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Wind Tunnel Physical Modelling of Coupled Above and Belowground Near-Surface Geo-Environments

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1 INTRODUCTION

The U.S. Army Corps of Engineers (USACE) has a long history of physical modelling, beginning shortly after the disastrous Mississippi flood of 1927. Over the last century, USACE has conducted numerous scaled physical modelling studies to develop innovative solutions and advance general knowledge regarding a wide range of coastal and riverine problems (Briggs, 2013). The USACE Centrifuge Research Complex, commissioned in 1996, has similarly been used to support a wide range of geotechnical, structural, and explosive engineering studies (Bowman et al., 2023). While computational modelling is being increasingly utilized in research, the USACE continues to invest in its physical modelling capabilities.

This paper introduces one of the USACE's newest research facility devoted to physical modelling, the Synthetic Environment for Near-Surface Sensing and Experimentation (SENSE). The SENSE was developed to support fundamental and applied research for a wide range of U.S. Army relevant problems involving thermo-hydraulic-mechanical (THM) processes occurring within the coupled near-surface atmospheric and subsurface/aquatic geo-environment. The facility is centred around a closed-circuit, climate-controlled, low-speed, micrometeorological wind tunnel that is interfaced with large test-beds containing soils, vegetation, and free-standing water. The wind tunnel and test-beds together form a physical model, or synthetic environment representative of environments and climates world-wide. A description of the SENSE facility, experimental considerations, and various applications are presented herein.

2 SENSE OVERVIEW

A wind tunnel can be simply described as an enclosed space or passage through which air is moved by some mechanical means. While simple in concept, the operating theory and design considerations behind wind tunnel experimentation is considerably more complex (Barlow et al., 1999). The SENSE wind tunnel was designed to support classical fluid dynamics studies, scaled atmospheric boundary layer and wind engineering applications, and THM process research. As such, considerable care was taken to ensure that the system can provide precision control over the flow field as well as produce suitable thermal and hydrologic boundary conditions for subsurface phensomena.

The wind tunnel forms a 40.8 m long closed loop (measured along its centreline) with the overall footprint being approximately equivalent to half an Olympic sized swimming pool (Figure 1). It is constructed out of 2.54 cm thick basswood panelling assembled in a modular fashion to facilitate disassembly; individual modules are mated using 12.70 cm wide (nominal) flanges with inset 'O' rings. All interior surfaces are painted with vapor blocking water-borne, acrylic, marine-grade coating to protect the wood from both operating climate extremes.

Flow conditioners are located along the length of the flow-circuit (Figure 1) to shape and control the flow so as to ensure that its is as uniform and low turbulent in nature as possible prior to it entering the test-section where all experimentation occurs. The test-section is a 8.84 m long, 0.99 m wide straight section of the wind tunnel which varies in height from 0.99 m to 1.2 m to accommodate flow blockages created by objects placed within. The two side walls and ceiling are comprised of large glass windows for both viewing and non-intrusive measurements. The floor of the test-section is removable so as to accommodate test-beds from below (see Section 3 for details). The test-section is outfitted with an active grid system at its entrance to provide further control over the incoming flow's turbulence properties and a series of particle traps at the exit to capture soil particles and

