

LiDAR monitoring for the Folkestone Warren landslide

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Abstract

The Folkestone Warren and adjacent sea cliffs have provided considerable challenges to students and practitioners in both engineering and geology since the decision was taken in the 1840s to use this route for the main line between Folkestone and Dover, Kent.

The paper describes the nature of the ground movements and how the monitoring techniques employed within the Warren have been adapted in line with the development of new technologies, including a satellite interferometry trial, focusing on the recent commencement of terrestrial laser scanning.

The effectiveness and limitations in the past and present monitoring will be discussed in relation to the requirements for maintaining the safety of the operational railway.

Geological and historical setting

Folkestone Warren is the name given to the area of coastal landslide between Folkestone and Abbot's Cliff, which occupies an area 3km long and between 50m and 350m wide. The back of the Warren is defined by the High Cliff, which is more than 100m high and composed of Lower and Middle Chalk.

In plan the Warren is cusped in shape and concave towards the sea. The hummocky lower ground within the Warren, known as the Warren Undercliff, comprises entirely landslipped material over which passes the railway. The geological sequence comprises some 200m of strata which dip gently at about one degree towards the north-east, commencing with the ferruginous sands of the Folkestone Beds (Lower Greensand), passing up through the Gault Clay and then into the Lower and Middle Chalk.

These deposits are overlain unconformably by thin and patchy deposits of clay with flints and red and brown sands with ironstones.

The selection of this dramatic coastal route for the railway between Folkestone and Dover was not without some controversy as the engineers were aware of the geological instability of the Folkestone Warren.

However, this route was adopted in preference to a more costly and



Folkestone Warren, between Folkestone and Abbot's Cliff, is 3km and backed by a 100m high cliff

time-consuming inland alternative to satisfy shareholders' aspirations of winning the race against a competing railway company to Dover, and thus secure the lucrative continental traffic.

The line was opened in 1844 amongst great pomp and circumstance with a declaration by the Inspector General of Railways that having inspected the construction of the railway with great attention, he took "...great pleasure in assuring your Lordships, not only that the railway itself is in a perfectly safe and efficient state, but that no part of the works are exposed to the smallest danger, either from the eruptions of the sea, or from the fall of the cliff: though it was natural for the public to have their doubts, in the first instance, as to the success of so arduous an undertaking".

However, the Warren continued to suffer a further seven major landslips two of which closed the line, in 1877 and again in 1915 (Figure 2), when the line was closed for four years.

Ground model

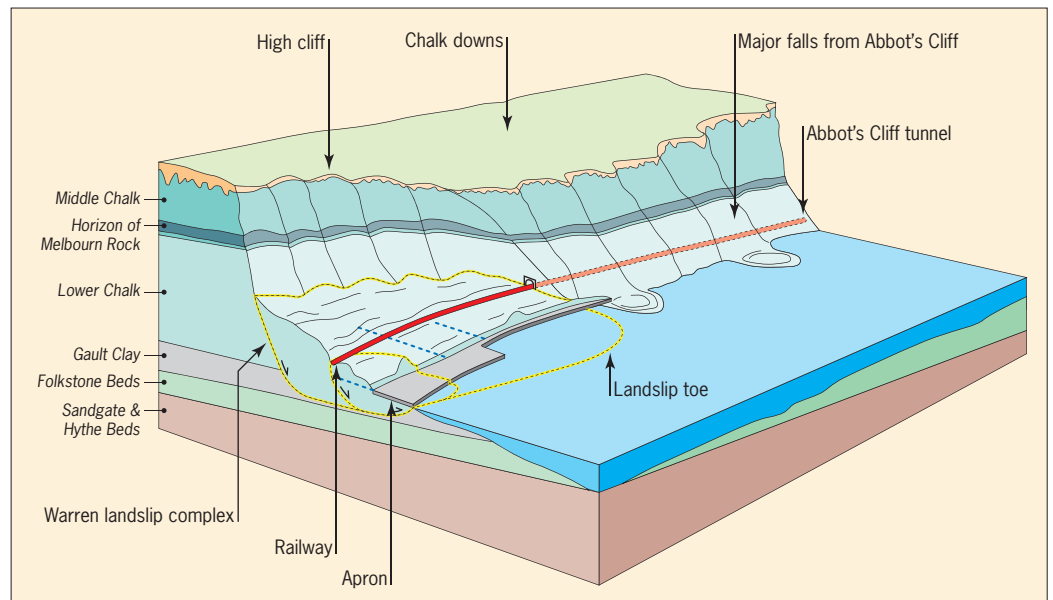
The early perception was that the failure mechanisms within The Warren took the form of circular slip surfaces penetrating into the underlying Gault Clay accompanied

