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Innovative Multiscale Sensing and Computational Simulations for Bridge Scour Risk Management

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ABSTRACT

This paper provides a snapshot of research activities at my group on the issue of bridge scour over the past 10-year period. These efforts aim to provide toolset of sensors that provide surveillance of field scour conditions and reduce the risk associated with scour failure. They also aim to understand the fundamental mechanism of bridge scour, which is accompanied with strong turbulent flow pattern around bridge piers. Computational simulations supplement the sensor development efforts. A multiscale simulation framework that couples macroscopic computational fluid dynamics and microscopic discrete element model is being explored and is promising to allow to probe into the fundamental mechanism of soil erosion under turbulent flow conditions.

KEYWORDS: *SHM, scour, Time Domain Reflectometry, Computational Fluid Dynamics*

1. INTRODUCTION

Bridge scour is the number one cause of bridge failures. Improving the method for bridge scour prediction and countermeasure design calls for innovative monitoring technologies and computational simulations. Advancement in this area will also bring about important economic and safety benefits. There are limitations in the existing theories for scour prediction in that they utilize sediment transport models that inadequately account for the effects of turbulence on the dynamic detachment process of soil particles. The current methods for bridge scour investigations are generally limited to scaled experiments, which do not accurately represent the bridge scour process under the field conditions. Therefore new monitoring and simulation tools are needed to understand the process of scour. This paper summarizes the research in my group aiming to provide new toolset for scour monitoring and understand the scour mechanism via computational simulations.

2. BRIDGE SCOUR MONITORING SYSTEM BASED ON TIME DOMAIN RERLECTROMETRY

2.1. Technology background

Time Domain Reflectometry (TDR) is a guided radar technology that has been widely used in electrical engineering for detection of cable breakages. It has become a widely used tool for field measurement of the soil water content due to the pioneering work by Topp et al. [1] among others. In civil engineering, Time Domain Reflectometry (TDR) has become an established technology for soil water content measurement [2-5]. It features the advantages of being rugged, accurate and automatic.

The TDR system generally includes a TDR device (including electrical pulse generator and data acquisition system), a connection cable, and a measurement probe. TDR works by sending a fast rising step pulse or impulse to the measurement probe and measuring the reflections due to the change of material dielectric permittivity. Due to the large contrast between the dielectric constant of water (around 81) and that of the air (1) or soil solids (the dielectric constant for dry solids is typically between 3-7), the bulk dielectric constant of soil is very sensitive to the change of water content. Because of the large contrast in the dielectric properties at the air/soil interface, one reflection takes place when the electrical signal enters soil from the air; another reflection takes place when the electrical signal arrives at the end of the measurement probe. From the time difference between these reflections, the time required for an electrical pulse to travel through the measurement probe can be determined. From the travel time, the velocity of electromagnetic wave traveling in the testing material can be calculated. Details of TDR technology can be found at referred literatures.

The application of TDR for bridge scour determination is the natural extension of its capability for interface detection. As illustrated in Figure 2.1, a TDR sensing probe is installed into the sediment. As the TDR electrical pulse propagates along the sensing probe, reflections will take place at sediment/water interface due to the large contrast between the dielectric constant of water (around 81) and the dielectric constant of sediment (typically between 20-40 for saturated sediments depending on the densities).

