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LiDAR Measurements for Surface Profiles of Waste Disposal Units and Application of Digital Twin Technology to DOE Structures – 23050

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ABSTRACT

The objective of this work was to assess Digital Twin Technology and Non-Destructive Evaluation (NDE) methods to complement visual and hands-on inspections of the exterior surface of Savannah River Site (SRS) Saltstone Disposal Units (SDU) which are engineered barriers and containment structures for low-level radioactive grout disposal. Saltstone Disposal Unit (SDU) #7 was selected as a platform for this feasibility evaluation because it is currently an operational facility and construction of this SDU is complete. The current SDUs are ~32-million-gallon concrete tanks in which Saltstone, a low-level salt waste form, is placed for final disposal. The SDU walls are cast in place concrete panels wrapped with multiple layers (352 miles, 566.5 km) of post-tensioning 3/8-inch (9.525 mm) galvanized steel strand. Multiple layers of shotcrete, e.g., sprayed on Portland cement-based concrete/mortar, are used to support and separate the layers of post-tensioning strand. Shotcrete is also applied over the layers of post-tensioned strand as a protective cover for the galvanized steel strand.

Multiple sensors were considered for this study. A high-resolution FARO Focus 3D Light Detection and Ranging (LiDAR) instrument was selected for the initial evaluation. This instrument determines variable distances by targeting points on a surface using a laser and measuring the time for the reflected light to return to the receiver. The FARO-certified resolution for this instrument is 4.2 mm (± 2.1mm). FARO SCENE Visualization Software ed. 2018 was used to evaluate the accuracy of the spatial measurements and to align the point measurement and data into a 3D map for the surface of SDU 7.

This LiDAR instrument was set up at 8 stations located around SDU 7 about 38 ft (11.6 m) away from the SDU's outer surface. A scan of each segment of the SDU was complete in 40 minutes. These point cloud maps were examined for surface uniformity and continuity. Irregularities on the outer surface caused by scaling were visible and examples are provided. In addition, the eight resulting point cloud maps were "stitched" together to create a "water-tight mesh" that was used to generate a solid object which was saved as a Stereolithography (STL) file. The STL file can be used to 3D print a scaled model of the surface.

This NDE method produced useful results and compliments manual sounding inspection (ASTM C805) [3] and photographs by: (1) providing a map of the entire SDU surface; (2) decreasing the time for evaluation and documentation of the entire surface; and (3) providing accurate spatial information for the initial and subsequent surface evaluations. The complete benefits of this NDE method are still being assessed and will require further refinements to implement this technology as part of routine deployment during the construction and filling stages and prior to backfilling and capping the SDF.

INTRODUCTION

Objective

The objective of this work was to provide DOE-EM with a highly accurate surface mapping / data collection method and functional package that can be rapidly deployed and used to characterize the current condition and subsequent changes in the surface of large structures.

In addition, the intent was to identify and resolve deployment issues thereby demonstrating the operational components, equipment, computational hardware and software required to make this type of mapping a routine service at radioactive facilities.

Approach

The concrete structure selected for this study was a large cylindrical tank, SDU 7, located in the Saltstone Disposal Facility (SDF) at the Savannah River Site (SRS). The SDF is managed and operated by SRMC. Currently it is an active radioactive waste disposal facility in which new SDU construction is underway.

A LiDAR FARO Focus 3D instrument was selected as the non-destructive evaluation (NDE) tool for the initial surface mapping. This unit has a high degree of accuracy and can make measurements with resolution to within ± 2 mm.

LiDAR data can be used to generate highly precise time specific "digital twin" representations / maps of surface features. Data registers generated from each scan can be compared to those from subsequent scans to generate a "Time Machine" evaluation (seamless scanning – forward and backward - over the time period under review). This capability enables evaluation of processes that have occurred over time. Monitoring the surface features over time, when coupled with complementary observations and data, can be used to predict changes in the surface of the structure.

Background

The SRS SDUs are used to store/dispose saltstone, a low-level radioactive grout waste form produced for DOE by Savannah River Mission Completion (SRMC). The current SDUs are 32 million (1.2E08 L) gallon cylindrical concrete tanks. See Fig. 1. Currently three tanks are complete and a fourth SDU 9 is under construction. See Fig. 2.