by the settlement of large blocks of essentially intact chalk into the underlying plastic clay. Removal of debris from the advancing toe of the slide was attributed to a process of solution or "chemical denudation".



Figure 1: View east of the major slip in 1915

Figure 2: Generic sketch illustrating the geology and geomorphology of the landslide complex



This 'ground model' has been improved over the years by the commissioning of several periods of ground investigations, laboratory testing, geomorphological mapping and topographic monitoring (Figure 2). These investigations led to remedial works being undertaken including:

- Sea defences – construction of 3km of sea walls, beach groynes and concrete buttresses;
- Beach replenishment – introduction of shingle to counter erosion and loss of toe loading;
- Drainage – construction of some 20 drainage headings from the foreshore;
- Stability enhancement – local re-profiling by moving spoil around within The Warren;
- Toe weighting – construction of concrete apron;
- Rock revetments – placing of large limestone rock armour protection in front of the seawall

These studies have revealed that the ground movements in the Warren comprise essentially a series of 'en echelon' semi-rotational slip masses, hinged about a point at their western corner. The basal shear surfaces of each slip mass are located within various horizons within the Gault Clay sequence, starting with the lowest horizons at the western end of the complex, but migrating upwards through the sequence towards the eastern end of the landslip complex. The larger

slips are accompanied by upheaval of the foreshore into ridges that have later been eroded by the sea.

The slip masses are subject to on-going creep, which continues at an average rate of up to 70mm/year, but increasing locally by up to 1m following prolonged periods of heavy rain. While the slow creep is manageable, periods of exceptional activity, such as over the winter of 2000/2001, give rise to movements which cause damage to concrete structures and distortion to the railway alignment (Figures 3 and 4).

Monitoring strategy

Folkestone Warren was selected by the European Space Agency (ESA) along with a handful of international sites to trial the application of satellites for ground deformation mapping at the 'engineering' scale. The technique, known as Interferometric

Synthetic Aperture Radar (InSAR), uses radar pulses emitted from satellites which orbit the earth at an altitude of approximately 800km.

Any difference in reflectance between successive images can represent ground deformation, which is displayed as interference fringes to which values can be assigned. While accuracies of a few millimetres can be achieved, this is dependant on the following success criteria:

- Suitability of satellite paths;
- Assumptions on earth flow directions;
- Good 'pixel' coherence;
- Good reflection characteristics;
- Availability of a Digital Elevation Model (DEM) for the map base;
- Availability of ortho-rectified aerial photographs to 'drape' over the DEM.

While the use of satellite interferometry showed great

potential for enhancing the geomechanical understanding of ground movements and process rates, the insufficiency of suitable satellite paths and inferior pixel coherence, compromised its effectiveness within the Warren itself. However, useful data was acquired for settlements along the crest of the Warren High Cliff, in the village of Capel-le-Ferne.