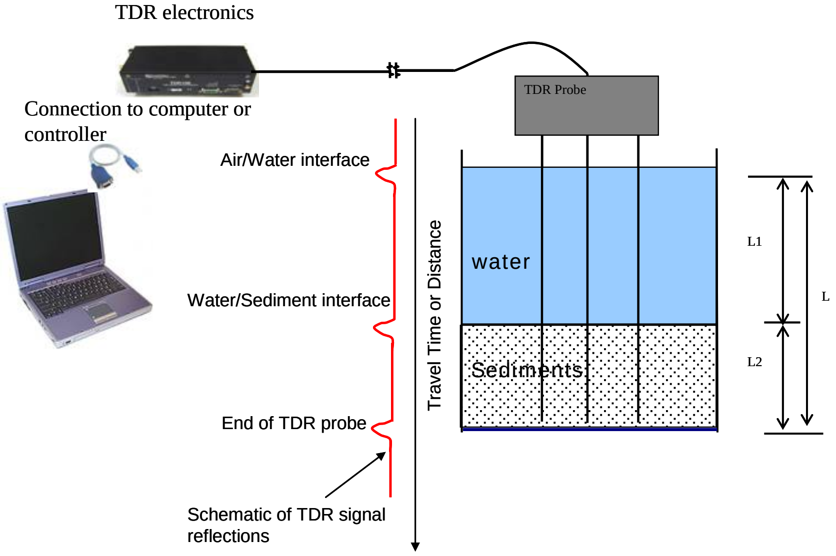


Figure 2.1 Conceptual model of TDR for scour depth measurement

2.2. Scour Sensor Design

A few generations of TDR scour sensors have been designed during the course of research. The set up that shows promise include regular TDR sensor probe that is made of parallel TDR rods and flexible TDR probe (Figure 2.2). The flexible TDR scour sensor was fabricated by mounting a flat strip sensor onto a supporting U-shaped e-glass element. The flat strip sensor was made of three inexpensive stainless steel strips accurately aligned parallel to each other. The metal strip is made of high-carbon steel with 12.5mm wide and 2.54mm inch thick. The metal strips are separated by a 2 mm gap. This gap is filled with Polytetrafluoroethene (PTFE) Teflon. The top and bottom surface are covered with tape. The width and spacing of the strips makes it close to 50 ohm impedance when exposed in air. A layer of adhesive coating was applied to both sides of the strip sensor. The total material cost for fabricating this flat strip sensor of 20ft long is less than $100.

After the strip was fabricated, it was bonded onto the flat surface of an e-glass U-channel using adhesive tape. The U-channel has dimensions of 2 x 9/16 x 1/8 (inch). The fiber glass U-channel provides structural support for the metal strip sensor to resist flow drag on a bridge site. For illustration purpose, the sensor shown in Figure 2.2 exposes portion of the strip sensor without the e-glass U-channel. The application prototype will attach the entire strip sensor on the e-glass U-channel. With a maximal enclosure diameter less than 3 inch in the cross section area, this sensor can be easily fitted into a standard geotechnical borehole.

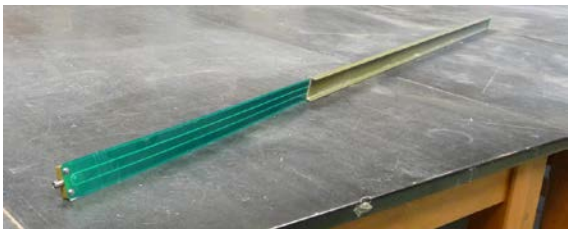


Figure 2.2 examples of TDR sensing probe left) 3 parallel rod; right) flexible strip scour sensor

2.2. Analyses Algorithm

While the sensing principle seems to be straight forward, the implementation is significantly hindered by lack of a robust and automatic analyses algorithm, as it can be very challenging to detect the intermediate reflection points from TDR signals. For example, Yankielun and Zabilansky [6] described the development of a TDR sensing probe. Field evaluation of the probe showed that this probe was sufficiently rugged to work under severe conditions including flooding and icing. The signal analyses, however, have been manual and are subjected to personal interpretation. This makes it difficult for a long term scour monitoring program. An algorithm based on a general principle is needed to ensure the signal analyses are accurate, robust and automatic. In view of the limitations of existing TDR scour sensing probe and algorithm, the authors developed an analyses algorithm based on accepted physics principles. A brief introduction of this algorithm and evaluation its performance under different conditions are described in the following.

The theoretical basis of the algorithm for TDR scour signal analyses is by extending the dielectric mixing model to layered soil sediment structure. The bulk dielectric constant of a mixture is related to its components by a semi-empirical volumetric mixing model [7].

$$\left(K_m\right)^\alpha = \sum_{i=1}^{n} \upsilon_i \left(K_i\right)^\alpha \tag{2.1}$$

where υi and Ki are the volumetric fraction and permittivity (dielectric constant) of each component. The exponent α is an empirical constant that summarizes the geometry of the medium with respect to the applied electric field. The value of $\alpha=0.5$ is suggested for homogenous and isotropic soils [7, 8]. For soils, the system is composed of soil solids, water and air.

