Comparison of Experimental and COMSOL Multiphysics® CFD Model Simulations of Erosional Growth of a Soil Pipe

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Introduction:

Subsurface erosion through soil pipes on the land can lead to significant changes in landscape morphology and slope stability. The erosion produces gullies and can also lead to landslides. Subsurface erosion in man-made structure features such as dams and flood levees can be devastating, resulting in significant property damage and loss of life. Experiments and numerical simulations of subsurface erosion via soil pipes can help us to gain more understanding and quantification of the processes involved.

Methods:

Experiments Wilson (2011) conducted a number of experiments in a laboratory setting in which a soil pipe was constructed, using a metal rod, into a soil tank 100 cm wide, 20 cm deep, and 140 cm long. A reservoir of water was applied at the upstream open end of the pipe to generate the flow. A schematic of the tank is shown in Figure 1. One of the soils tested belongs to the soil series Providence, which is a silt loam. The soil was compacted to dry bulk density, 1,400 kg/m^3. The experiment was run by exposing the upper end of the soil pipe to the reservoir (15 cm deep above the pipe opening), and running the experiment for 30 minutes. At the end of the experiment the soil tank was excavated to measure the pipe diameter at 10 cm increments along the length of the pipe. The average diameter of pipe at the end of the experiment was 24 mm, with a standard deviation of 7.2 mm.

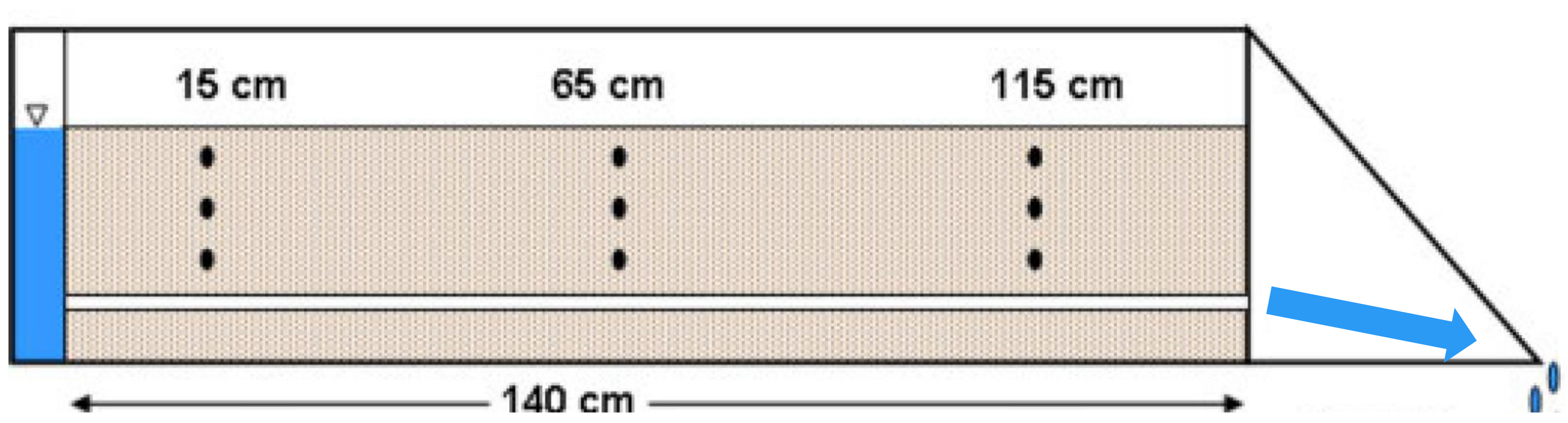

Figure 1. Illustration of the experimental setup used by Wilson (2011) for studying the erosion of soil pipes. The black ovals are locations of tensiometers used to measure soil water pressure.

Modeling The analysis is based on the solution to the governing equations for turbulent flow in a pipe to derive the distribution of water pressure and velocity, and the convection-dispersion equation to derive the transport of detached soil particles. The stationary form of the *k*-ω model for turbulence was selected, with 'automatic' chosen for wall treatment. The pipe wall erosion rate (kg/m^2-s) is given by the 'excess shear stress equation' (Wilson, 2011) expressed as $q = k_{ero}(\tau_w - \tau_c)$, where k_{ero} is the empirical erodibility coefficient (s/m), τ_w is the wall shear stress (Pa) calculated from the turbulent velocity profile, and τ_c is the critical shear stress (Pa) required to initiate erosion. This expression is applied along the wall of the soil pipe to produce the source of sediment transported in the soil pipe, and to determine the rate of wall expansion due to wall erosion. The transport of sediment in the soil pipe was simulated with the numerical solution of the advection-dispersion equation.

