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Structural health and performance monitoring of floating cover at the western treatment plant: Our chronology

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Abstract. This paper provides a historical overview of the development of a diagnostic tool and its integration with the operational characteristics of a floating cover for structural health assessment and performance monitoring in terms of biogas harvesting of the floating covers at the Western Treatment Plant, Melbourne, Australia. Large membrane-like covers used in several environmentally sensitive application contexts, including (i) floating covers for clean water reservoirs, to prevent evaporation and pollution, (ii) landfill liners to stop leakage of hazardous chemicals or harmful matter, (iii) mining applications such as heap leaching, salt evaporation ponds and tailings impoundment are high value assets. Floating covers for anaerobic reactors in wastewater treatment plants are also constructed with these membrane structures. The covers on the anaerobic lagoons at the Western Treatment Plant, west of Melbourne, Australia is a large structure whose construction and installation costs mounts to tens of millions of dollars. They are used to collect biogas emitted during the anaerobic digestion of the raw sewage beneath the cover making it an important asset from an environment standpoint. The research team were provided with an opportunity to develop a diagnostic tool to assist with the safe and efficient operation of this critical asset.

Introduction

Large membrane-like covers are used in several environmentally sensitive application contexts, including (i) floating covers for clean water reservoirs, to prevent evaporation and pollution, (ii) landfill liners to stop leakage of hazardous chemicals or harmful matter, (iii) mining applications such as heap leaching, salt evaporation ponds and tailings impoundment [1], in addition to being used as floating covers for anaerobic reactors in wastewater treatment plants. These covers are high value assets whose construction and installation costs mounts to tens of millions of dollars. This floating cover will also benefit the environment as it is used to collect biogas emitted during the anaerobic digestion of the raw sewage and convert it into electricity which is used at the plant. In this respect, the research team was presented with an opportunity to explore the relevance of recent advances in structural health monitoring technologies with the aim of transitioning them into innovative engineering and maintenance practices to ensure the safe and efficient operation of this large critical infrastructure.

Floating covers are used at Melbourne Water's Western Treatment Plant (WTP) in Werribee, Victoria, (see Figure 1). The floating covers are made from a high-density polyethylene (HDPE)

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material that is extremely durable. It is estimated from accelerated testing that HDPE geomembranes should have a service life of over 300 years at 20°C, and over 45 years at 40°C [2-4]. Consequently, well-designed HDPE geomembranes should have long trouble-free lifetimes. However, the mechanical performance of HDPE in real life can be difficult to ascertain [5]. Upon the untreated wastewater entering these anaerobic lagoons solidified matter (i.e., scum) can develop and accumulate under the covers into heaps also known as **scumbergs** that press against and lift the covers. This deformation has a length scale of around one metre in the vertical direction (uplift) and several metres laterally. The scumbergs can be displaced laterally due to hydraulic loading from incoming sewage, which gives rise to excessive cover displacement and mechanical stress, and in the regions in the vicinity of the welded joints (see also [5]).

Figure 1: Anaerobic lagoons at the Western Treatment Plant

The covers typically span an area of 470 m x 200 m, as illustrated in Figure 1. All sewage inflow is unscreened and passes first through an anaerobic reactor. As the raw sewage undergoes anaerobic digestion, biogases are produced, which are trapped below the floating cover and harvested for electricity generation. The formation of these scumbergs is also known to distort the biogas channels built into the cover and can affect the efficiency of the collection of this valuable renewable energy source. Therefore, it is imperative that this critical asset be managed and maintained to operate safely and efficiently. This cover will bring about significant environmental, social, and economic savings because, without it, the odour and biogas will be released into the atmosphere. The ability to collect the biogas makes this floating cover an important renewal energy generating asset. In addition, effective integrity management and maintenance of the floating cover is useful in planning for future cover replacement program, and the potential of delaying its replacement. These will bring about millions of dollars of savings to the asset operator. An efficient integrity assessment ability will assist and improve current maintenance practice that involves simple visual walk-around inspection, which is subjective and time-consuming, but, more importantly, does not provide advance warning of possible failures, or clear indications of distress in the covers.