Assuming the TDR sensor is completely immersed in the water and applying the mixing formula (Equation 2.1) to a layered system consisting of water and sediment, there is

$$L_1\sqrt{K_{a,w}} + L_2\sqrt{K_{a,bs}} = L\sqrt{K_{a,m}} \tag{2.2}$$

where $K_{a,w}$ is the dielectric constant of water; $K_{a,bs}$ is the dielectric constant of bulk sediment (sediment with water mixture); Ka,m is the measured bulk dielectric constant of the water and saturated sediment layer system; L_1, L_2 and L are the thickness of water layer, sediment layer and total thickness respectively.

Setting the thickness of sediment L_2 equal to x, then the thickness of water layer L_1 can be written as L-x. Substituting L_1 to Equation 2.2 and normalizing both sides by $\sqrt{K_{a,w}}$, the following equation can be obtained:

$$\frac{\sqrt{K_{a,m}}}{\sqrt{K_{a,w}}} = \frac{x}{L}\left(\frac{\sqrt{K_{a,bs}}}{\sqrt{K_{a,w}}} - 1\right) + 1 \tag{2.3}$$

Equation 2.3 indicates that the square root of the measured bulk dielectric constant of layered system is linearly related to the thickness of sediment layer (assuming $K_{a,bs}$ and $K_{a,w}$ are constants). An advantage of normalization by the dielectric constant of bulk water in this relationship is to reduce the effects of possible system errors. Equation 2.3 can also be rewritten as a linear relationship shown in Equation 2.4.

$$\frac{\sqrt{K_{a,m}}}{\sqrt{K_{a,w}}} = a x_r + 1 \tag{2.4}$$

where xr=x/L, a represents the slope of the linear relationship, i.e.,

$$a = \frac{\sqrt{K_{a,bs}}}{\sqrt{K_{a,w}}} - 1 \quad . \tag{2.5}$$

Based on Equation 2.4, an analyses algorithm for TDR scour signals is developed as described below (Figure 2.3):

- Determine the bulk dielectric constant, Ka,m, from TDR signal (step 1)
- Determine the ratio of sediment layer to TDR probe length (step 2)
- Estimate the scour depth, D, from xr (step 3) ;

A schematic plot of implementing these procedures is shown in Figure 2.3. A key component of implementing this algorithm is to determine Equation (2.3) (which is referred as Scour Estimation Design Equation in this paper) for different sediments. This can be achieved from empirical curve fitting of the laboratory experiment data or from theoretical estimation.

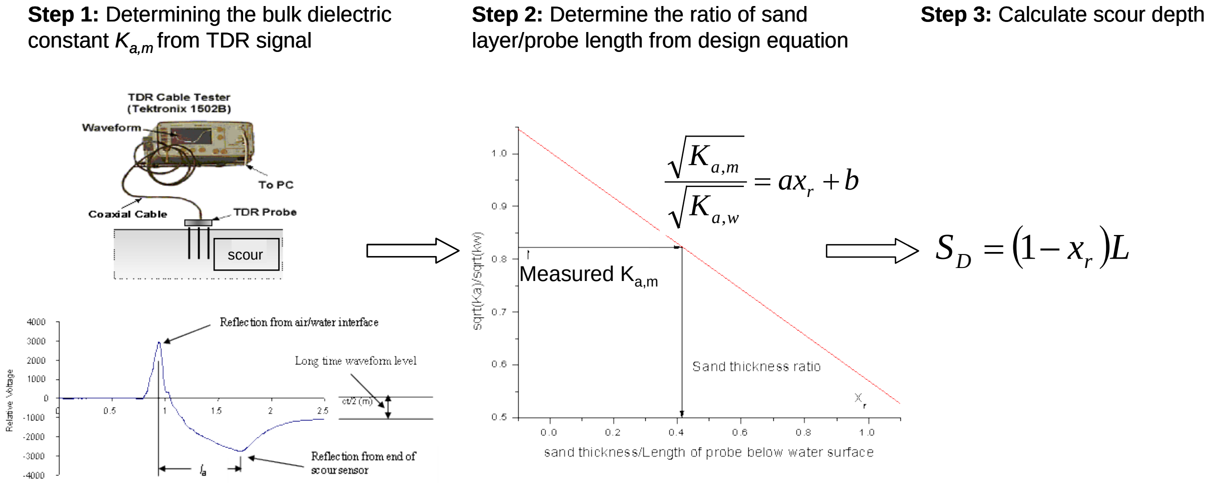


Figure 2.3 Schematic procedures for scour depth estimation from TDR measurement

2.3. Lab and Field Performance

The performance of scour sensor and algorithm are evaluated under both laboratory and field conditions. For the laboratory, factors considered include types of sediments, water salinity, temperature, water turbidity (suspended particles), entrance of air bubbles, etc. TDR reading is found to be robust under these conditions typical of a flood event. The suspended high plastic clay can causes attenuation of high frequency EM wave due to its high electrical conductivity. This has to be mitigated with proper insulation and improvement of signal analyses algorithms (i.e., by frequency domain analyses rather than time domain analyses algorithm).

