*IAEG2006 Paper number 78*

# Technical developments in the monitoring of the Folkestone Warren landslide complex

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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 1840's to use this route for the main line between Folkestone and Dover, Kent.

Our appreciation of the processes at work, failure mechanisms and impact of man have changed over the years in the light of new information and extended periods of monitoring data. The paper will describe how the investigation and monitoring techniques employed within the Warren have been adapted to the changes and to the development of new technologies, including satellite interferometry. The effectiveness and limitations in the past and present monitoring will be discussed in relation to the actual consequences for the railway.

**Résumé***:* Depuis la decision prise en 1840 d'utiliser la route pour la grande ligne entre Folkestone et Douvres a Kent a travers la labyrinthe (the Warren) de Folkestone et les falaises adjacentes, de grosses difficultes se sont presentes aux etudiants aussi bien qu' aux practiciens de l' ingenierie et de la geologie.

A la lumiere de nouvelles informations et de periodes extensives de surveillance, notre comprehension des processus en jeu, des mecanismes de surete et l' impacte de l' homme s' est changee au delai des annees. Ce papier explique comment l' enquete et les moyens de controle employes dans la labyrinthe (the warren) ont ete adaptes aux defis et au development des nouvelles technologies, y compris l' interferometrie satellite. L' effacacite et les limitations des controles d' autrefois et au present seront discutees par rapport aux consequences pour la chemin de fer a l' epoque actuelle.

**Keywords***:* 3D models, geological hazards, geomorphology, landslides, monitoring, remote sensing.

## INTRODUCTION

### *Geological and historical setting*

Folkestone Warren is the name given to the area of coastal landslide between Folkestone and Abbots Cliff, which occupies an area 2.7km long and between 50m and 350m wide, Figures 1 and 2. The back of the Warren is defined by the 'High Cliff', which is over 100m high and composed of Lower and Middle Chalk. In plan the Warren is cuspate 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 dips gently at about one (1) 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.

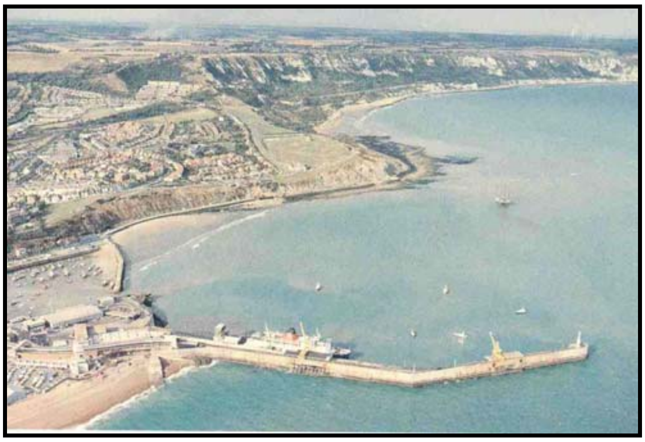


**Figure 1.** View east from Folkestone Harbour.

**Figure 2.** View east of the major slip in 1915.

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 time-consuming inland alternative in order 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, 1877 and again in 1915, when the line was closed for four years.

## Early investigations and monitoring

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".

Notable amongst those who strove to understand the nature and significance of the ground movements was Karl Terzaghi, an eminent farther of the science of soil mechanics, who journeyed from his home town of New Orleans, Louisiana, to advise on how to handle the land instability both here at The Warren and at a landslip near Sevenoaks.

His report to the Southern Railway Company in 1939 likened the situation to tackling a complex military battle. His analogy was to consider holding a line against a surprise attack by a small but mobile opposing force;

> *"This can be accomplished in two different ways. Either we excavate trenches along the entire line, spread our forces fairly uniformly over our fortified line, and wait for what is going to happen next or else we adapt our policy to the characteristics of the opponent. That means, instead of fortifying our line, we send out scouts to watch the movements of the enemy and we keep our own resources mobile and ready for concentrated action. The first procedure may have the advantage of creating in the civilian behind the line, a feeling of security, because the civilian sees that something rather spectacular is being done. At the same time, the procedure is obviously wasteful and dangerous, In addition, because we cannot judge whether or not our line will be strong enough to stand up against a wedge-action of unknown intensity. Hence there is no doubt that the second method deserves the preference, provided the scouts are trustworthy and thoroughly familiar with the local topography."*

This philosophy has stood the test of time and the continued efforts to maintain the safety of the line are driven by the programme of monitoring and vigilant observation. The extensive work undertaken to date, including additional toe-weighting and drainage measures put in place to improve stability, have done much to reduce the propensity for major movements. However, ground movement is ongoing with fresh cracks appearing in several places in the Warren, most notably in the vicinity of Horsehead Point.