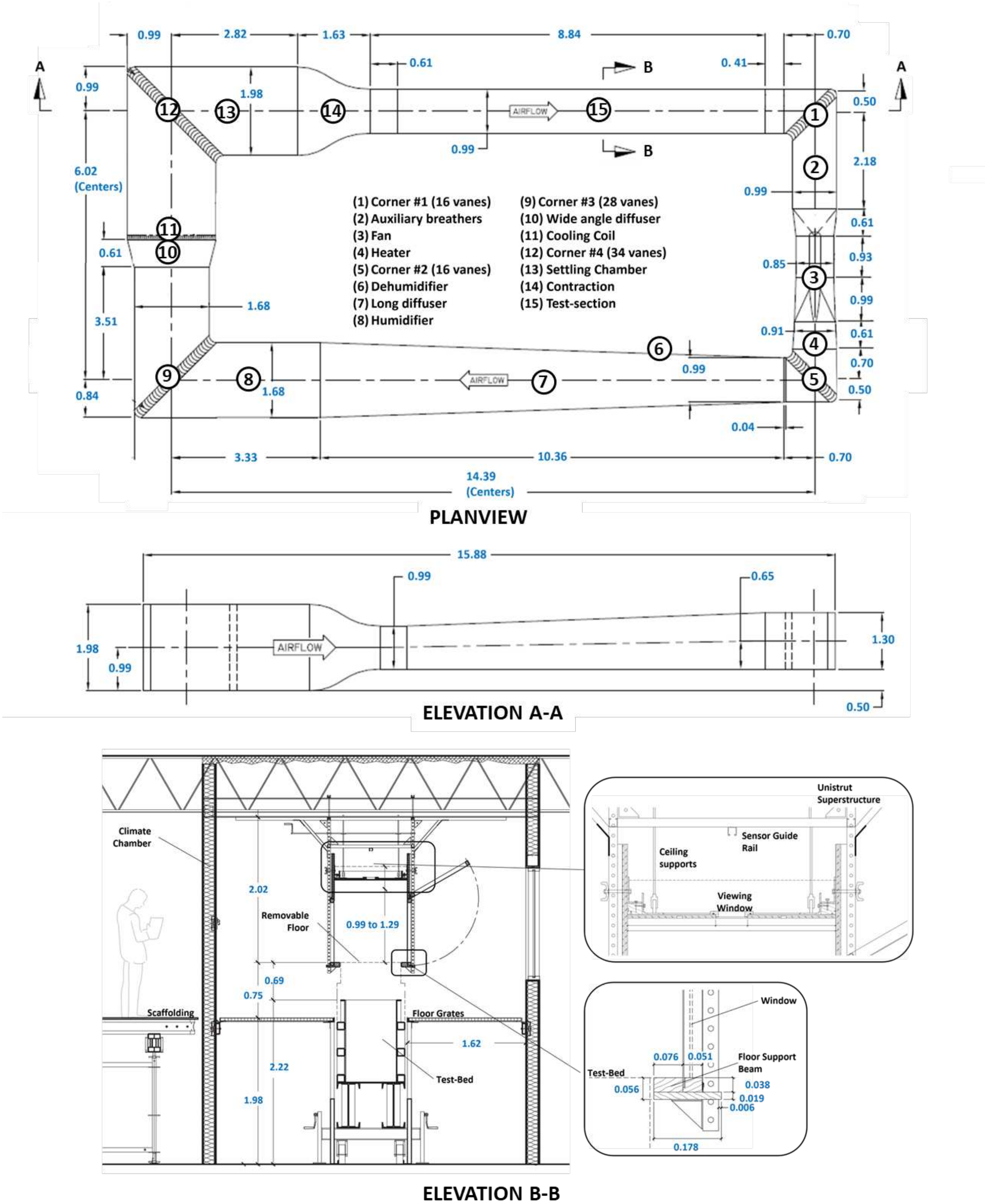

Figure 1. Wind tunnel flow-circuit dimensions and cross-sections of the test-section.

airborne dust. A fully automated three-dimensional traverse spans the length of the test-section, providing researchers with access to models mid-experiment without the need for opening the windows and disturbing the flow. The test-section is housed within a 8.41 x 4.55 x 4.87 m (l x w x h) environmental climate chamber to help stabilize conditions within the test-section and maintain constant external temperatures of the test-beds.

The wind tunnel test-section is able to accommodate test-beds with a maximum width of 0.84 m, length of 7.69 m and total depth of 2.73 m. The current test-bed in use at the SENSE Research Facility has internal dimensions of 7.21 x 0.65 x 0.96 m (l x w x d). The sidewalls are comprised of clear, 2.5 cm thick acrylic glass to facilitate subsurface visualization; a series of four drains are located at the bottom corners to allow water to be introduced or removed during experiments. The test-bed's overall superstructure is raised and lowered using six cylinder self-leveling hydraulic lift system capable of supporting up to 30,000 kg. The entire system is mobile, moved on a series of eight casters, each rated for 3,720 kg.