Figure 2.4 shows summary of performance under laboratory conditions.

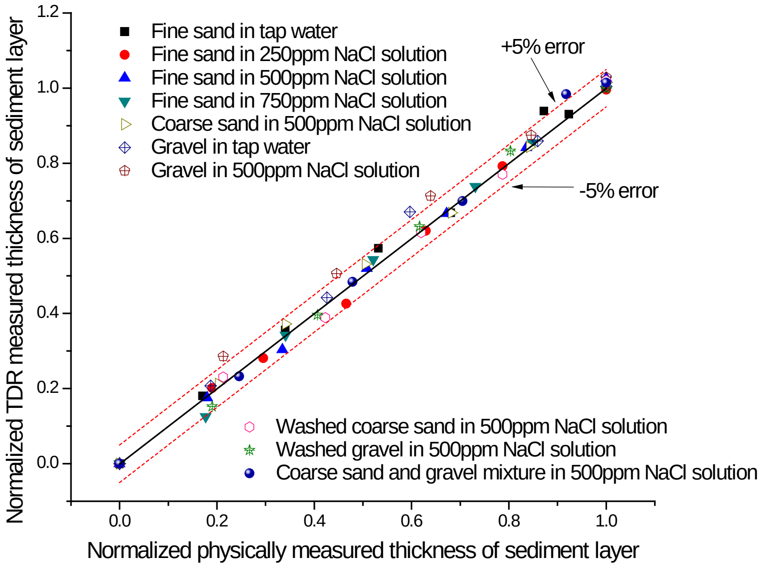


Figure 2.4 Results of TDR scour estimation versus those of physical measurements for all sediments

The system has also been installed under an in-service bridge. The bridge under monitoring is the seven-span BUT-122-0606 Bridge on State Route 122 over the Great Miami River in Butler County, OH. According to USGS stream flow statistics, the annual average discharge at this location is about 6,209 ft3/s (26). And during year 2004 and 2008, there were three major flood events with discharge over 50,000 ft3/s. Under-water inspections in 2004 and 2007 indicated a significant increase (around 2ft) of local scour around several piers, due to the flood events. The installation of this pilot monitoring station is expected to further provide real-time scour data, which will assist operational decision making and provide information for countermeasure design.

Five TDR sensors were installed at different piers. The sensors are located approximately 1ft from the corresponding piers and 6ft from the side walk (Figure 2.5); these locations are selected considering the maximum shear stress location and the easiness to install.

The TDR sensors are installed through routine geotechnical site investigation equipment and procedures (Figure 2.5a). The procedure can be summarized as: 1) to locate the equipment at the designed location on the bridge deck; 2) to core through the bridge deck; 3) to drill in the river bed to the design depth; 4) to lower the TDR sensor into the borehole; 5) to backfill the borehole with sand, pull out the assisting borehole casing and seal the coring hole in the bridge deck; 6) to move the equipment to the next location and repeat steps 2 to 5.

The field monitored cumulative scour depth after installation is illustrated in Figure 2.5b. It is interesting to observe that the scour developed fast in the first several days after installation and it tended to be stable in long time. The fast growing scour depth in the initial stage is probably due to the disturbance of the local sediments during scour sensor installation; after most of the weak soil was eroded, the scour evolves gradually. The system survived major flood events and provided valuable data on the scour process in field conditions.