Topographic surveys

While conventional topographic methods dominate the base surveys, the system is limited effectively to two sub-parallel survey lines, one along the railway track bed and the other along the seawall (Figure 6). These lines are supplemented locally by points aside from these two survey traces, but ideally one would be looking to regularly scan the entire Warren Undercliff to complete the full 3D picture >>



Figure 3: Severed concrete apron at Horsehead Point in 2001



Figure 4: Track distortion at Warren Halt in 2010

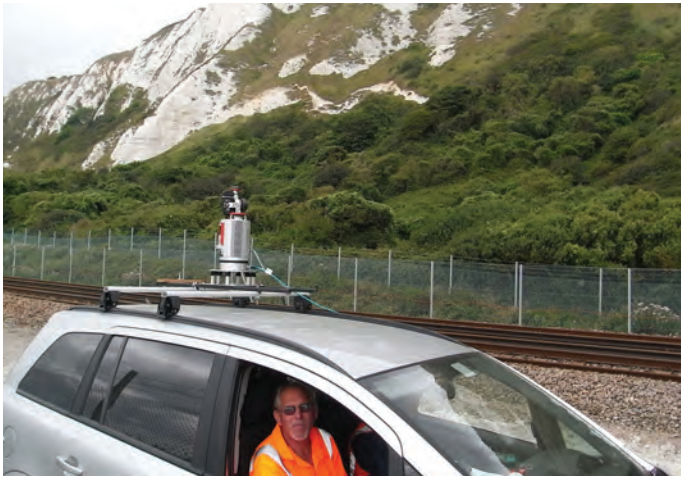


Figure 5: Vehicle-mounted scanner setup

» of ground movements. The principal constraint on this is vegetation density and its sensitivity to disturbance by intruding surveyors equipped with GPS. The relative high vantage points from around the crest of the Warren High Cliff provide scope for LiDAR scanning with the potential to expand the spatial distribution of monitoring points, while at the same time reducing the exposure of survey teams to the dangers of working near a live railway.

Terrestrial laser scanning Methodology

The established point monitoring regime provides a good coverage of point data and importantly provides a quantifiable historic record of deformation movements at Folkestone Warren. For this reason, the recommendation to use terrestrial laser scanning at Folkestone was based on complementing the existing monitoring regime rather than replacing it.

The existing monitoring regime is by its nature and design based on the measurement of specific survey points within the Folkestone Warren landslide complex, and representative points based on known geological structure of the site and locations to which survey teams could safely access. As a result we have a number of precisely measured points, but no comprehensive overview data of the site.

Terrestrial Laser Scanning (TLS) provides a rapid, non-contact method of data collection, giving the capability and opportunity to deliver a comprehensive overview dataset, which can be used for the following:

- To analyse areas of known instability inaccessible to ground based survey team;
- Provide survey data between point monitoring locations;

■ Provides a quantifiable dataset for the management of the landslide.

The Folkestone Warren landslide does, however, present a number of site constraints which need to be considered when determining the type of scanner to be used and the data capture methodology. Of particular note is the actual size of the site, being 3km in length, the extent of vegetated areas and the density of that vegetation, the available tidal window for working on the foreshore area and the public nature of the site and the potential health and safety implications.

Taking these constraints into account, the scanning system would be required to operate at a medium to long range, perhaps up to 400m, provide relatively fast data capture and options for reducing the effects of vegetation. With these as the initial hardware requirements, it was decided that a Riegl scanner would be used, with initial proposals being based around the LMS-Z420 scanner which offered a measurement range up to 1,000m and a measurement speed up to 10,000 points per second. However, prior to commencing the scanning, Riegl launched their VZ-400 scanner, which, while only offering a measurement range up

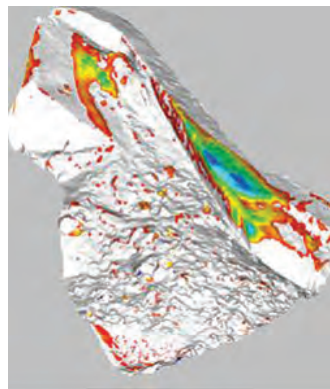


Figure 6: A tripod-mounted setup

to 600m, did offer a measurement speed up to 120,000 points per second, a range accuracy of 5mm and, importantly, echo digitisation and online waveform processing.

The scanner also combines with a high resolution digital camera calibrated to the scanner, which allows coloured pointclouds to be generated with RGB (red, green, blue) values and the texturing of surface meshes. The scanner uses a class 1 eye safe so presents no health and safety issues regarding the use of the equipment within a public area or within the presence of untrained staff. In addition, the laser utilises an invisible beam presenting no visible distraction which could otherwise represent a potential distraction to train drivers or members of the public.