Each large SDU has between 10 to 6 layers of shotcrete around the outer circumference of the concrete tank dependent upon height above the floor slab. Prestressing wire is wrapped around the tank with the number of strands applied calculated on the basis of hydraulic head. At the base of the wall, six layers of prestressing strand are applied. The number of layers of strand is reduce in a taper such that at the upper wall elevation, only two layers of strand are applied. The functions of the inner layers of shotcrete are to provide (1) a surface on which the post tensioning strand is placed and (2) separation and support for each of the layers of strand. The function of the outer shotcrete layers which is approximately two inches thick is to provide corrosion protection for the post tensioning strands. Approximately 352 miles (567 km) of galvanized 3/8-inch (0.953 mm) steel strand is used in construction of each of the 32 M gallon SDUs [2].

Fig. 1. Aerial view of the Saltstone Disposal Facility and locations of the existing and planned Saltstone Disposal Units. As of November 2022, Savannah River Mission Completion has complete SDU 8 and SDU 9 is well underway.

Fig. 2. SDU 9 under construction Summer 2022.

At the time of this evaluation, map cracking was observed on the outer shotcrete layer of Tank 7. The condition of SDU 7 at the time this request was made is shown in Fig.3. The outer layer of shotcrete delaminated near the bottom of one side of the tank. See Fig. 3. These features posed no structural issues to the SDU but were useful references for evaluating the accuracy and precision of the LiDAR mapping.

Fig.3. SDU 7 March 2022.

The standard methods used by SMRC for assessing the SDUs exterior surface are visual inspection and the ASTM C803 Schmidt hammer rebound method for detection of irregularities such as subsurface debonding. Neither of these methods are remote and both require proximity of the technician to the concrete surface. Other issues include localized data collection versus entire surface evaluation, manual data processing, provision for an elevated working platform, testing time and cost.

NON-DESTRUCTIVE EVALUATION METHODS

There are a multitude of NDE sensors that had the potential of being used for surface inspection of SDU 7. The following were initially considered: ultrasonic concrete testing, ground penetrating radar (GPR), additional rebound (Schmidt) hammer testing, Light Detection and Ranging (LiDAR) mapping, and short-wave infra-red (SWIR) sensors. The ultrasonic concrete test required contact or close proximity to SDU 7. The ground penetrating radar (GPR) had a larger range of options. Most require close proximity to the structure, but some have the capabilities of being deployed remotely using a drone as the transportation method. Unfortunately, the shotcrete layers are < 19 mm (0.75 inches) which is not thick enough for an accurate reading and would acquire unreliable results.

The Schmidt hammer test is currently being used as the NDE method for the structural integrity of the SDUs. This method requires preparation of the surface, a dry (no humidity is allowed and no rain) area, and repetitive hits in the same area throughout the SDU. This process requires a large amount of time and personnel to complete and analyze.

LiDAR scans the outer surface of the structure use laser light and time-of-flight calculations between the laser being emitted and the sensor receiving the reflected light feedback. This analysis can be done without any contact with the SDU surface and can have an accuracy of millimeters. Another potential NDE instrument / sensor is a Short-wave infrared (SWIR) camera. This sensor detects anomalies that are typically not visible, such as humidity spots, millimeter cracks, and chemical alteration of differences on the surfaces of materials.

After studying the different NDE sensors, LiDAR and SWIR were selected as methods for a further structural inspection in addition to the current Schmidt hammer test. The SWIR camera selected was from Vision Systems, model Acuros 1930L (Fig. 4) along with a 9 mm lens. This instrument was sent as a demonstration for a non-cost trial to SRNL's site. Unfortunately, the camera was not received on time and the demo was not completed. However, this sensor is widely a used for detecting surface chemistry by the Department of Defense for weapons accuracy and by private industry for concrete and structural material inspections.

Fig. 4. Vision Systems Acuros 1930L SWIR

The LiDAR used was the FARO Focus 3D shown in Fig.5, is a commercial LiDAR sensor with its own proprietary software algorithm [4]. This sensor was available at SRNL and met all requirements of accuracy. The FARO Focus 3D has a Ranging error of two millimeters (plus or minus), the capability to collect billions of points of data, RGB color applied to each corresponding point, Global Positioning Systems (GPS), compass, and automatic registration. The maximum distance capable of scanning is over 20 meters. This sensor is also capable of being used outdoors (high temperatures or rain).