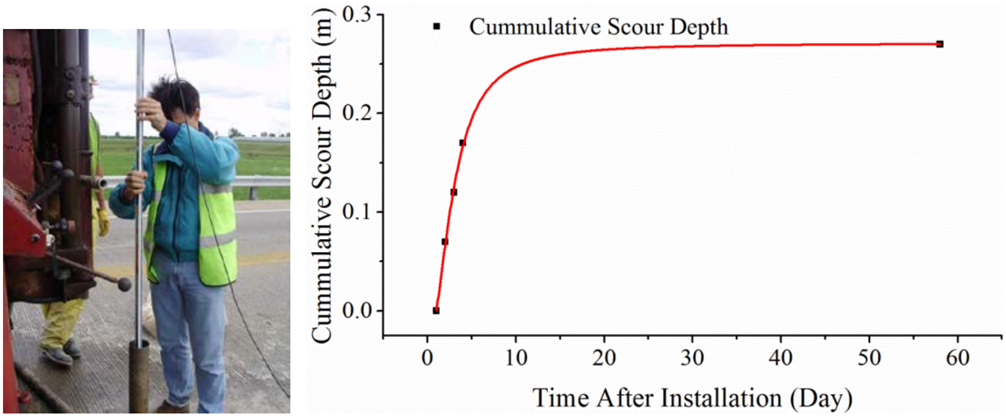


Figure 2.5 a) installation of TDR scour sensor; b) Scour evolution at Location 1 during the first two months.

3. COMPUTATIONAL SIMULATIONS FOR BRIDGE SCOUR

3.1. 1D and 2D Scour Simulations

1D and 2D models have been explored for scour prediction. HEC-RAS (River Analysis System) is bridge scour prediction software developed by the Army Corps of Engineers Hydrologic Engineering Center (HEC). It has been widely used by state DOTs and private design practitioners. The detailed hydraulic evaluations have been performed using techniques outlined in. It provides predictive scour-depth computations using parameters from a one-dimensional hydraulic analysis based on Hydraulic Engineering Circular No. 18 [10]. Field observations show that bridge scour predicted by HEC-RAS generally overestimated the actual scour depth. One of the reasons is that scour prediction equations used in HEC-RAS was developed based on scaling up the laboratory results, which are difficult to satisfy both the hydraulic and hydrodynamic similitude. The assumption of one dimensional flow is another potential source of errors. The basic computational procedure in HEC-RAS is based on solving the one dimensional energy equation. Energy losses are accounted for by friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilized in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e., hydraulic jumps), hydraulics of bridges, and evaluating profiles at river confluences (stream junctions) [11].

Flo2DH, part of the Federal Highway Administration’s (FHWA) Finite Element Surface-water Modeling System (FESWMS), is a two-dimensional finite element model that was developed by the U.S. Geological Survey in cooperation with the FHWA. The software was developed for analyzing backwater and flow distribution at width constrictions and highway crossings of rivers and flood plains [12]. It supports both supercritical and subcritical flow analysis. This code solves two dimensional flow equations based on the continuity of mass and momentum; it assumes a depth-averaged flow, as opposed to cross-section averaged flow in one dimensional models. This program can simulate movement of water and non-cohesive sediment in rivers, estuaries, and coastal waters. The software was special designed to model highway river crossings where complex hydraulic conditions exist, which is to address the shortcomings that conventional one-dimensional flow calculations cannot provide the needed level of solution details at these locations [12]. This code is not widely used due to difficulty in use and also the very limited number of actual applications that subjected to field verification.

Computational software such as HEC-RAS and Flo2dh simulates the flow field under different levels of assumptions. They are combined with scour prediction formulas for scour depth estimation.

Figure 3.1 compares the flow velocity calculated by HEC-RAS and Flo2dh. For HEC-RAS, the distribution of flow velocity along two cross sections are plotted, i.e., the cross section along the bridge crossing and the cross section just upper stream of the bridge. The difference clearly shows the effects of bridge piers in obstruction of the flow. There are several obvious velocity drops on the velocity profile calculated by HEC-RAS. The location of these drops correspond to the location of piers, the discontinuity might also be attributed to the one-dimensional flow assumption by the HEC-RAS model