Following Terzaghi's advice a number of actions were pursued in order to advance the understanding of ground movements which included;

- Test borings to survey the top of the Gault Clay and observe variations in groundwater, in particular, to ascertain the effects of subsequent drainage.
- Laboratory investigations to determine the physical properties of the Gault Clay and any variations in properties over the depressed area.
- Installation of offset targets on the railway line and accurate devices within drainage headings to measure their change in length in response to the on-going ground movements, Figures 3 and 4.

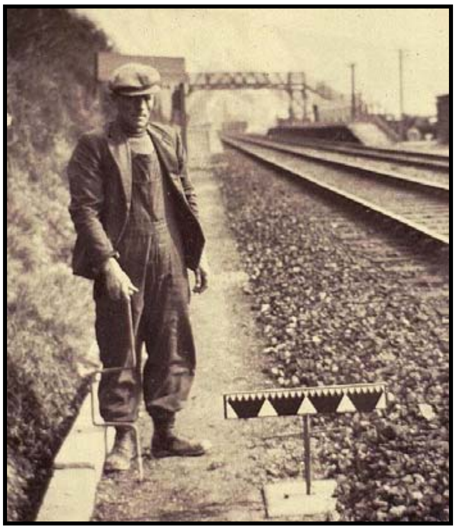


**Figure 3**. Offset targets survey in 1950.

**Figure 4**. Heading extension measured by weighted tie wire.

### *Mitigation measures*

Site investigations undertaken in the early 1900's following major landslips led to the implementation of a variety of measures designed to mitigate the land slipping processes, including;

- Drainage – construction of some twenty drainage headings from the foreshore
- Sea defences – construction of 3kms of sea walls
- Beach replenishment – introduction of shingle to counter erosion and loss of toe loading
- Stability enhancement - local re-profiling by moving spoil around within The Warren
- Toe weighting – construction of concrete apron.

## DEVELOPMENTS

### *Post war investigations*

Four periods of study and ground investigation have been carried out since the Second World War, each following periods of renewed activity, vis 1948-55, 1969-70, 1983 and 2001, Table 1.

These studies have revealed that the ground movements in the Warren are controlled by a number of inter-related processes. The larger slips are accompanied by upheaval of the foreshore into ridges that have later been eroded by the sea. The slip mass is subject to on-going creep and ground movements which continue at an average rate of up to 70mm/yr, but increasing locally by up to 1m following prolonged periods of heavy rain. Whilst the slow creep is manageable, periods of exceptional activity, such as over the winter of 2000/2001, give rise to movements which cause loss of track foundation and disruption to the railway services, Figures 6 and 7. However, the greatest threat to life has been from chalk falls from the Warren High Cliff, which can occur very rapidly and without warning.

There is no doubt that following these further investigations, there is now a better understanding of the Warren slips and the groundwater conditions and consequently where to place any additional remedial measures to achieve optimum effect whether they be installation of additional groynes, toe-weighting or drainage headings. However, it should be pointed out that, even if such measures were installed, on-going monitoring of the Warren and the adjacent Abbotscliff and Shakespeare Cliff, through which the railway runs in tunnels, and which are affected by chalk falls and sea erosion, will always be required. The coastline is ever evolving and the evidence does suggest that construction of Folkestone Harbour wall had a major impact on landslide activity in the Warren by cutting off the supply of shingle to beaches in the Warren (Hutchinson et al 1980). An analogous effect was felt following a post 1952 (probably early 1960's) chalk fall below Gallery 8 of Abbotscliffe Tunnel which effectively blocked the movement of sand further east leading to subsequent removal of a sand bar and Lydden Spout Pool and subsequent erosion of the cliffs resulting in a fall of chalk in 1988.

### *Hydrogeology and drainage measures*

Generally speaking, there is no hydraulic continuity between the Chalk and the Folkestone Beds, there being a reduction in the porewater pressures through the intervening impermeable Gault Clay (Hutchinson 1969). It should be stated that effectiveness of dewatering the slip depends to large extent on the depth of the basal slip surface below sea level (i.e. 5m at the west end and 50m at the east end) and the lowest level at which the drainage headings can conveniently discharge by gravity (i.e about 6.5 m OD., high tide being +4.5 m OD). When Professor Terzaghi visited the Warren it was pointed out that all the existing headings were at too high a level for natural drainage of the water from the Folkestone Beds and the possibility was discussed of sinking shafts to extract water from these beds (Toms

1946). However because the Folkestone Beds appear to be hydraulically connected to the sea this would appear impractical.