Fig. 5. FARO Focus 3D

SDU 7 LiDAR Mapping

Before deploying the LiDAR in the SDF, the number of stations needed to obtain full coverage of the SDU 7 exterior surface was determined geometrically with the understanding that the goal was to collect as many data points as possible without excess redundancy. This was accomplished with 8 LiDAR instrument locations spaced orthogonally from the exterior SDU 7 surface about 38 feet or (11.5 m) from points about 70.7 ft (21.5 m) apart around the circumference of SDU 7 and the final station set up is shown in Figure 6. The location of each scan is shown in Fig. 6.

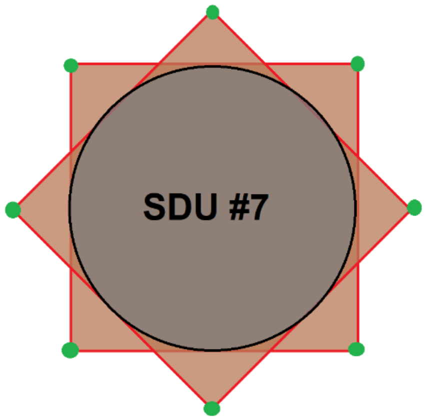

Fig. 6. The location of each scan is shown in Figure 6.

The calculations for determining the distance (r) of each station from the surface of the SDU are provided below.

The diameter, D, of the SDU is 180 feet (54.864 m). The radius R of the SDU is ½ the diameter. The variable r is distance beyond the surface of the SDU that will extend the radius to form an equilateral triangle with the long side tangent to the SDU. See Fig. 6 and Fig. 7. It will inform how far the LiDAR needs to be positioned away from the SDU surface to achieve complete surface coverage with minimal overlap. The distance O-C is R + r (calculated between the surface of the SDUs and the LiDAR is to be about 38 feet or 11.5 meters.

Equation 1. $PO = R = \frac{D}{2} = 90\ ft = 27.432\ m$

Equation 2. $OC = R + r = 90\ ft + r = \sqrt{PO^2 + PC^2}$

Equation 3. $PC = \sqrt{r^2 + 2Rr}$

Equation 4. $cos(45°) = \frac{PC}{OC} \equiv \frac{1}{\sqrt{2}} = \frac{R}{R+r}$

$$r = 37.2792\ ft = 11.3627\ m\ or\ \ 38\ ft$$

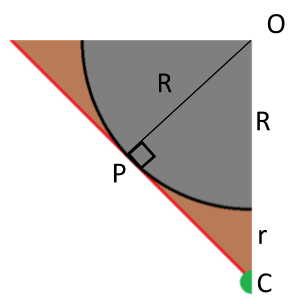

Fig. 7. Mathematical representation of determining station locations.

Once the LIDAR set up locations were calculated and marked, scans of SDU 7 were completed at all eight locations in 5.5 hours. LiDAR measures distance by calculating how long it takes a pulse of light energy to return to the sensor. LiDAR data is an extensive collection of data points consisting of millions of accurate 3D points (X, Y, Z) with other attributes like intensity, classification of features and global positioning system (GPS) time which are essential and supplemental information. The data product for a LiDAR scan is referred to as a point cloud. Post processing these data can be performed in many ways for a wide range of outputs. Creation of digital twins at various time intervals is one application that results in a highly accurate, easily accessed library of a structure and can be used for "Time Machine" analyses.

Digital Point Cloud Data Processing

The SDU 7-point cloud data were downloaded onto a computer for post-processing using FARO proprietary software, FARO SCENE, which analyzed the data collected in each of the 8 scans and reconstructed it into one point cloud representing the entire object. Uploading the individual scans is referred to as registering the point clouds and the combining the registered point clouds is referred to as stitching. By converting the point cloud to a watertight mesh with no gaps between the points, the data can be saved in Standard Triangle / Tessellation Language (STL) which is format fora standard for stereolithographic computer aided design (CAD) applications such as printing 3-D scaled models.

RESULTS

After receiving the LiDAR, completing laboratory and site training, one week was spent recording the eight scans in SDU 7. Each scan took 40 minutes with a resolution of half and quality of 6X. The original length of the scan was planned to be one hour with a resolution of one and quality of 4X. Unfortunately, due to weather (rain and low sun visibility) the quality of the scan had to be decreased. The working time was six hours including transporting and positioning the LiDAR instrument and tripod to the 8 locations. The total time spent was four days "in the field" at SDU 7. Three people were required for the SDU scans; one person who was knowledgeable on the FARO Focus 3D, one provided physical labor (carrying the instrument and tripod to the 8 locations, setting up postings and marking and roping off the stations), and a radiation protection person since this work was performed in an operating radiological facility.