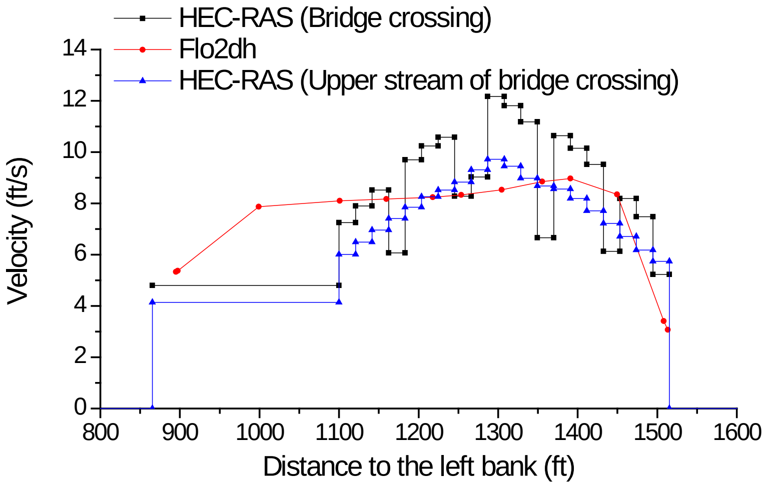


Figure 3.1. Comparison of velocity magnitude at cross section with bridge piers

3.2. 3D Scour Simulations

3D computational models are also used to simulate the flow fields around piers with different cross-sectional shapes, aspect ratios and attack angles. The effects of such factors on altering the flow pattern around the pier are evaluated. The vortex structures, the downflow in front of the piers and the bed shear stress patterns are compared and analyzed. A new equation is proposed to estimate the maximum bed shear stress considering the effect of both attack angle and aspect ratio. The typical patterns of scour, flow, and bed shear stress are analysed to provides insights into the scour mechanism.

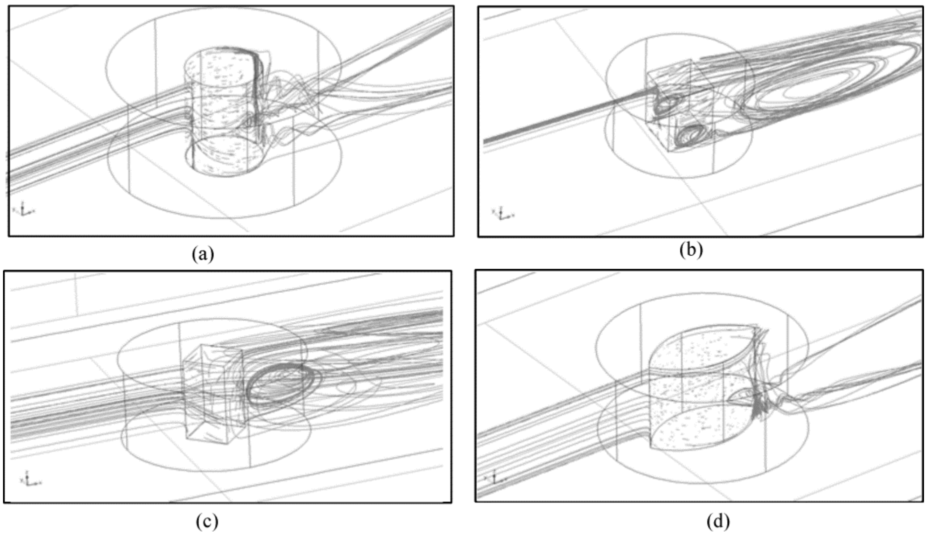


Figure 3.2 Limited streamlines around piers with cross-sectional shapes of circular (a), square (b), diamond (c) and lenticular.

3D computational model provides realistic description of the flow field. It, however, does not directly predict the scour process. For soil erosion, the macroscopic behavior of soil particles is controlled by the interaction between soil particles and surrounding fluid. A coupled CFD-DEM model provides direct scientific description of the fluid particle interactions. An example of erosion of pile of sand in a pipe flow was studied to illustrate the advantages of CFD-DEM simulations. Pipe flow has a relatively simple boundary condition and was chosen to demonstrate the erosion process. The pipe has a length of 0.6 m and a diameter of 0.1 m. The pressure drop between inlet and outlet is 200 Pa. Non-slip boundary is used for the pipe wall. Sand particles with diameter of 2 mm were generated at location between 0.1 m and 0.2 m. This model consists of 10829 tetrahedral elements in CFD phase and 9375 particles in DEM phase. The simulation conditions are described in Figure 3.3. Examples of simulation results are shown in Figure 3.4. These advanced simulation models provide direct insight on the process of soil erosion under turbulent flow conditions.