The success of any drainage heading in terms of "tapping" water therefore depends on the nature of strata through which it extends (e.g. Gault or chalk, intact or broken etc.) and the available head of water. New heading H2 was quite successful in tapping large quantities of water trapped towards the back of the Warren since a large inrush of water totaling 150 to 600 l/min and carrying red sand and chalk rubble took place during construction some 220 metres in from the entrance. The heading had the immediate effect of lowering the water level in a nearby borehole by 7m from 22 m OD to 15 m OD. Similar large inflows were recorded recently in heading H5 when exploratory probes, 60mm in diameter, were drilled in a landward direction through the Gault and Chalk Marl strata across a major slip boundary into saturated broken Middle Chalk rubble existing beneath the railway in this area. Inflows of 10 l/min emerged from the holes following drilling and did not diminish with time suggesting recharge from above the impermeable Gault Clay.

The ultimate solution would be 3km long drainage gallery running below the High Cliff, within the intact chalk strata along the back of the Warren, the elevation of which would be the minimum practical given the need to drain the water to the sea. Such a gallery would intercept groundwater recharge emanating above the Chalk Marl outcrop in the High Cliff e.g. the spring emerging out of the cliff face at +53 m OD further north-west of Warren Halt (Muir Wood 1955).

**Table 1.** Chronology of investigations and key developments.

| **Period of Investigations**<br>***Reference*** | **Remarks** | **Advances in knowledge and monitoring** |
|---|---|---|
| Post 1915 following major slip and chalk falls that affected whole length of Warren<br>*Osman 1917* | Reinstatement of certain drainage headings destroyed by 1915 slip | Outline of general geology & arrangement of slips. |
| 1938 - 50 following slips and chalk falls that occurred at the western end near heading H2<br>*Terzhaghi 1939*<br>*Toms l946*<br>*Muir Wood 1955*<br>*Viner Brady 1955*<br>*Hutchinson 1969*<br>*Muir Wood 1970* | Boreholes concentrated at western end. Standpipes installed in chalk<br>Concrete apron built between west end and Horsehead Point<br>New drainage<br>Heading H2 built<br>Establishment of monitoring stations in the Warren and telltales in the drainage headings | General arrangement of slips particularly at western end.<br>Delineation of slip zones by using macrofossil and detailed lithological composition of the various Gault beds.<br>Discussion on origin of "set features" in the High Cliff. |
| 1969 - 1970 following minor movements at Horsehead Point<br>*Halcrow 1970*<br>*Hutchinson et al 1980*<br>*Muir Wood 1994* | Boreholes at Horsehead Point. Standpipe piezometers installed. | Identification of depressed pore pressures in the Gault |
| 1982 - 1984 following minor movements at Warren Halt<br>*Trenter & Warren 1996*<br>*Warren & Palmer 2000* | Boreholes along whole length of Warren.. Inclinometers and standpipe piezometers installed. Survey of drainage heading and geological mapping of foreshore. Cliff survey.<br>Review of survey results related to points established in the Warren and telltales in the drainage headings. | Three-dimensional geological arrangement of slip masses along Warren influencing pore pressures and rate of movements observed.<br>Use of macrofossils to identify slip zones<br>Hingeing mechanism of movement further east of Warren Halt .<br>Evidence of slickensided features in the in situ Gault towards the rear of the Warren.<br>Limited evidence for development of set features as indicated by Hutchinson et al 1980 |
| 2001 - present following increased movements and chalk falls in the Warren that occurred January - February 2001<br>*This paper* | Automatic monitoring of electrolevels established at critical locations along the railway e.g. Warren Halt to provide warning of movement.<br>Topographical surveys extended to include the cliff top | Increased movements at Horsehead Point and appearance of fresh backscars extending further west towards Warren Halt.<br>Observation of ‘graben’ features against principal backscars. |

## *Nature of the ground movements*

With regard to the nature of the slips, the recent evidence would suggest a large discrepancy between the movements recorded in recent historical times along the Warren including the 1915 slip, and the magnitudes of the movements as determined from mapping the strata outcropping along the foreshore and headings (Trenter and Warren 1996). For example, at Warren Halt, where ongoing movements of only 200mm have been recorded since 1960, actual displacements across the main slip zone total over 100 metres, there being no historical evidence to support such a large displacement in recent times. It is therefore concluded that modern movements are often reactivations of major ancient slip surfaces which were initiated some 5500 to 2800 BP during a period of rising sea level following the last glaciation. The minimum date is supported by carbon dating of displaced topsoil profiles (Hutchinson 1969, Trenter & Warren 1996). Furthermore in relation to the nature of the failure zones, two types can be recognized:

