Case Study: 2D Shape Sensing of Bored Tunnel Soil Settlement

Sensuron, LLC
+1 512-827-2040
info@sensuron.com
www.sensuron.com

Table of Contents

1 Introduction

The world's underground infrastructure is ever growing. Subway and underground train networks are expanding, mining, drilling, and fracking exploration is accelerating, and the vast land beneath us is being increasingly utilized as a safe storage space. These and many other subsurface engineering projects require dirt and rock to be bored and removed, resulting in large excavated voids in the Earth's crust. These trigger a redistribution of stress and settling of the surrounding soil. It is critical to understand the nature of this settling to confirm the short and long-term integrity of the underground project, to determine reinforcement requirements, and to ensure the safety of nearby underground and surface structures.

The Sensuron technology was recently utilized to measure the settling movement related to a metro boring project in Beijing, China. A 2D sensor was placed in a reduced scale boring test setup to measure the soil displacement resulting from a simulated excavation process. The existing methods of Digital Image Correlation (DIC) and electronic-based displacement sensors, due to their inherent limitations, are unable to produce the desired measurements within the test volume. The fiber-based 2D shape sensor acquired an accurate soil displacement distribution along a continuous line of the surrounding soil and provided sub-millimeter validation of their settling models.

2 Experimental Setup and Description

Testing was carried out using a 2D shape sensor that was approximately 3 meters long. A Sensuron 2D shape sensor consists of a thin, flexible beam with one or more optical fibers bonded to the beam's top or bottom surfaces. Depending on the length of the 2D sensor, each optical fiber is comprised of hundreds to thousands of fiber optic strain gauges. When the beam is flexed, the measured bending strain distributions are used to obtain a spatially continuous measurement of the beam's bending radius. Using these values, a 2D displacement profile is derived along the beams' entire length. The 2D sensor is constructed to be inherently self-compensating for temperature even if temperature gradients are present along the beam's length. A layer of heat shrink was applied around the beam to protect the fiber installation from damage. Figure 1 illustrates the core capability of Sensuron's 2D shape sensing solution.

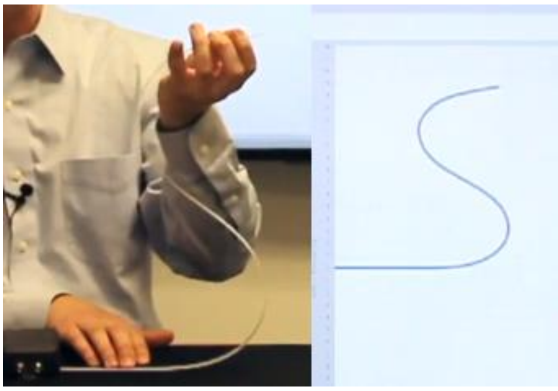

Figure 1: Sensuron 2D shape sensing

To simulate the post-boring settling process, an acrylic chamber was filled with a sand, soil, and rock mixture which represented a scaled version of Beijing's underground material. The acrylic volume contained a cylindrical hole near the mid height of the container to allow for a variable-diameter cylinder to be inserted. The soil mixture was filled in around this cylinder to create the bored tunnel. Once the volume was entirely filled, the cylinder was slowly reduced in diameter and removed, thus creating a cylindrical void. The team of researchers utilized the Sensuron equipment to obtain a soil displacement profile along a horizontal line located 12 cm above the simulated tunnel. To accomplish this, the 2D beam sensor was buried within the soil volume and positioned at the desired height above the cylinder insert. Figure 2 illustrates the experimental setup.

