Transportation Pooled Fund Program TPF-5(552) Quarterly Progress Report

Quarter 1, January – March 2025

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TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): _FHWA_______________________________________

INSTRUCTIONS:
Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.

Transportation Pooled Fund Program Project # *(i.e., SPR-2(XXX), SPR-3(XXX) or TPF-5(XXX)* *TPF-5(552)*	**Transportation Pooled Fund Program - Report Period:** ☒Quarter 1 (January 1 – March 31) ☐Quarter 2 (April 1 – June 30) ☐Quarter 3 (July 1 – September 30) ☐Quarter 4 (October 1 – December 31)

Project Title: **High Performance Computational Fluid Dynamics (CFD) Modeling Services for Highway Hydraulics**		
Name of Project Manager(s): *Kornel Kerenyi*	**Phone Number:** *(202) 493-3142*	**E-Mail** *kornel.kerenyi@fhwa.dot.gov*
Lead Agency Project ID:	**Other Project ID (i.e., contract #):**	**Project Start Date:**
Original Project End Date:	**Current Project End Date:**	**Number of Extensions:**

Project schedule status:

☒ On schedule ☐ On revised schedule ☐ Ahead of schedule ☐ Behind schedule

Overall Project Statistics:

Total Project Budget	Total Cost to Date for Project	Percentage of Work Completed to Date

Quarterly Project Statistics:

Total Project Expenses and Percentage This Quarter	Total Amount of Funds Expended This Quarter	Total Percentage of Time Used to Date

Project Description:

The Federal Highway Administration established an Inter-Agency Agreement (IAA) with the Department of Energy's (DOE) Argonne National Laboratory (ANL) Transportation Analysis Research Computing Center (TRACC) to get access and support for High Performance Computational Fluid Dynamics (CFD) modeling for highway hydraulics research conducted at the Turner-Fairbank Highway Research Center (TFHRC) Hydraulics Laboratory. TRACC was established in October 2006 to serve as a high-performance computing center for use by U.S. Department of Transportation (USDOT) research teams, including those from Argonne and their university partners. The objective of this cooperative project is to:

- Provide research and analysis for a variety of highway hydraulics projects managed or coordinated by State DOTs.
- Provide and maintain a high-performance Computational Fluid Dynamics (CFD) computing environment for application to highway hydraulics infrastructure and related projects.
- Support and seek to broaden the use of CFD among State Department of Transportation employees.

The work includes:

- Computational Mechanics Research on a Variety of Projects: The TRACC scientific staff in the computational mechanics focus area will perform research, analysis, and parametric computations as required for projects managed or coordinated by State DOTs.
- Computational Mechanics Research Support: The TRACC support team consisting of highly qualified engineers in the CFD focus areas will provide guidance to users of CFD software on an as needed or periodic basis determined by the State DOTs.
- Computing Support: The TRACC team will use the TRACC clusters for work done on projects; The TRACC system administrator will maintain the clusters and work closely with the Argonne system administrator's community; The TRACC system administrator will also install the latest versions of the STAR-CCM+ and OpenFOAM CFD software and other software that may be required for accomplishing projects.

Progress this Quarter:

(Includes meetings, work plan status, contract status, significant progress, etc.)

1: Computational Mechanics Research on a Variety of Projects

1.1. CFD Modeling of Infiltration from Ditches into Roadway Embankments

Road ditches are built along roadways to prevent accumulation of rain on the pavement. They intercept rainwater from the pavement as well as from the adjacent land. Water can move freely in a ditch away from the road surface, thus making the road safer for the vehicular traffic. South Carolina DOT expressed interest in studying infiltration of water from ditches into roadway embankments. As part of the current design criteria, it is recommended that the road sub-grades be one foot above the design high-water level to protect the pavement from water infiltrating soil and subgrade under the road from the ditches. The distance between the water surface and bottom of the subbase is referred to as "freeboard". This requirement is put in place to reduce the risk of pavement damage. With changes in roadway design standards, larger shoulders and flatter cross-slopes have moved ditches further out. The additional embankment width may warrant a smaller freeboard without risking negative effects to the subbase. Computational fluid dynamics (CFD) modeling was selected as a method of testing how water infiltrates from the ditch into the embankment and how far the percolating water can travel into the embankment, with the goal to assess if the freeboard and horizontal distance between the road and the ditch can be reduced. A typical cross section through a road, embankment and ditch is shown in Figure 1. Main elements of the design, such as travel lanes and shoulder were marked in the figure, along with the freeboard as defined earlier.

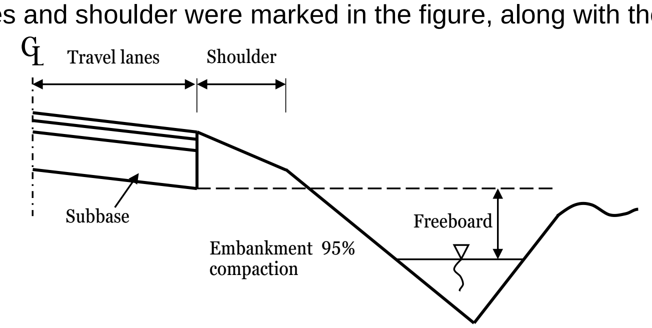

Figure 1. Typical section of a road with marked freeboard - clearance between the water free surface and bottom of the road subbase.

