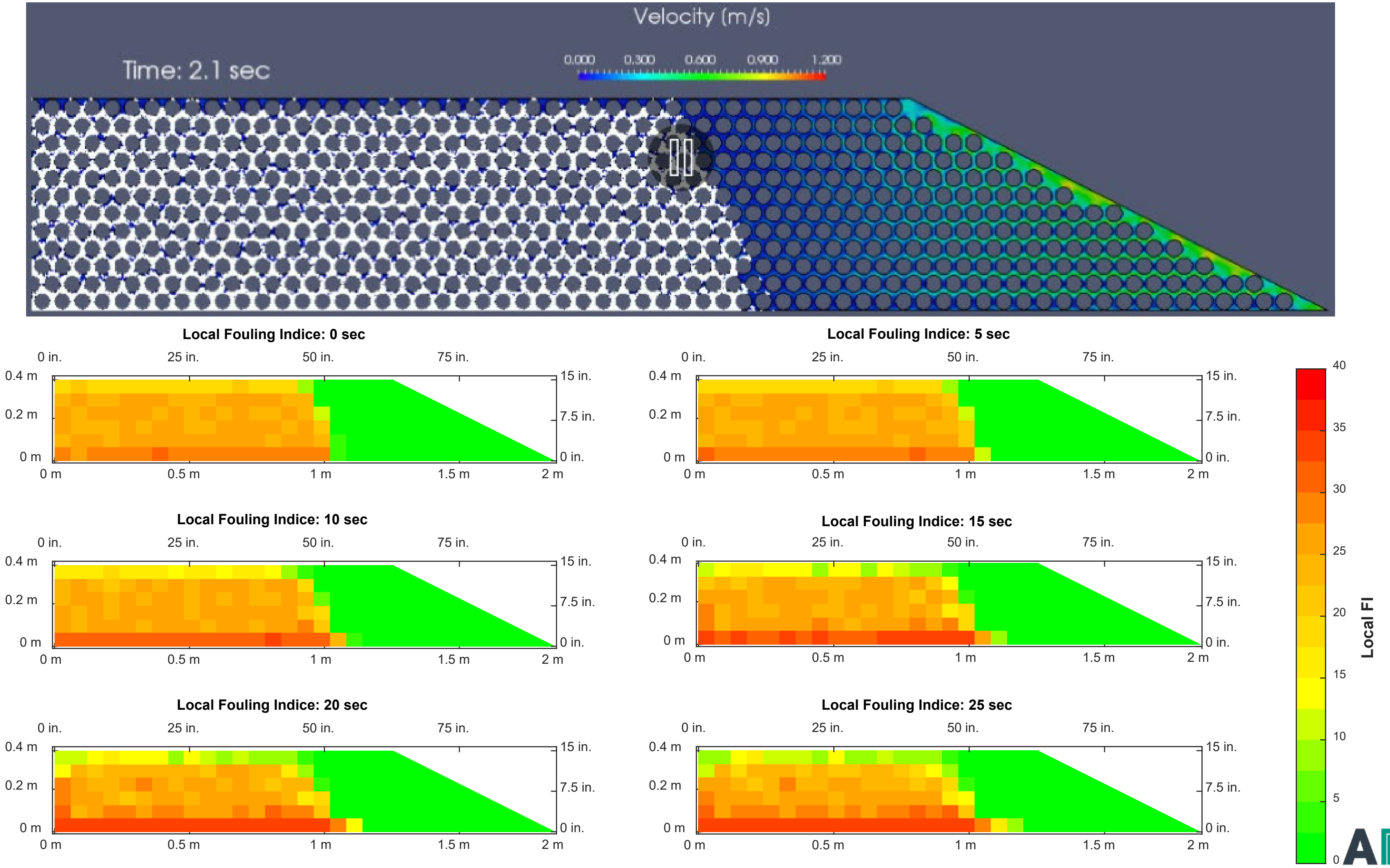
We dye the water with Green color

More greenish appearance indicates more water retention

Numerical Simulation Results