The echo digitisation and online waveform processing capability of the scanner gives the ability to resolve multiple targets for each laser pulse, allowing for more points to be measured through vegetation. This results in more information being collected about the structure of the vegetation on scanned surfaces which ultimately aids the interpretation of the pointcloud and filtering of data.

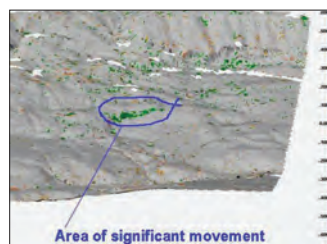
Due to the extent of the Warren site, and to ensure comprehensive data coverage, scans are recorded from positions along the sea defences, the rail side and from the

cliff top. Both sea defence and rail side areas provide lines of site onto the high cliff areas at the back of the landslide, and use is made of the scanners range to collect data of these cliff areas whenever possible. Scans from the cliff top provide an opportunity to infill 'shadow areas' and provide data at the back of the landslide.

To maximise productivity on site a 'Stop and Go' scanning methodology was employed for the scans along the sea defences and rail side. This method of working sees the scanner mounted on a mobile platform, which, in the case of Folkestone, is a motor vehicle. The access road network at the Warren allows for vehicle access along the rail side and the sea defences.

The scanner is mounted on the vehicle's roof rack (Figure 5) and driven to each scan position, where the vehicle is parked and remains static during the scanning and photography. This methodology negates the need to de-mobilise the equipment after each scan position and provides for an effective method of working. From a practical perspective, consideration is given to weather conditions, particularly for the sea defences scanning, as it has been noted that high winds can cause movements of the vehicle which may affect the data. However, the scanner uses an inclination sensor to monitor and adjust for small movements of the instrument during scanning.

The Stop and Go methodology is very effective for the sea defences and rail side areas, where there is vehicular access. However, access to the cliff top area is restricted to foot, and for these scan positions the scanner is mounted on a survey tripod setup over a co-ordinated survey marker (Figure 6). At every scan position a 'Panorama' scan is collected, which uses the scanners



Figures 7 and 8: Examples of point cloud surface comparisons.

full field of view and range. For the majority of positions this data provides sufficient resolution for the purpose of the survey, and the measurement time for this is approximately three minutes per scan. Where areas of high cliff or other areas of interest are visible, more detailed scans of specific areas are undertaken, providing a higher resolution data set.

On completion of the scanning, each individual scan position is positioned and orientated based on the scanners internal co-ordinate system at 0, 0, 0. The individual scans therefore need to be aligned together to create a single pointcloud and referenced to the required co-ordinate system, in this case Ordnance Survey (OS) grid.

To undertake this process a number of targets have been installed at optimum scan positions, and these targets are picked out by the scanner during the data collection process. These same targets are co-ordinated by total station observations and the computed OS co-ordinates for each target are then used to position and orientate those scans which contain targets.

Typically, a minimum of six targets is used for the registration process, providing redundancy and statistical analysis of the resultant alignment.

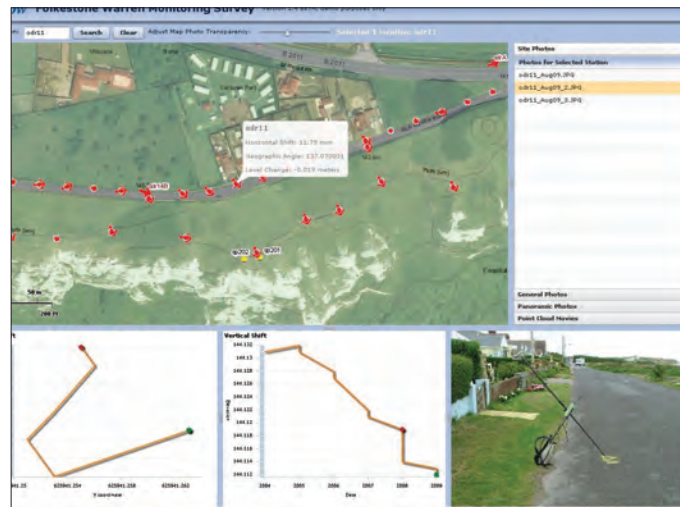
Once the targeted scans have been aligned, the intermediate scans are registered to the fixed target scans using a pointcloud to pointcloud registration method, which uses the overlapping geometric data in each scan to provide an alignment solution. The quality and accuracy of the alignment process is provided by statistical outputs position and orientation parameters, together with visual inspection of the overlapping data.