Road ditches are drainage elements with an almost constant cross-section and a longitudinal grade. During rain events, which uniformly fill up the ditch, it can be assumed that the geometry and flow conditions are the same in each cross-section. Moreover, water infiltration and movement in soil is mostly parallel to the cross-section. Therefore, it was decided to represent a thin section of a full-size ditch with elements: (1) soil extending up to the subbase on one side and beyond the ditch on the other, (2) soil extending downwards by a distance that exceeds the extent of the percolating waterfront; and (3) a volume of air above it, big enough to capture the free water surface in the ditch.

A Eulerian Multiphase model with two phases: water and air, and Volume of Fluid approach to compute the interface between the two phases are selected for modeling the open channel flow. The unsteady Reynolds-Averaged Navier-Stokes solver is used with a two-layer realizable k-epsilon turbulence model to solve for the flow field. Water migration through the soil is solved with the use of a porous media model.

A porous medium is characterized by three main parameters: porosity, porous inertial resistance, and porous viscous resistance. The resistance to flow within the porous media is related to the surface area per unit volume, which is determined from the aggregate size and porosity. The porous resistance was estimated from the Ergun relationship between pressure drop across a length, L, of a porous region and fluid velocity for a packed bed of spheres:

$$-\frac{\mathrm{d}p}{L} = P_v v_s + P_i v_s^2,$$

$$P_v = \frac{150\mu(1-\chi)^2}{\chi^3 D_p^2},\ P_i = \frac{1.75\rho(1-\chi)}{\chi^3 D_p} \tag{1}$$

where P_v is the viscous term, P_i is the inertial term, ρ is fluid density, μ is fluid dynamic viscosity, v_s is fluid superficial velocity through the medium $(v_s = \chi v)$, v is the physical velocity, and D_p is the equivalent particle diameter (aggregate size).

When the saturated permeability k_s or saturated conductivity $K_s = \frac{\rho g k}{\mu}$, of the medium is known, the equivalent particle diameter can be calculated from Darcy's law:

$$-\frac{\mathrm{d}p}{L} = \frac{\mu}{k} v_s. \tag{2}$$

Comparing Eq (1) and (2) gives:

$$D_p = \sqrt{\frac{150\mu(1-\chi)^2 k_s}{\chi^3}},\ \text{or}\ D_p = \sqrt{\frac{150\mu(1-\chi)^2 K_s}{\chi^3 \rho g}}. \tag{3}$$

The definition of the porous medium resistance in Eq. (1) and (2) assumes constant saturated permeability and conductivity. In order to take into account the increased flow resistance due to the presence of air, as occurs in unsaturated flows, researchers proposed an empirical model of hydraulic conductivity as a function of the reduced saturation. One of the widely used relationships is that of Genuchten [Genuchten, 1980]:

$$K(\theta) = K_s\sqrt{\theta}\left[1 - \left(1 - \theta^{\frac{1}{m}}\right)^m\right]^2 \tag{4}$$

where the relative volume fraction of water is

$$\theta = \frac{\theta_w - \theta_{w,r}}{\theta_{w,s} - \theta_{w,r}}, \tag{5}$$

with θ_w is the volume fraction of water, and $\theta_{w,s} = 1$ and $\theta_{w,r}$ are the saturated and residual volumetric water content, respectively, and m is a constant derived empirically for each soil type.
The viscous porous resistance is redefined as:

$$P_v(\theta) = \frac{K_s}{K(\theta)} P_v \tag{6}$$

As a part of the validation of the CFD models used in this study, the above modifications were introduced to the porous media model and their impact on the CFD results was evaluated on an example case found in literature. Watson [Watson, 1966] published results of an experimental study of the hydraulic conductivity in unsaturated soils. The researcher determined the conductivity vs. water content relationship from measurements obtained during drainage of an initially saturated sand column. A well-rounded sand fraction 150-300 microns was used. The sand column was 57-cm-tall, with a cross-section 10 cm by 15 cm. The saturated water content was 0.35 and the room temperature was 69 F. Initially in the experiment, a steady-state saturated condition was achieved, then water was draining from the sand column to the atmosphere. During the experiment, the researchers measured the pressure suction and water content at various times and several column elevations. Using this information, profiles of instantaneous velocity were obtained at the times stated.

Next, the total potential, equal to the sum of negative suction and gravitational component, was calculated, as well as the potential gradient. Finally, the instantaneous conductivity for an elevation and time was determined by dividing the velocity value at that point in space-time by the corresponding potential gradient value.

The results obtained with two CFD models with resistance independent and dependent on the water content are presented in Figures 2 and 3, respectively. The data points correspond to cell values intersected by a 7-by-7 grid of vertical lines uniformly distributed in the volume at various times during the simulation.