Numerical Simulation Results



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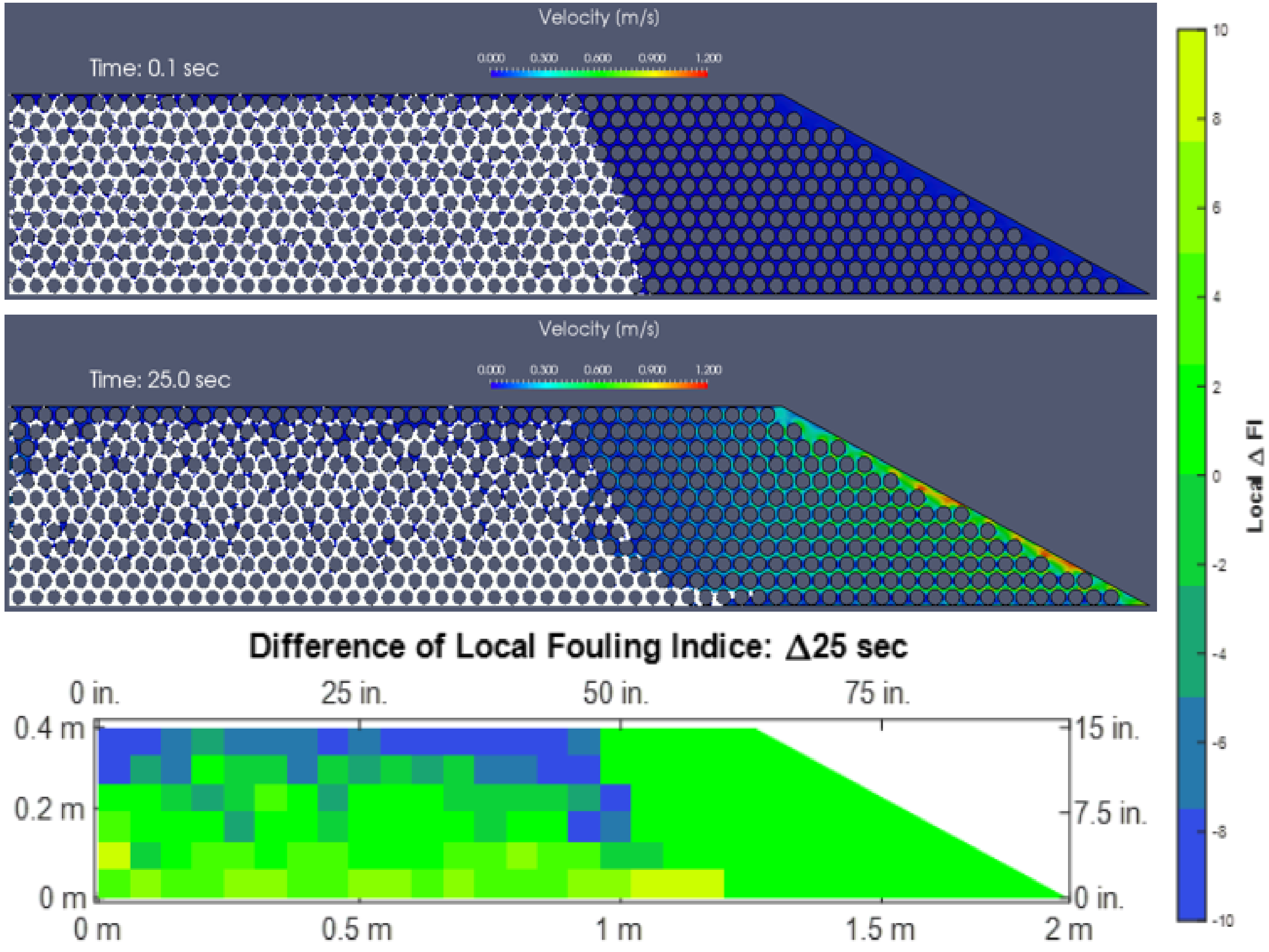
Numerical Simulation Results