This paper provides a historical account pertaining to a series of collaborative projects conducted to develop a non-contact technique to assist with the structural integrity assessment and the performance management of these covers. It will describe an approach developed for monitoring these floating covers using an Unmanned Aerial Vehicle (UAV) equipped with optical cameras and GPS tracker, to measure the displacement field of the floating cover, and, from that information, determine the state of its structural integrity or “physical health” (e.g., stress and deformation). Photogrammetry has been shown to be a low cost, safe, and effective tool for terrain mapping [6]. This paper will provide a historical account of the work performed by the multi-disciplinary team that explored the feasibility of a non-contact assessment technique to assess the integrity of the floating cover, and to monitor the development of scum and formation of scumbergs beneath the floating cover. It will also discuss the potential of integrating the diagnostic tool with the operational characteristics of the floating cover to derive a performance monitoring tool for this critical asset.

Non-contact assessment of cover deformation

A research program was developed to investigate into the use of unmanned aerial vehicles (UAV) to overcome the physical size (400 m x 200 m) of the asset and the hazardous environment. This non-contact means of assessment have the potential to reduce, if not remove, the requirement of a person walking on the cover to conduct an inspection of the asset. From a safe work practice standpoint, this is also highly desirable. The investigations led to the development of a UAV-enabled photogrammetry assessment technique that has been verified to be capable of determining the up-lift of the floating cover due to the scumberg accumulation [7-11]. The work presented in [11] highlighted the transitioning of the exploratory tool to engineering practice. Figure 2a – 2g shows the time-progression of the floating cover vertical displacement created from the optical images acquired by the UAV over the floating cover at the Western Treatment Plant. The digital representation of the floating cover is useful in determining the accumulation of scum-berg beneath the cover.

It is postulated that the scumberg when formed can adhere to the membrane. The continual inflow of raw sewage will displace these scumberg resulting in the lateral movement of the membrane, causing it to wrinkle. These wrinkling patterns are determined by the inflow conditions. The digital model of the floating cover can be analysed to reveal the extent and the progression of the cover wrinkles. These results provide useful information to inform the operator of the asset on the effects of the inflow conditions on the deformation of this critical asset [11].

The development of scum and formation of scumbergs is also noted to distort the biogas channels built into the cover. Therefore, it can affect the efficiency of the collection of this valuable renewable energy source. An ability to estimate the depth and extent of the scumberg formation and how it affects the biogas collection is useful in establishing the performance of this asset. These field measurements are currently being performed by the human operator walking and working on the floating cover to determine the depth of the scum at pre-determined locations. This information is integrated with the digital representation of the floating cover. As described in the work reported in [12], the research team has proposed a machine-learning capability to predict the total volume of the scum under the covers. Work is in progress on linking these datasets to the biogas collection. A brief outline of this work is discussed in a later section of this paper.

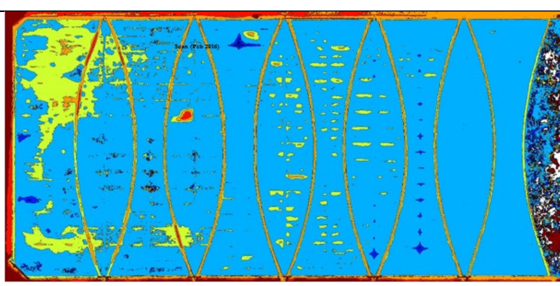

Figure 2a: First scan (Date, D)