The results from the CFD model with soil flow resistance independent of the water content do not align well with the experimental results by Watson. Only at saturation level, when water content is 0.35 (m3/m3), is the hydraulic conductivity comparable. For lower water content, the CFD model underestimates the conductivity as compared to the experiment. Also, the relationship between the conductivity and water content varies in time – the conductivity becomes lower with time in the unsaturated zone. The CFD results from a model with implemented van Genuchten model give a better representation of the experimental results. Even though there is a visible spread of data, the general trend is very close to Watson's measurements.

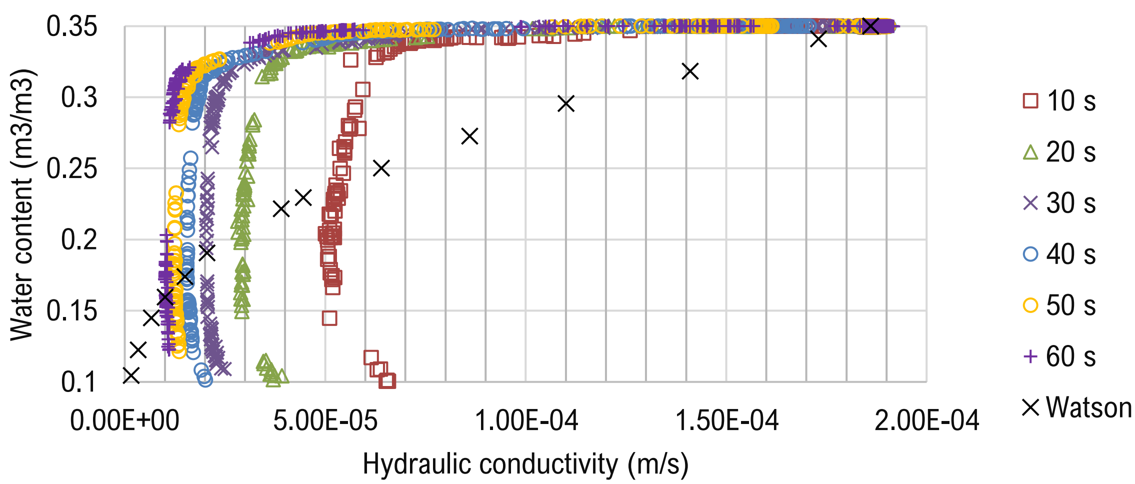

Figure 2. CFD results from a model with soil flow resistance independent of the water content compared with the experimental results by Watson.

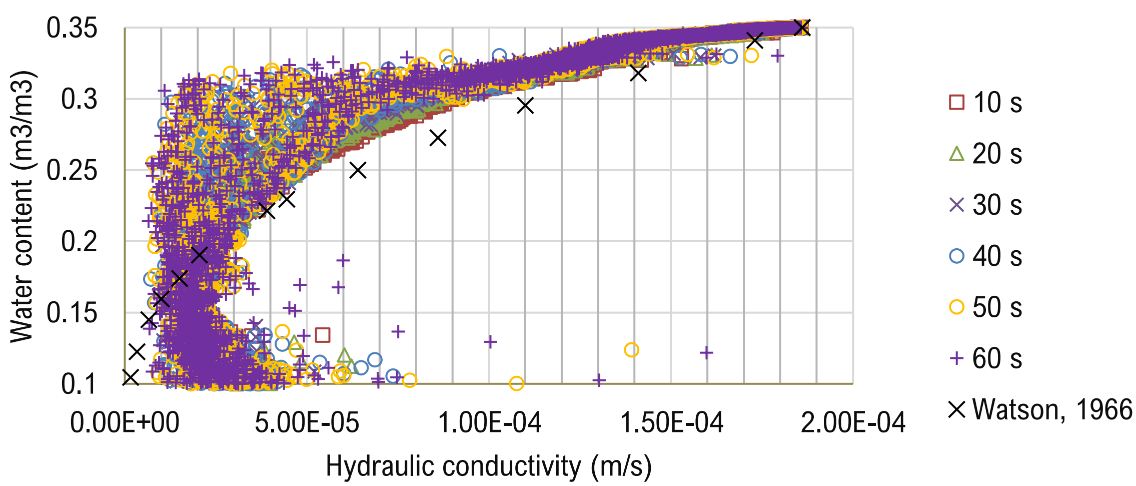

Figure 3. CFD results from a model with implemented van Genuchten model of water flow in unsaturated soils compared with the experimental results by Watson.

The findings of this exercise will be incorporated into the full-scale models of the roadside ditches and the impact of the varying saturation on the water movement in soil will be evaluated.

Anticipated work in the next quarter:

1: Computational Mechanics Research on a Variety of Projects

- hydraulic analysis of catch basins on grade and in sump
- infiltration of water from roadside ditches

2: Computational Mechanics Research Support

This work will continue.

Task 3: Computing Support

This work will continue.

Circumstance affecting project or budget.

(Please describe any challenges encountered or anticipated that might affect the completion of the project within the time, and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).

None.