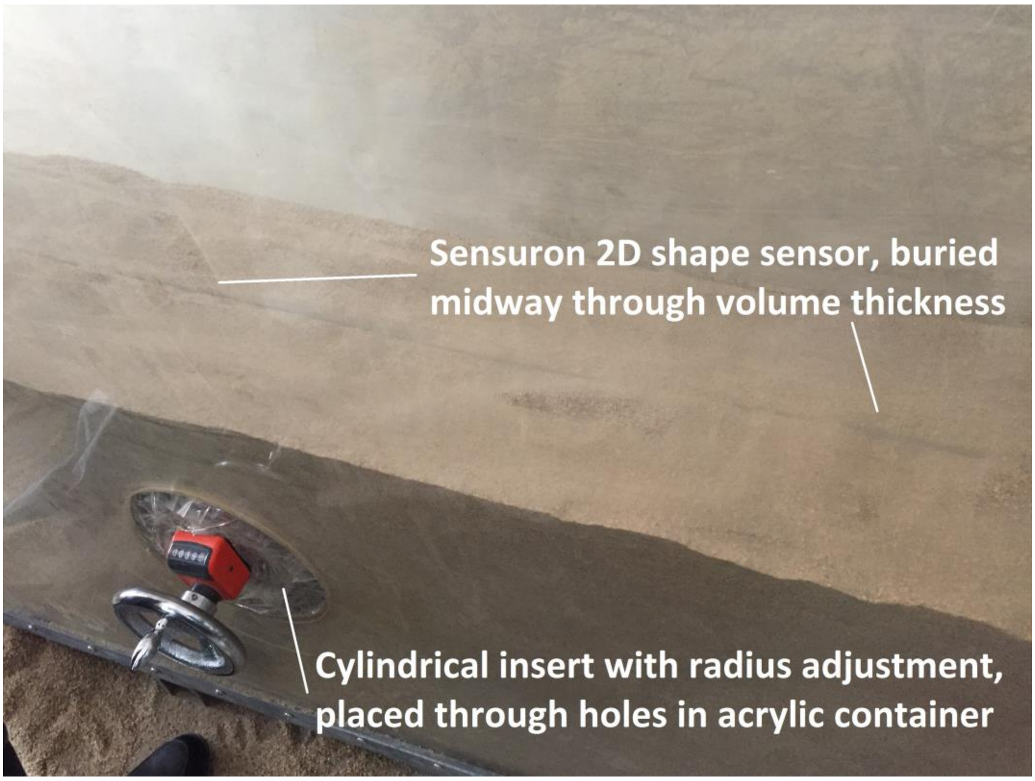

Figure2: Experiment setup

In the figure above, one can see the walls of the acrylic container, one of the holes for the cylindrical insert, the cylindrical insert with radial adjustment, and the 2D beam sensor resting on top of the soil mixture. This image was captured just after the 2D sensor was set in place. Once the remaining volume was filled with soil, an initial measurement was taken as a reference before the cylindrical insert was removed to induce settling. Once the insert was removed and enough time transpired to allow for settling to reach equilibrium, a second displacement measurement was obtained for comparison to the original state.

In this experiment, researchers were interested in the absolute displacement from the original state to the final state. This was calculated as the following:

$$d_i = \sqrt{\left(x_i^{reference} - x_i^{measurement}\right)^2 + \left(y_i^{reference} - y_i^{measurement}\right)^2} \qquad (Eq.1)$$

$$i = [1 \dots N] \quad where\ i = 1\ is\ the\ 2D\ sensor\ origin, i = N\ is\ the\ distal\ end$$

Bending strain distributions were measured using Sensuron's RTS125+, and were streamed over ethernet in real-time to a laboratory PC which calculated 2D shape. The 2D displacement profile was recorded and visualized throughout the experiment. The final 2D absolute displacement measurement is shown below.

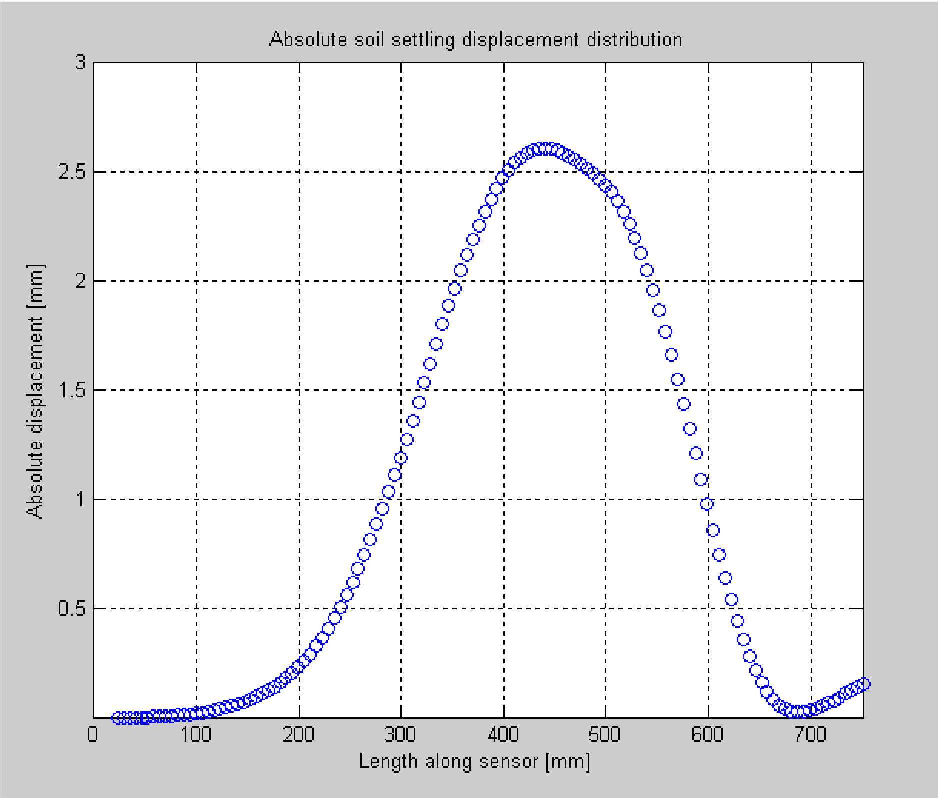

Figure 3: Absolute displacement distribution

The displacement profile shown in Figure 3 was calculated using Equation 1. The x-axis represents the length along the 2D sensor, and the y-axis is the absolute displacement relative to the reference shape acquired after the sensor was buried, the volume was completely filled with the soil mixture, and before the cylindrical insert had been removed. The final measurement was taken after the insert was reduced in diameter and removed, producing a void in the soil. This distribution agreed well with the expected Gaussian distribution indicated by the researchers' soil settling models.

3 Summary

Sensuron's 2D shape sensing system enabled researchers in Beijing to measure soil settlement due to tunnel boring operations in a way not possible with any other technology. Shape and displacement were measured within a volume where the use of Digital Image Correlation (DIC) is not possible due to line of sight restrictions. The equipment also provided spatially continuous information, filling in the large gaps between LVDTs and other conventional techniques. Furthermore, the Sensuron solution provided bidirectional information as opposed to displacements in only the vertical or horizontal planes. The measured displacement distributions agreed well with and validated the researchers' soil settling models, providing them confidence in using them for future work.

Sensuron's 2D shape sensing technology can be applied to a large variety of media or structures which are undergoing changes in their shape. Aircraft, automotive frames, boat masts, surfaces such as plates or shells, sand, soil, concrete, or many other structures and materials can all be instrumented with these sensors to understand the deformations or movement they see in testing and operation.

For more information, please contact info@sensuron.com