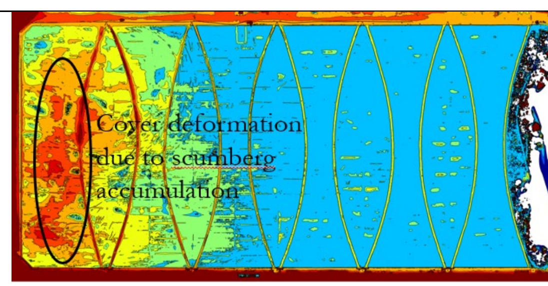

Figure 2b: Date of scan ($D_1 = D + 2$ years

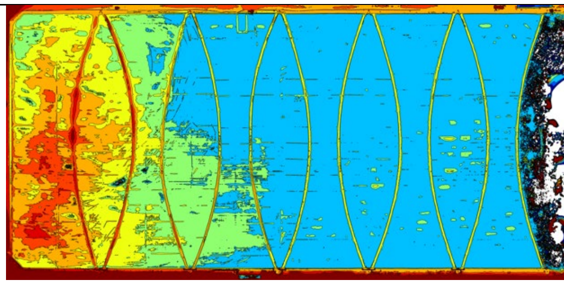

Figure 2d: Date of scan ($D_3 = D_2 + 3\ months$

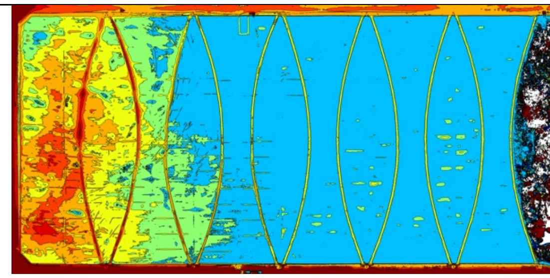

Figure 2c: Date of scan ($D_2 = D_1 + 1\ month$

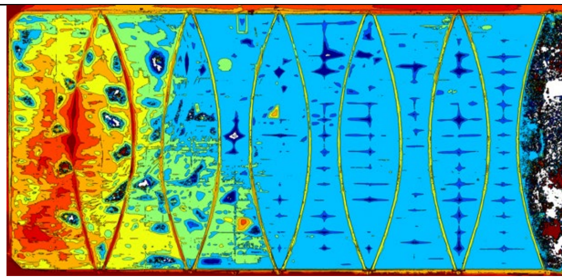

Figure 2e: Date of scan ($D_4 = D_3 + 3\ months$

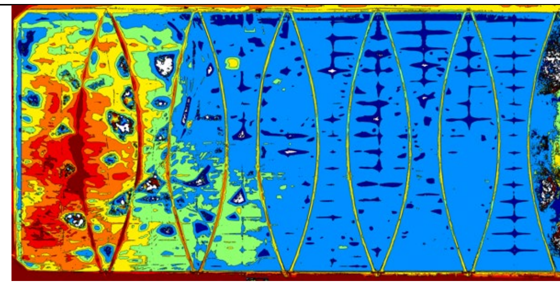

Figure 2f: Date of scan ($D_5 = D_4 + 3\ months$

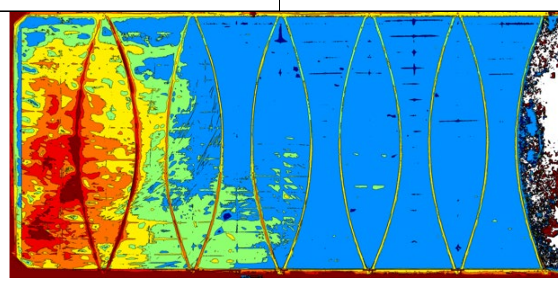

Figure 2g: Date of scan ($D_6 = D_5 + 3\ months$

The UAV-enabled photogrammetry provides a series of optical images of the floating cover. These optical images are processed to yield the ortho-photo of the floating cover. An opportunistic approach was tested to ascertain the ability of using these outputs to determine the global in-plane displacement of the floating cover. Wong et al. in [13] presented a finite element-based formulation that uses the information from the optical images to track the motion of known artefacts on the floating cover. By analysing the principal components of the in-plane motion, the results yielded regions of membrane stretch and regions of membrane wrinkles (see Figure 3). Given that the state of strain of the floating cover is unknown during installation, the ability to estimate this global in-plane motion is helpful in assessing the impact of the development and motion of the scum. The results shown in Figure 3 are the maximum principal component of the relative in-plane displacement predicted with respect to a pre-defined start time. The formation of wrinkles is depicted by the "blue" regions. The regions of global membrane stretch are represented by the "red" regions. In this respect, the regions of expected tensile loading and the extent of wrinkling can be determined. The progression and the geometry of the wrinkled region and the extent of membrane stretch are evident in these results, thereby providing a global perspective into the response of the cover. This will be integrated in our current work to develop a global-local algorithm to provide local strain information on the critical regions of the floating cover.