The modeling is composed of a series of steps of steady-state solutions for the flow field and sediment transport, where within each step the wall erosion is calculated and the pipe dimension for the subsequent steady-state solution is calculated based on the erosion rate, using the formula, $\Delta n = \frac{q}{\rho_d}\Delta t$, where Δn is the local outward normal movement of the pipe wall (m), ρ_d is the dry bulk density (kg/m^3) of the soil, and Δt is the selected time increment (seconds). After each steady-state solution is derived and the outward movement calculated, the grid for the new pipe geometry is generated to maintain a grid of good quality. This procedure would allow the pipe wall to expand non-uniformly, subject to the local wall shear stress and the local soil parameters (k_{ero} , τ_c , ρ_d), which do not need to be uniform. However, in the present application the pipe wall expansion was calculated using the average wall shear stress and assuming the k_{ero} and τ_c were uniform along the length of the pipe.

Results:

The experiments by Wilson (2011) were run for several different initial pipe diameters, but for the case shown here the initial diameter was 6 mm. The boundary conditions for the flow were specified pressure at the inlet (1471 Pa) and outlet (0 Pa) of the pipe, zero advective flux of sediment at the pipe entrance, and zero concentration gradient at the pipe outlet. The walls of the pipe imposed zero fluid velocity. In the present application a non-uniform time step was used. Based on the analysis of the experimental data the soil erosion parameters were chosen to be $k_{ero} = 0.0025\frac{s}{m}$ and $\tau_c = 0.0\ Pa$.

A summary of the flow and sediment concentration results for the simulations is presented in the following table. The table presents the pipe discharge calculated by the CFD model, and the pipe discharge calculated from the well-known Darcy-Weisbach equation. For both calculations it was assumed that the pipe wall roughness was proportional to the increase in pipe diameter starting with the 6 mm initial diameter. The proportionality was determined from the variability of pipe diameter (7.2 mm) measured at the end of the experimental run. The pipe discharge computed by the CFD solution is in reasonable agreement with the discharge derived from the Darcy-Weisbach equation. The wall shear stresses are in good agreement with the expected shear stress for the case of a fully developed boundary layer flow. The wall shear stress for such a case is calculated as $\tau_w = \frac{P(r_p - \varepsilon)}{2L}$, where P is the inlet pressure, r_p is the pipe radius, ε is the wall roughness, and L is the pipe length. The CFD result for wall shear stress should be (and is) less than the shear stress for fully developed flow due to the momentum increase that occurs during boundary layer development along the length of the pipe.

Pipe flow, mean wall shear stress, and concentration of suspended sediment in the discharge for an eroding soil pipe.

Pipe diam. (mm)	Wall roughness (mm)	Pipe flow (l/hr), CFD[&]	Pipe flow (l/hr), Darcy-Wesibach[#]	Mean wall shear[&] (Pa)	Mean wall shear[**] (Pa)	Time to reach diameter (s)	Suspended sediment concentration (g/l)
6	0.0	46	55	1.55	1.58	0	8.0
8	0.1	97	103	2.0	2.05	310	6.3
12	0.5	264	243	2.81	2.89	778	4.6
16	1.2	498	488	3.50	3.58	1,161	3.8
20	2.0	775	719	4.07	4.2	1,502	3.3
24	3.1	1,045	1,057	4.52	4.67	1,828	3.0

[&]Computational fluid dynamics model results
[#]Discharge calculated with the Darcy-Weisbach equation for full pipe flow
[**]Computed assuming fully developed boundary layer flow

A graphical display of the comparison between the experimental measurements of pipe diameter and the CFD solution is shown in Figure 2. Also shown is the comparison of mean sediment concentration exiting the pipe, measured and simulated. As illustrated by the graphic, the measured and simulated pipe temporal variation of soil pipe discharge are in good agreement. The measured and simulated temporal variation in sediment outlet sediment concentration are in good agreement after the 600 second mark.

