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Application of airborne photogrammetry for the visualisation and assessment of contamination migration arising from a Fukushima waste storage facility☆

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ABSTRACT

Airborne systems such as lightweight and highly portable unmanned aerial vehicles (UAVs) are becoming increasingly widespread in both academia and industry - with an ever-increasing range of applications, including (but not limited to), air quality sampling, wildlife monitoring and land-use mapping.

In this work, high-resolution airborne photogrammetry obtained using a multi-rotor system operating at low survey altitudes, is combined with ground-based radiation mapping data acquired at an interim storage facility for wastes removed as part of the large-scale Fukushima clean-up program. The investigation aimed to assess the extent to which the remediation program at a specific site has contained the stored contaminants, as well as present a new methodology for rapidly surveying radiological sites globally. From the three-dimensional rendering of the site of interest, it was possible to not only generate a powerful graphic confirming the elevated radiological intensity existing at the location of the waste bags, but also to also illustrate the downslope movement of contamination due to species leakage from the large $1m^3$ storage bags. The entire survey took less than 1 h to perform, and was subsequently post-processed using graphical information software to obtain the renderings. The conclusions within this study not only highlight the usefulness of incorporating three-dimensional renderings within radiation mapping protocols, but also conclude that current methods of monitoring these storage facilities in the long term could be improved through the integration of UAVs within the standard protocol.

1. Introduction

March 2017 marked the six-year anniversary of the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident that occurred on Japan's eastern coast. Like the Chernobyl accident that occurred twenty-five years earlier, the events at Fukushima were similarly rated at Level 7 on the INES ranking system (IAEA, 2008) – representing a severe incident with far-reaching global ramifications. In these succeeding years, a considerable amount of financial expense has been devoted to the study of the various forms of radiological contamination that were released into the environment, but also (and the focus of this work) in the remediation of the large areas of Fukushima Prefecture that were radiologically contaminated by the event.

The principal radioisotopes of concern are the highly-volatile fission product isotopes of cesium, ^{134}Cs and ^{137}Cs, with half-lives of 2.0652 and 30.1 years respectively. Both of these species are strong gamma-ray emitters – formed as fragments from the fissioning of the uranium dioxide fuel used in each of the plant's six nuclear reactors. As a result of this and the earlier Chernobyl accident, a large number of studies have examined the behaviour of radiocesium within the environment. These studies have confirmed that fine-scale cesium particles have a strong affinity for sorption on to the frayed-edge sites of microscopic clay minerals (e.g.

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kaolinite, montmorillonite and smectite) and fine-scale mica minerals, both of which are common in soils and comprise a significant component of Fukushima-specific soil matrices. Once physically sorbed onto the active-sites, it has been shown that they then remain strongly bonded - even under harsh chemical regimes that would not exist within the environment. It is therefore considered that the transportation of cesium does not occur as discrete isolated particles, but rather in response to the movement of the larger minerals that they are bonded to.

As part of the extensive remediation program that is occurring within the north-west trending plume affected region of Fukushima Prefecture, the uppermost 15 cm of sediment material is being removed from all contaminated land surfaces along with forest and all other organic material. Once removed, this material is placed into approximately 1 m^3 high-density plastic storage bags, before being transported to interim storage facilities ahead of its final (yet to be fully determined) disposal within a long-term storage facility. It has estimated that approximately 30 million tonnes of contaminated soils and wastes will be produced following this large-scale remediation (Japanese Ministry of the Environment, 2012), producing over 10 million bags of waste material. The total cost of this remediation has been estimated to range from JPY1.55–5.12 trillion (depending on eventual dose-reduction and decontamination scenario selected), with upper estimates placed at potentially exceed JPY16 trillion, if all contaminated forest areas were similarly remediated (Yasutaka and Naito, 2015).

Many of these small-scale temporary storage facilities exist, with numerous interim storage facilities (ISF) located across the entire Fukushima Prefecture. They consist of a secured fenced enclosure within which several hundred of the storage bags are carefully stacked - typically between four and eight units high (Fig. 1). Prior to the location of storage bags the storage facility must first be made suitable. This preparation includes the underlining of the entire site with an impermeable geo-polymer before being overlain by a thickness of imported made-ground (Fig. 1). After preparation of each of the facilities is completed, a vent network is installed in order to ensure flammable gases (produced as a result of anaerobic decomposition) do not build-up within the site. Finally, an impermeable cover is placed over the completed stack to severely limit water-ingress.

During facility preparation, the large black waste bags (stacked in an offset-cubic arrangement) are not protected against the effects of water ingress from the typhoon-type meteoric conditions typical of the region (Japan Meteorological Agency) – it is only after completion of preparation works that the site is made water-tight. As well as being classified climatically as typhoon-affected, the topography of the Fukushima Prefecture region also presents several challenges to the remediation effort. In addition to the inherent difficulties associated with the physical removal of material from the landscape, the mountainous terrain associated with the Abukuma Mountains (which constitute a considerable portion of the plume-affected region) represents a further issue with respect to the long-term environmental remediation of the region when combined with the heavy rainfall experienced. As has been concluded in several works (Nagao et al., 2013; Ueda et al., 2013; Yamaguchi et al., 2012) investigating the downslope movement of material (and hence radiation), the enhanced topography is responsible for dramatically increasing the rate at which this transport occurs.

Building from the conclusions and findings of earlier work developing UAV-based radiation mapping techniques (MacFarlane et al., 2014; Martin et al., 2015, 2016a, 2016b, 2016c; Connor et al., 2016), the following text outlines the methods employed to create a three-dimensional (3D) radiation map of an interim storage facility within the Fukushima Prefecture (Fig. 2). The site in question sits around 35 km north-west from the Fukushima Daiichi Nuclear Power Plant (FDNPP). Within this zone, a large number of bags containing contaminated topsoil have been placed for storage, with further bags still to be added at the time of the investigation (October 2016). The process of infilling the bags and placing them on-site takes approximately between 2 and 4 months to complete from initiation. During this time, the site in question experienced anywhere between 494 and 794 mm^3 precipitation (Japan Meteorological Agency), which could feasibly create a contaminant transport pathway downslope of the bale stack. The objective of the current work was to successfully constrain the relationship between the precipitation, topography and distribution of radiological material across the interim storage facility. Low-altitude aerial photogrammetry is employed to create a high resolution digital surface model (DSM), which is overlain with a colour-scaled

Fig. 1. Photograph of a typical waste storage study site within Kawamata (Date District), Fukushima Prefecture, prior to final waterproofing of the structure.