This NDE method detected distances across the entire SDU with an average accuracy of 2.2 mm. The most incorrect distance in the digital twin was only off by 2.2 mm. The LiDAR instrument was also able to successfully detect any bulging, delamination of the outermost surface layer of shotcrete, surface map cracking (cracks < 1mm wide) and surface color data.

After the scans were collected, the registration was completed, and a digital twin of SDU 7 was created. Fig. 8 shows the image of the entire SDU 7 digital twin. A localized area where delamination of the outer ¾ inch (19 mm) sacrificial layer of shotcrete occurred is shown in Fig. 9. The LiDAR instrument used in this NDE demonstration provided the surface texture and color difference data for the bulk shotcrete surfaces and accurate layer thickness measurements with ≤ 2 mm resolution.

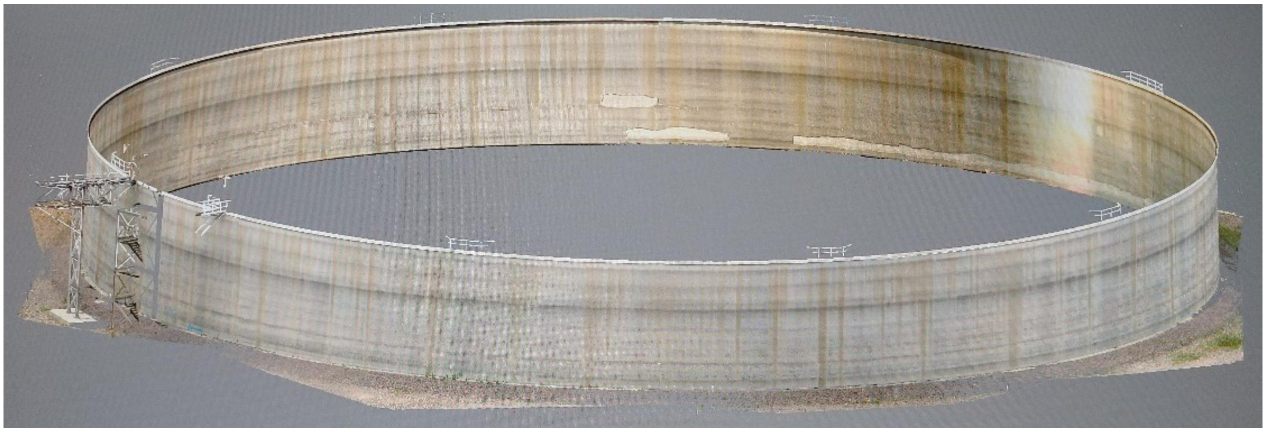

Fig. 8. Digital Twin of SDU 7.

Figure 9. Delamination of Layer 8 of SDU 7.

CONCLUSION

Mapping the surface of SDU 7 provided the opportunity to develop a low cost, rapid NDE package including post processing capabilities that supports the SRNL NDE portfolio.

LiDAR surface mapping of a large concrete structure was demonstrated to be a useful NDE method that has applications in documenting physical features of structures in locations that can pose access challenges. NDE mapping was demonstrated for SDU 7, a large concrete structure, located at SRS in the SDF, an operating low level radioactive waste disposal facility. The LiDAR mapping was completed in 6 hours and provided high resolution data over the entire 22,608 ft^2 (2100 m^2) surface of SDU 7. These results compliment those obtained by the ASTM C803 Schmidt hammer rebound method which was used to spot check localized regions suspected of outer shotcrete layer debonding.

This effort demonstrated that LiDAR measurements and data processing and surface analysis of large industrial structures can be performed rapidly and remotely. Future areas in the DOE-EM complex where LiDAR NDE may provide useful information include 1) nuclear facility deactivation and decommissioning, 2) radioactive landfill mapping during interim closure and post closure, 3) environmental restoration monitoring, and 4) new construction documentation. With minor modifications to this demonstrated study, LiDAR may also be useful for remotely monitoring operating radioactive disposal facilities.

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