Where photography has been taken, this can be applied to the scan data as RGB values extracted from the photo pixels at the same coordinate as the scan points. This provides for a coloured pointcloud to be visualised, which in the case of the Warren gives a good representation of geological boundaries, and areas of vegetation.

The final process is to combine the scans into a single geo-referenced pointcloud, using both the panorama scans from each position together with the high resolution scans of the cliff areas. data provides both extensive coverage and high resolution of the landslide site.

Output

For Folkestone Warren, the data deliverable is a series of cross sections at approximately 50m intervals



Figures 9 and 10: Examples of website layout

through the landslide site, from cliff top to foreshore. In addition, specific areas of the site have been identified for which surface comparisons will be provided to give a visual overview of movement within these selected areas.

For the cross section extraction a band of data is cut from the combined pointcloud along the line of the section. This data is initially filtered by extracting the vegetation identified by the waveform digitisation process. A further visual inspection is undertaken and additional manual filtering and cleaning of the pointcloud is undertaken as required. Once complete the cross section is generated from the pointcloud data and as subsequent remeasure surveys are undertaken, cross sections for each survey are overlain on the baseline survey to show areas of movement.

For the surface comparison outputs, the baseline survey has at the selected areas been modelled,

and subsequent remeasure surveys are compared against this model and a colour contoured output is generated, an example of which (from another site) is shown in (Figures 7 and 8).

While the current output from the pointcloud data is cross sections at specified internals and surface comparisons at selected areas, the overall comprehensive data coverage provides a valuable resource which can be retrospectively analysed if further areas of movement are identified, or if specific areas are deemed to require section information at more frequent intervals.

The pointcloud data provides a further way of managing Folkestone Warren, with the extensive data being used to better quantify the nature of the landslip and to allow more informed decisions to be made on the installation of additional point monitoring markers and other geotechnical instrumentation, so using the pointcloud as a

management tool as much as a spatial analysis tool.

Web delivery

Historically the monitoring data for Folkestone Warren had been delivered in report format, utilising tabular and graphical outputs of point monitoring horizontal and vertical movement. The graphical format provides an excellent method of visually displaying the extent of movements at specific points. The data was also linked to site plans, showing vector plots to give an overview of the point monitoring results.

Network Rail required that the historic data and subsequent survey data be delivered via a web portal. An interactive website was designed which acts as a project dashboard for the Folkestone Warren monitoring project.

The project dashboard provides a variety of windows with which to view the data generated from the monitoring activities and based around a GIS map window, which allows for the viewing of both base mapping and aerial photography, and on which is shown the point monitoring locations, cross section and surface comparison locations. Clicking on a marker generates graphical plots and numeric data and displays photography as appropriate.

The website is also the repository for the survey reports, additional photography and studies. Example screenshots from the website are shown in Figures 9 and 10.

Conclusions

The natural forces driving the Folkestone Warren landslide complex cannot be engineered out. However, fundamental to the safe operation of the railway, passing through it is to maximise understanding of the ground movements and ensure a robust monitoring programme continues.

The benefits of utilising terrestrial laser scanning at Folkestone Warren are:

- Rapid, non-contact data measurement;
- Comprehensive data coverage over the entire landslide complex;
- Provision of data on the high cliff areas;
- Provision of data between existing monitoring points;
- Pointcloud comparisons can be used as the basis for both detecting and analysing change.

Acknowledgements

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