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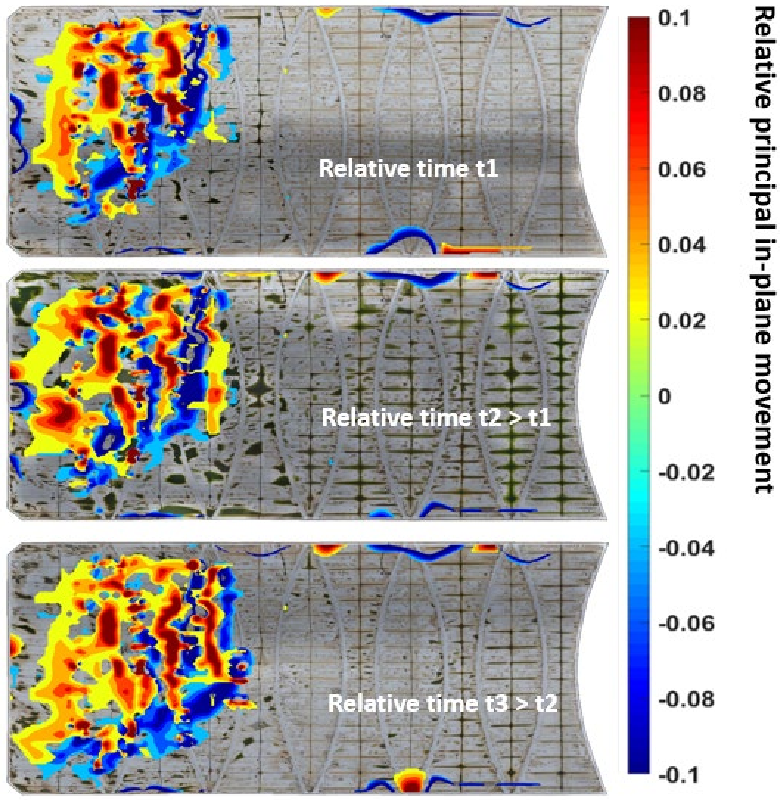

Figure 3: Time progression of wrinkle plots with respect to a reference time.

Non-contact assessment of scum formation beneath the floating cover

A research opportunity also arose to develop a capability to predict the state of scum formation beneath the opaque floating cover. Given the flat and open terrain at the Western Treatment Plant, the research team developed a non-contact quasi-active thermographic technique to predict the state of scum formation beneath the cover. A series of laboratory scale experiments were conducted on a roof-top test area [14-16]. The scum beneath the floating cover is known to transition from a liquid state to a soft and fluffy state and eventually to a solid and hard state. The work presented in [15] shows the workings of a thermographic methodology that utilises the transient thermal response of the membrane/matter composite during the sunrise and sunset to determine the presence of solid material on the underside of the membrane. Figure 4 shows a three-day experiment conducted with a membrane specimen applied over a region of soil to simulate scum-berg. The test rig was exposed to ambient sunlight at a roof-top area. The solar radiation and the thermal response of the membrane over the three days are shown in Figure 5. Additional soil was added each morning to simulate scum-berg growth. The algorithm developed in [15] was used to predict the extent of the soil development under the cover. Figure 6 shows the actual soil extent and the predicted region when analysing the thermal response over the membrane. A series of finite element analyses were presented in [16] to show how this technique can be extended to determine the state of scum formation beneath the cover.

Figure 4: Test fixture showing installation of simulated scum-berg and membrane over simulated scum-berg

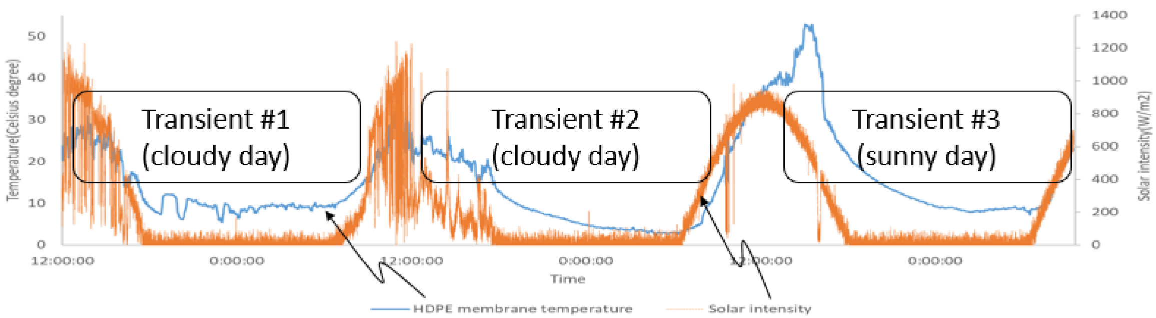

Figure 5: Thermal response and the solar intensity plots during the 3-day experiment