Flow within the wind tunnel is driven by a 0.93 m diameter direct drive axial fan with a 1,800 RPM totally enclosed air over motor that is governed by a variable frequency drive controller. Air temperature within the flow-circuit is controlled using independent heating and cooling systems consisting of a 12 kW resistance heater and a propylene-glycol hydronic-based chiller system with a 500 m^3 min^{-1} capacity. Humidification and dehumification of the flow-circuit is achieved with a 5.4 kg hr^{-1} steam-based humidifier and a heated dessicant-based system, respectively. The fan and four HVAC systems integrated into the wind tunnel are controlled by a building automation system controller interfaced with via a web browser application. A summary of the operating ranges afforded by these systems is provided in Table 1. The wind tunnel is also outfitted with a rainmaker, snowmaker, particle (smoke/haze) generator, growlights, full-solar spectrum lights, and gas injection ports for providing additional control over the atmospheric conditions during tests; see Table 1 for details.

Table 1. SENSE Operating Conditions

Parameter	Value
Flow	0.8 to 9.6 m s^{-1} 0.25 % minimum TI*
Air Temperature	-4 to 45 °C
Relative Humidity	5 to 95 %
Light/Radiation	UV, VIS, SWIR, LWIR
Precipitation (mist, rain, snow)	0.6 to 60 mm
Atmospherics	haze, smoke
Vegetation	user specified
Soil type /packing	user specified
Gas concentration	User specified
Soil Temperature	-2 to 35 °C
Soil Saturation	0 to 100 %

*TI: turbulence intensity

Experiments conducted at SENSE utilize a large number of different sensors for persistent above and below ground environmental monitoring as well as current advanced measurement techniques for high spatiotemporal measurements, visualization and general system characterization. The latter can be roughly divided into several classes pertaining to: flow, vegetation, spectroscopy, electro-optical and infrared imaging, soil characterization, as well as gas aerosol, and dust monitoring. Various 3D printers, computer numerical control (CNC) machines, and laser cutters are available for the fabrication of models.

3 EXPERIMENTAL CONSIDERATIONS

Scaled wind tunnel physical modelling is a critical tool in aerodynamics, atmospheric boundary layer, and fluid dynamics research. The SENSE wind tunnel was constructed to adhere to key similarity considerations, allowing scaled flow studies to be performed within. Kinematic, dynamic, and thermal similarity is based on the inspectoral analysis of the dimensionless governing equations for mass, momentum, and energy conservation in the atmosphere. Dynamic similarity is satisfied when the Rossby (Ro), Richardson (Ri), Reynolds (Re) numbers are equivalent. Thermal similarity likewise, is dependent on Reynolds number as well as the Prandtl (Pr) and Eckert (Ec) numbers. Note that the Froude (Fr), Mach (Ma), and Grashof (Gr) numbers also appear based on the overall formulations used. While not required for ensuring exact similitude, the Euler (Eu), Nusselt (Nu), Pectlet (Pe), Rayleigh (Ra), Schmidt (Sc), and Strouhal (St) numbers dimensionless numbers are also commonly considered in problems involving heat and mass transfer processes (Cermak, 1971; Mehta and Bradshaw, 1964).

The majority of the research conducted at SENSE however is 1:1 – the spatiotemporal scales of the physical model and prototype systems are the same. While many of the same considerations as scaled physical modelling apply (e.g., boundary effects, flow blockage), strict Reynolds number similarity can be relaxed which is beneficial given the relatively small 1 x 1 m cross-sectional area of the test-section.

1:1 scale physical modelling at SENSE involves the creation of synthetic environments that are simple, yet still relatively complex geo-environmental representations of real-world environments and climates (Figure 2). The goal in these experiments is to reproduce the key THM and biological processes as well as atmospheric conditions associated with earth's biosphere; note, length limitations necessarily constrain experiments to the vadose zone and near-surface vegetation canopies. The concept for synthetic environment physical modelling was originally inspired by a combination of large test-bed experimentation (e.g., Illangasekare et al., 2005), mobile and fixed wind tunnels use in aeolian transport studies (e.g., Maurer et al., 2006; Dong et al., 2003), historic wind-induced bare-soil evaporation studies (e.g., Yamanaka et al., 1997), as well as plant biophysical and canopy flow investigations (Dixon and Grace, 1984; Finnigan et al., 2009).