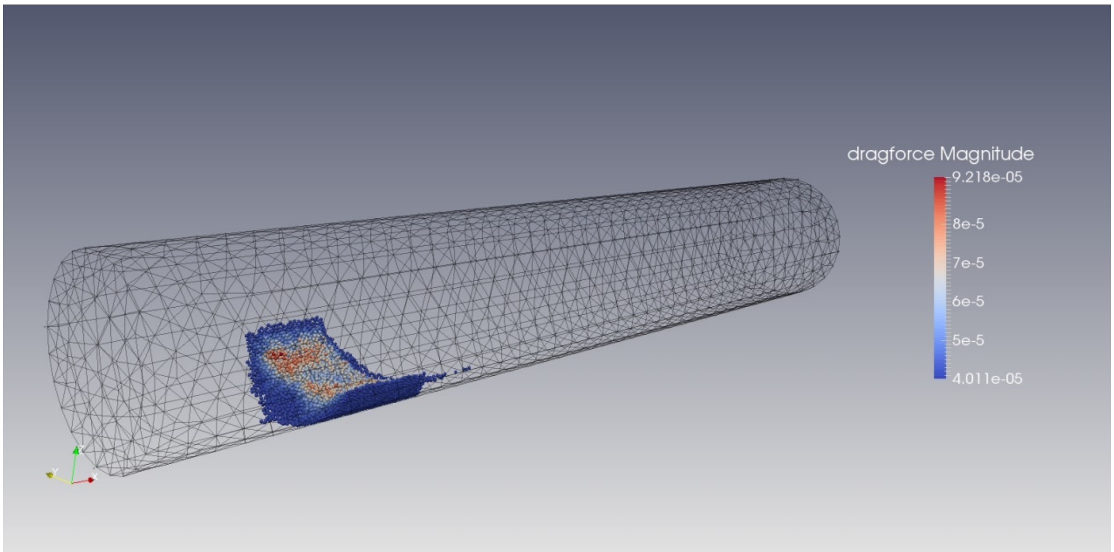
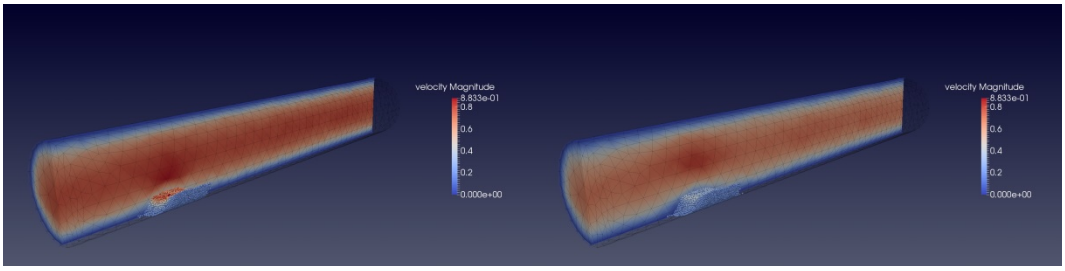
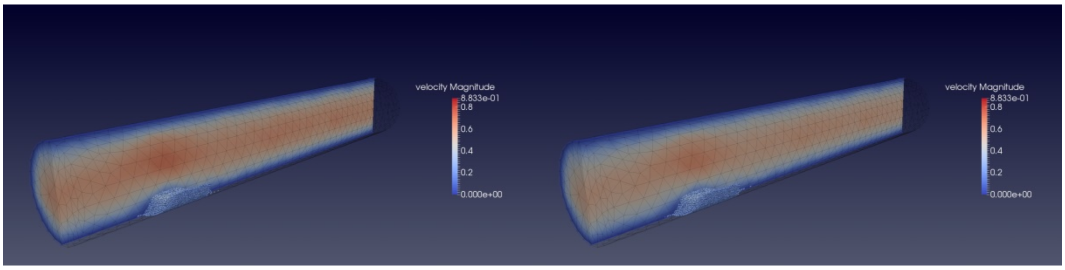


Figure 3.3 Model for sand erosion in a pipe flow



t = 0.0 sec t = 0.3 sec



t = 1.0 sec t = 5.0 sec

Figure 3.4. Particle movement in the pipe flow under laminar condition (color scale represents fluid velocity)

4. CONCLUSION

This paper summarizes the efforts in developing sensor and computational simulations to study bridge scour, from which an effective risk management strategy could be implemented. A few generations of TDR scour sensors have been developed that aims to monitor the scour process under field turbulent flow conditions. Laboratory and field tests have validated the performance of the scour monitoring system. In conjunction with developing scour monitoring sensors, our team has engaged in developing advanced computational simulations to study the scour process. The multiscaled approach provides opportunity to understand the fundamentals and ensure the decision of scour countermeasures are based on sound engineering principles [13-16].