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Concluding Remarks

- The developed ballast flume is a good setup to *visualize the fine particle migration* trend within the ballast layer and can be used to quantify potential benefits of different track maintenance activities.
- No obvious water accumulation was observed for both clean ballast and fouled ballast with shoulder cleaning.
- Water accumulation and surface flow was observed for fouled ballast without shoulder cleaning and the water table decreased towards the ballast toe area.
- Shoulder ballast cleaning opens the critical drainage paths at the shoulder area and water can easily flow out of the ballast layer. Without shoulder cleaning, fouled ballast acts as a dam, preventing water drainage.

Concluding Remarks and Future Work

- Generally, fines migrate towards the bottom and the toe areas of the ballast layer. However, the local fouling index at different locations may increase or decrease depending on the interactions between the ballast, fines, and water.

- Using local fouling index values instead of a single fouling index to represent the entire ballast layer can better illustrate the localized ballast fouling condition.

Future Work

- For future work, we will perform test with different fouling materials.

- The numerical simulation will be used to reveal how particle migrates within the ballast layer under different conditions.

- Find the critical drainage path(s) and help optimize maintenance activity

Thank you !
&
Questions ?

Contact Information

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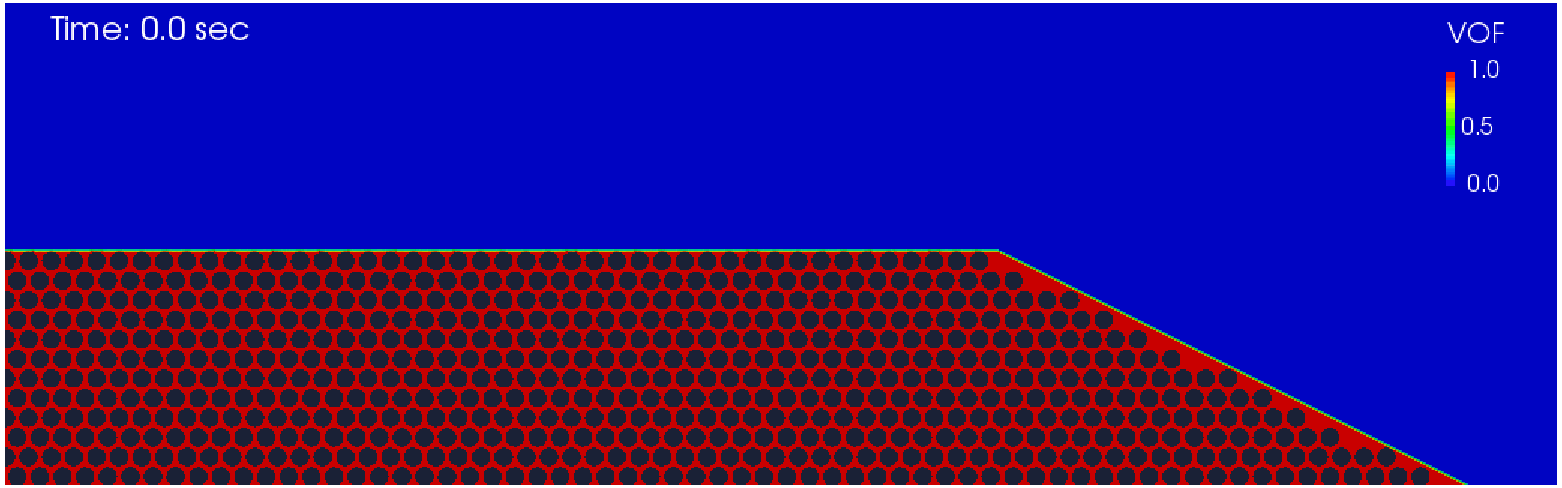
Assistant Professor
Email: yuqian@sc.edu



Three-phase coupled simulation: air-water-particle interactions