The underlying approach to synthetic environment physical modelling entails involves combination of traditional wind tunnel experimental techniques and the principles of intermediate-scale laboratory experimentation introduced by the hydrologic community to simulate flow and transport phenomena in aquifers. These experimental considerations can be succinctly summarized as follows:

- The experimental configuration must allow small-scale phenomena to manifest and be isolated at large scales so that their contributions can be quantified,
- The test system must be small enough so as to enable control over the boundary and initial conditions,
- The dimensionality and size of the test must be compatible with measurement and sampling techniques employed.

Figure 2: Synthetic environment creation in the SENSE wind tunnel

Synthetic environment experimentation generally follows a multi-step process. Work begins by first defining a scenario or selecting a specific geo-environment or geo-region for study. The key characteristics of the environment of interest are identified including: terrain features (micro-topography), soil conditions, vegetation types/properties, and climate/meteorology. Thirdly, the soils, vegetation, and other environmental clutter (e.g., rocks, deadfall, etc.) are either sourced directly from a field site or fabricated/engineered at SENSE to have the same physical, hydraulic, and thermal properties. With the materials in hand, the test-bed can next be prepared. The test-bed is typically packed with a variety of materials to simulate open water bodies and variably saturated soil horizons; combinations of the two can be used to simulate transitional environments such as wetlands, marshes, or coastal zones. Subsurface instruments are installed concurrently during the packing process. The fifth step entails planting vegetation following appropriate population dynamics and placing any other environmental clutter or objects of interest to finalize the synthetic environment. The plants are provided ample time to establish themselves and recover from the stress of being transplanted prior to the start of the experiment. When everything is ready for testing, the test-bed will be raised into place from below the wind tunnel test-section so that the soil surface is flush with the floor of the wind tunnel (Figure 2); any atmospheric or surface sensors are installed and the test-section sealed tight. The climate controls are next engaged and the climate scenario initiated, creating a self-sustaining environment in which to manipulate and or observe. Conditions are monitored continuously throughout the experiments and manual measurements made on a as need basis according to the experimental objectives.

4 WIND TUNNEL MODELING OF THM PROCESSES

SENSE strives to adapt and innovate in light of the changing experimental research and engineering needs of the USACE, the U.S. Armed Forces, and the United States as a whole. The research facility desrcribed above can support a number of different applications or end uses related to fate and transport modeling, biophysical processes, wind engineering, aerodynamic testing and sensor/material prototyping testing and evaluation. The facility is furthermore, well suited for supporting a number of different geotechnical and geomechanical applications where atmospheric conditions have either direct or indirect impacts on THM processes. Example relevant problems include:

- Permafrost heave/thaw
- Aeolian and water driven particle transport
- Matric suction
- Slope stability
- Heat induced desiccation cracking
- Gas induced subsidence
- Vegetation impacts on erosion

Results from a recent dust suppression study performed at the SENSE research facility are presented below to provide a demonstration of its various uses in THM applications. Fugitive dust emissions from bare earth surfaces are a significant concern as it can cause ablative damage to mechanical assets, create brown out operating conditions and pose inhalation hazards (McAlpine et al., 2010; Sing & Sing, 2010). Airborne dust can be reduced by binding fine soil particles onto larger particles that cannot become airborne; example additives/binders include hydraulic cement, petroleum-based and organic hydrocarbon palliatives, hygroscopic/humectant materials and liquids adequately affecting surface tension.

A series of experiments were performed in the SENSE wind tunnel to test the performance of a new commercial palliative, in reducing aeolian transport in two different soils (a fine- and coarse-grained sand). A 45 cm wide, 10.6 cm tall undulation spanning the width of the wind tunnel test-section was constructed out of foam board as shown in Figure 3. A 20.6 cm gap was left in the center of the model which was filled iteratively with untreated and treated soils. The model created a flow blockage that caused the flow to accelerate over the top of the undulation. This provided additional kinetic energy to lift soil particles whenever flowrate was above and individual soil's threshold velocity, or the minimum velocity for inducing particle transport (Table 2). Note that the threshold velocity was determined by incrementally increasing the fan speed until particle lofting was observed from a small sample placed within the test-section.

Figure 3. Model undulation with (a) untreated soil core and (b) treated soil core.