REFERENCES

1. Topp, G. C., Davis, J. L., and Annan, A. P. (1980). Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research* 16(1), 574-588.
2. Dowding, C.H. and Pierce, C.E. (1994). Use of Time Domain Reflectometry to detect bridge scour and monitor pier movement. Proc. Symp. And Workshop on Time Domain Reflectometry in Envir., Infrastruct. And Mining Applications, Northwestern University, Evanston, III., 579-587, 1994.
3. ASTM D6565 (2005). Test Method for Determination of Water (Moisture) Content of Soil by the Time-Domain Reflectometry (TDR) Method, *Annual Book of ASTM Standard*, American Society of Testing and Materials.
4. ASTM D6780 (2005). Measurement of the Soil Water Content and Dry Density of Soil by Time Domain Reflectometry (TDR) Method, *Annual Book of ASTM Standard*, American Society of Testing and Materials.
5. Benson, Craig H. (2006). “Plenary Lecture: Geotechnical Applications of TDR”, Proc. TDR 2006, Purdue University, West Lafayette, USA, Sept. 2006, Paper ID A3.
6. Yankielun, N.E. and L. Zabilansky. (1999). “Laboratory investigation of time-domain reflectometry system for monitoring bridge scour”. *Journal of Hydraulic Engineering*, 125(12): 1279-84.
7. Birchak, J. R., Gardner, C. G., Hipp, J. E., and Victor, J. M. (1974). High Dielectric Constant Microwave Probes for Sensing Soil Moisture, Proc. IEEE, Vol.62, pp. 93-98, 1974.
8. Ledieu, J., De Ridder, P., De Clerck, P., and Dautrebande, S. A (1986). Method for Measuring Soil Moisture Content by Time Domain Reflectometry, *J. Hydrology*, Vol, 88, pp. 319-328.
9. Richardson, E. V., and Davis, S. R. (2001). ‘‘Evaluating scour at bridges.’’ FHWA NHI 01-001: *Hydr. Engrg. Circular No. 18*, 4th Ed., U.S. Department of Transportation, Washington, D.C.
10. Brunner, G.W., 2002, HEC-RAS, River analysis system hydraulic reference manual: U.S. Army Corps of Engineers Report CPD-69.
11. Parr, A. D., Milburn, S. and Malone, T.: A Model Study of Bridge Hydraulics. Report No. K-TRAN: KU-03-4, Kansas Department of Transportation, 2007.

12. Froehlich, D. C. (2003). “User’s Manual for FESWMS FST2DH, Two-dimensional Depth-averaged Flow and Sediment Transport Model.” U.S. Department of Transportation, Federal Highway Administration, McLean, Virginia.
13. Yu, X.B., Zhang, B., Tao, J. and Yu, X. (2013). A New Time Domain Reflectometry Bridge Scour Sensor, *Structural Health Monitoring*. 2013 vol. 12 no. 2 99-113, doi: 10.1177/1475921713476331.
14. Yu, X.B. and Yu, X. (2011). Assessment of An Automation Algorithm for TDR Bridge Scour Monitoring System, *Journal of Advancement in Structural Engineering*, ISSN 1369-4332, Volume 14, Issue 1, p13.
15. Tao, J.L and Yu, X. (2014). Flow and Scour Patterns around Bridge Piers with Different Configurations: Insights from CFD Simulations, GSP 234, *Geo-Congress 2014 Technical Papers: Geo-Characterization and Modeling for Sustainability*, Proceedings of the 2014 Geo-Congress, held in Atlanta, Georgia, February 23-26, 2014.
16. Tao, J.L, Yu, X.B., and Yu, X.(Bill) (2013). Real-time TDR Field Bridge Scour Monitoring System, Structures Congress 2013: pp. 2996-3009. doi: 10.1061/9780784412848.262, *Structures Congress 2013: Bridging Your Passion with Your Profession*, Edited by Brian J. Leshko and Jonathan McHugh. ISBN (print): 978-0-7844-1284-8, Publisher: American Society of Civil Engineers.