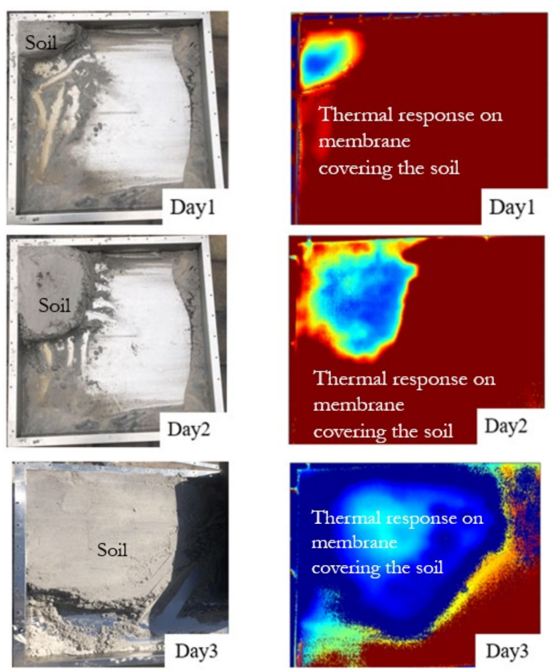

Figure 6: Physical simulated scum-berg and the predicted scum-berg extent derived from the membrane surface thermal response

Towards asset performance monitoring – from diagnostics to prognostics

The floating cover on the wastewater treatment lagoon at Melbourne Water's Western Treatment Plant (WTP), in Werribee, is a critical asset whose primary functions are to allow for the anaerobic breakdown of organic matter in the raw sewage and to collect the biogas that is released during this process. The work outlined above is focused on the development of asset-based diagnostic capabilities to understand how the floating cover respond to the prevailing physical conditions [10, 17, 18]. An opportunity exists to couple these diagnostic capabilities with service-based performance requirements. The aim is to derive a new coupled capability for the structural health and performance monitoring of this engineering structure. This new monitoring strategy will incorporate a machine learning capability to predict the biogas collection rates based on past operational decisions and conditions. The study presented in [19 20] presents a series of work pertaining to the development of machine-learning capability including a Bayesian Long Short-Term Memory neural network model. The aim is to investigate the effectiveness for the probabilistic prediction of biogas collection rates at Western Treatment Plant. The probabilistic approach is based on a Gaussian distribution output layer and Monte-Carlo dropout method to estimate the aleatoric and epistemic uncertainties, respectively. The data pre-processing and optimisation of the neural network model are reported. The findings also indicate using a dropout probability beyond 40% adversely prevents learning of complex patterns in the data and overly regularises the network model prediction. The study serves as a fundamental basis in implementing machine learning to transit high-value assets into smarter structures with diagnostic and prognostic capabilities by providing an example where service requirements are also considered.

Practical implications of the research outcomes

The floating cover is a high value asset whose construction and installation costs mounts to tens of millions of dollars. One of its critical functions is to protect the environment as it is used to collect biogas produced and released during the anaerobic digestion of the raw sewage. Therefore, this cover will provide significant savings on environmental, social, and economic aspects by controlling the odour and biogas without releasing into the atmosphere. Moreover, this floating cover becomes an important renewal energy generating asset due to its ability to collect the biogas. In this respect, an effective integrity management and maintenance of the floating cover will deliver the above-mentioned benefits, these intelligent strategies are also crucial for planning future cover replacement program. In addition, a knowledge of the behaviour of this floating cover during its service lifetime will also be useful in life-extension decision making with the potential of delaying its replacement. These acquired knowledge will also serve as guidelines to future cover design. These will bring about millions of dollars of savings to the asset operator. This efficient integrity assessment will assist and improve current maintenance practice, which involves simple visual walk-around inspection by providing data-based advance warning of possible failures, or clear indications of distress in the covers (i.e., deterministic methods). Therefore, the research team was indeed presented with an opportunity to explore the relevance of recent advances in structural health monitoring technologies with the aim of transitioning them into innovative engineering and maintenance practices to ensure the safe and efficient operation of this large critical infrastructure.

The overview of work conducted in this collaboration has yielded principles and methodologies that have been translated into engineering practice. The data acquired from the UAV photogrammetry capabilities have led to the development of tools that are complementary to and enhance the management of the floating cover. The information pertaining to the elevation of the floating cover and its in-plane translation provide important information on the cover response to the prevailing operational conditions. Ongoing research work is progressing that focuses on integrating these diagnostic tools into an intelligent capability for prognostic decision making.

Conclusion

The historical overview of the development of diagnostic tool and its integration with the operational characteristics of a floating cover to monitor its performance in terms of biogas harvesting is presented. The diagnostic tool and its integration with the operational characteristics will lead to a capability to enhance the management and maintenance practices for the floating cover assets at the Western Treatment Plant. Work is progressing to further develop the machine learning capabilities for an intelligent prognostic decision making tool for the cover performance management at the Western Treatment Plant.

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