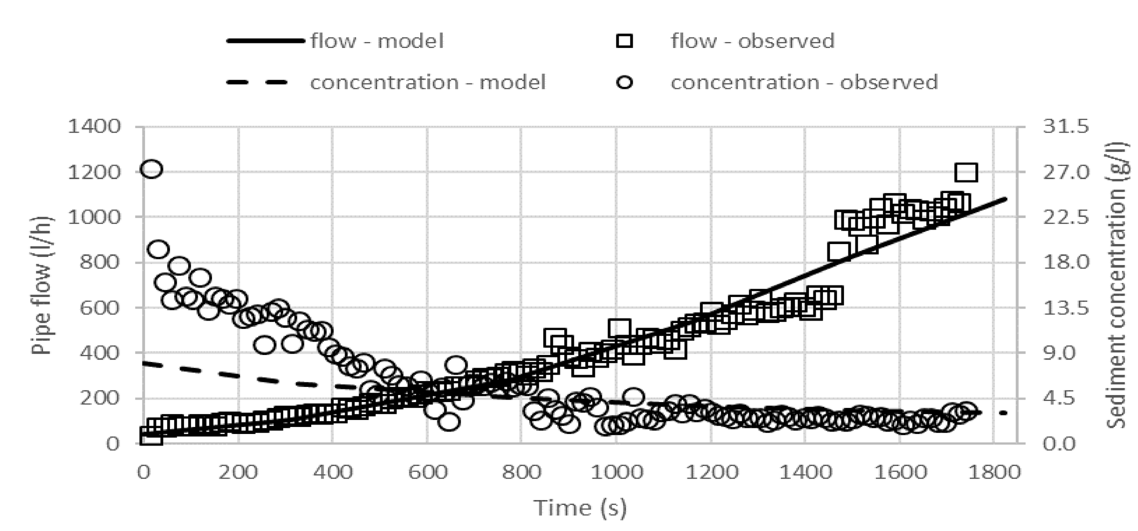

Figure 2. Simulated and observed pipe flow and suspended sediment concentrations versus time.

The disagreement in sediment concentration at earlier times is attributed to fact that the simulation assumed the erosion parameter, k_{ero}, to be constant with time. To illustrate that this parameter should not be held constant, the experimental measurements of sediment flux were used with an analytical solution derived for the Hole Erosion Test (Wan and Fell, 2004), to derive values of k_{ero}. These values are illustrated in Figure 3. It is seen that the derived k_{ero} is not constant with time, but tends to vary with time, exponentially decreasing from 0.0080 s/m initially to 0.001 s/m at the end of the experiment.

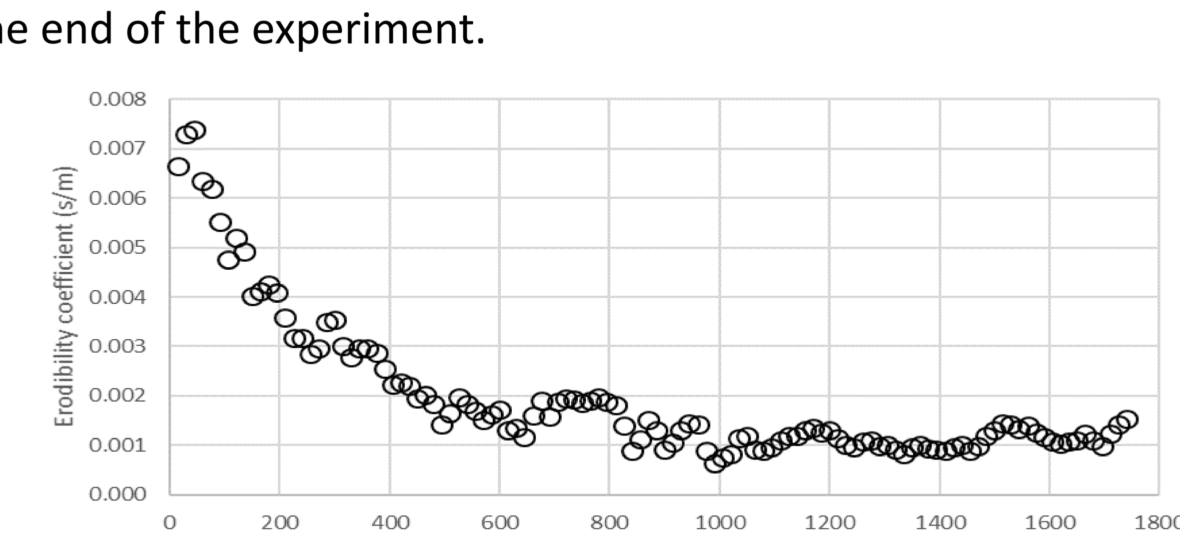

Figure 3. Erodibility coefficient versus time calculated using sediment flux data reported by Wilson (2011) with the Hole Erosion Test analysis (Wan and Fell, 2004).

Conclusion and Future Work:

The CFD solution for the *k*-ω turbulent flow model for an eroding soil pipe along with the solution of the advection-dispersion equation yielded results in good agreement with the experimental measurements reported by Wilson (2011). Differences between the simulated and measured concentration of the exported sediment are possibly the result of assuming a time-independent erobility coefficient. Planned future work includes:

1. Simulation of pipe erosion in which the pipe expansion rate is not constrained to be uniform along the pipe length, and
2. Incorporation of a more process based erosion equation that will account for the temporal variability of the erodibility coefficient.
3. Incorporation of spatial variability of the local soil parameters (k_{ero} , τ_c , ρ_d).

References:

Wan, C. F. and Fell, R. 2004. Laboratory test on the rate of piping erosion of soils in embankment dams. *Geotechnical Testing Journal* **27**(3): 295–303.
Wilson, G.V., 2011. Understanding soil-pipe flow and its role in ephemeral gully erosion, Hydrological Processes, 25: 2354–2364