Table 2. Soil threshold velocities

Soil	Velocity [m s^{-1}]
Fine Grained Sand	8.00
Coarse Grained Sand	8.41

During each experiment, the drive fan's speed was increased to its maximum operating value (i.e., 9.6 m s^{-1}) and the soil allowed to erode freely for 120 seconds. Laser Doppler Anemometry measurements showed that the velocity at the crest of the undulation was 10.63 m s^{-1}, well above the soils' threshold velocities.

Surface deformation was monitored throughout each experiment iteration (Figure 4) using an Intel RealSense D455 depth camera mounted to the wind tunnel's automated traversing system positioned above the model. The rainbow plots shown in top portion of Figure 4 correspond to elevation maps with blue and red denoting the highest and lowest elevations, respectively. At the start of the experiments, the crest of the soil core and foam sides were equivalent (i.e., solid dark blue band). Soil loss due to wind driven erosion lowered the height of the soil core as indicated by the lighter blue color. Direct comparison of the results show that the undulation comprised of the fine sand was more susceptible to erosion as expected according to the findings in Table 2.

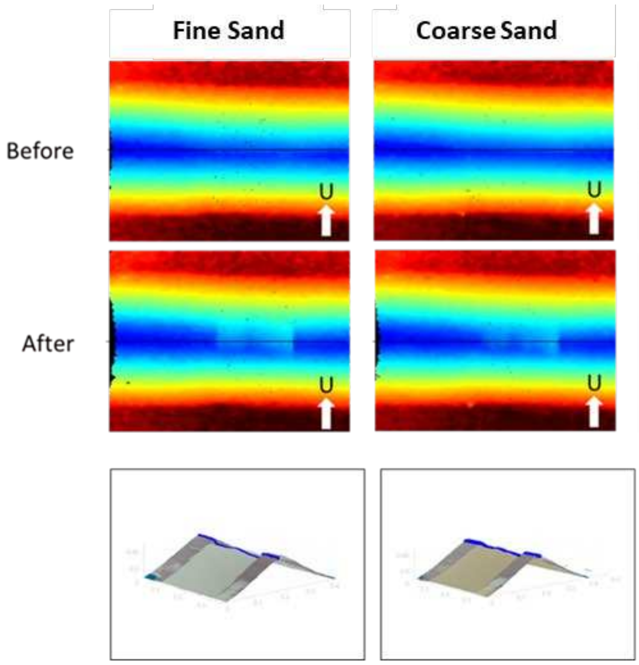

Figure 4. Erosion results from the untreated soil tests as measured by the D455 depth camera.

The D455 measurements were converted to a point cloud that were in turn, segmented into thin slices spanning the width of the soil core as shown in the bottom part of Figure 4. These slices were integrated accordingly as follows to calculate the total eroded soil lost from the undulation:

$$V_l = \sum_{i=1}^{N} w_i \int_0^{20.6} S_{i,t=0}(y) - S_{i,t=120}(y)\, dy$$

where i is the number of a given slice with thickness , w (cm), S (cm) the surface elevation measured at the start and end of the measurement period, and y (cm) the position across the width of the soil core. Results showed that the fine sand and play sands lost 155 cm^3 and 107 cm^3, respectively. No measurable soil loss was observed in the case of the treated soils, indicating the effectivenes of the soil palliative in supressing aeolian transport. The application of the additive created a thin crust only a few sand grains thick. The individual soil grains in this crust were bound together and immobilized with sufficient strength so as to resist wind shear, exactly as desired.

5 CONCLUSIONS

SENSE is a new experiment research facility, centered around a closed-circuit, climate-controlled wind tunnel that is operated by the US Army Engineer Research and Development Center in Vicksburg, MS USA. While the facility can support traditional wind engineering and aerodynamic testing applications, its unique design feature – a test-section with removable floor – expands its range of uses. Large test-beds of varying sizs and packed with any granular media, vegetation, and fluids of interest can be interfaced with the test-section from below. When combined with the wind tunnel's climate control capabilities, researchers are able to create well-defined and carefully controlled synthetic geo-environments (i.e., simplified representations of real-world environments and climates) which can be used to explore fundamental THM processes and test/calibrate sensors.

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