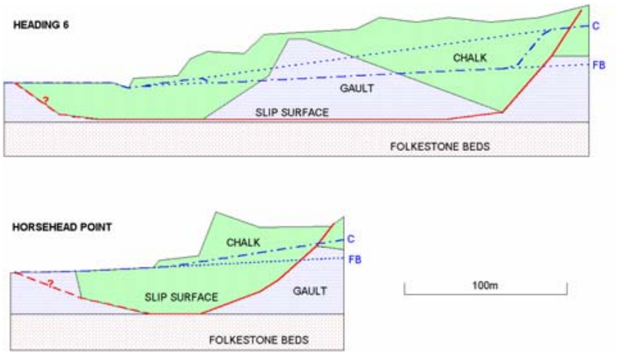
- *fissured sheared and slickensided material*. This is typical where the basal slip surface is overlain by a large thickness of Gault (usually Slip 1 slides). The Gault is similar in character to the adjacent slipped Gault bed but possesses distinct lustrous and slickensided surfaces along which movement takes place e.g. shear zone in borehole 82/9 located towards the back of the Warren at Warren Halt. It should be noted that similar slickensided surfaces have been observed in the in situ Gault below the High Cliff; being located usually adjacent the more competent glauconitic beds within the Chalk or Gault succession i.e. below the Glauconitic Marl, above and below Gault Bed XII and above Gault Bed I. These represent intra-formational shears due to flexural bedding plane slip. Additional evidence was also provided at Holywell Coombe further north during excavation of a 15m cut through in situ Gault Clay as part the Channel Tunnel construction. During the course of the excavation, minor movements totaling 5-10 mm were detected above the more competent glauconitic Bed XII, again highlighting the occurrence of preferential planes of weakness within the Gault.
- *fully or partly disturbed, softened and remoulded material*. This is typical where large Gault thicknesses have been removed and the Chalk almost rests on the Folkestone Beds (usually Slip 2 slides). Most of the original Gault Clay fabric is lost and the material has been reduced to a firm clay having a notably higher moisture content e.g. shear zone in borehole 82/5 located on the seawall below Warren Halt.

It is intimated that the nature of the material forming the basal slip will impact the nature of movements within any given slip mass. For example one might expect ongoing creep movements to occur where the basal slip zone is formed of fully softened and remoulded material as compared to generally slipped yet intact Gault Clay containing discrete slickensided surfaces, where stick-slip movements are much more likely. Further research into this aspect together and also on the actual pore pressures acting on the shear surfaces needs to be undertaken before the true nature of movements in the Warren and the stability within any given three-dimensional slipped mass can be adequately explained.

The Chalk and Gault landslipped strata in the Warren appear to reflect ancient multiple movements which commenced at the west end and moved progressively eastwards along the Warren towards Abbotscliff Tunnel. The movements at the west end were of such a scale that the whole of the cliff and underlying strata appears to have moved bodily seawards with the cliff top then collapsing into the void so created (Warren & Palmer 2000). East of Warren Halt, a "hinging mechanism" of movement is invoked, influenced by the easterly dip of the sulphur band, above which the basal slip surface usually occurs, and the passive resistance and confinement provided at the west end by the adjacent slip mass; this produced a series of backtilted blocks of relatively intact chalk arranged in "en echelon" fashion with the backscar trending towards the High Cliff.

Four such slips have been recognized in the Warren, east of Warren Halt (Warren and Palmer 2000). The nature of the movements was such that the greatest lateral displacement, rotation and downthrow occurs at the east end furthest from the hinge point. The excessive nature of the rotation at the east extremity can be observed immediately offshore of Horsehead Point where upthrust Glauconitic Marl/Gault dips steeply landward at 70 degrees. Further landward of this location shallower dips of 45 degrees are recorded in the Melbourn Rock (Middle Chalk) forming the Horse's Head itself. Increased movements have been reported in this area since the end of 2000 and this has led to the appearance of fresh cracks extending further west towards Warren Halt. The magnitude of these movements and stability of the Horsehead Point slip block is dependent on the three-dimensional geological make-up of the slip mass which itself is likely to influence the pore pressures acting on the basal slip surface, Figures 5 and 6.

East of Horsehead Point the landslip blocks appear to have slipped "en masse" and intact and generally have suffered less rotation. Little or no ongoing movement is apparent in this area possibly indicating the increased stability as a consequence of the increased passive resistance due to the greater depth to the basal slip surface above the sulphur band (Trenter and Warren 1996). No slip surfaces were observed on the foreshore suggesting that the movement is accompanied by upthrusting of strata on the foreshore (Muir Wood 1955) rather than emergence of actual slip surfaces.



Heading 6/6A
1983 – 2005 Movement 270 - 385mm
Back analysed ’$_{r}$ = 6
Pore pressure on basal slip surface more likely to reflect groundwater level in Folkestone Beds.

Horsehead Point near Heading 8
1983 – 2005 Movement 1910mm
Back analysed ’$_{r}$ = 16
Pore pressure on basal slip surface more likely to reflect groundwater level in Chalk.

**Figure 5.** Generic cross sections for the Horsehead Point Slip.

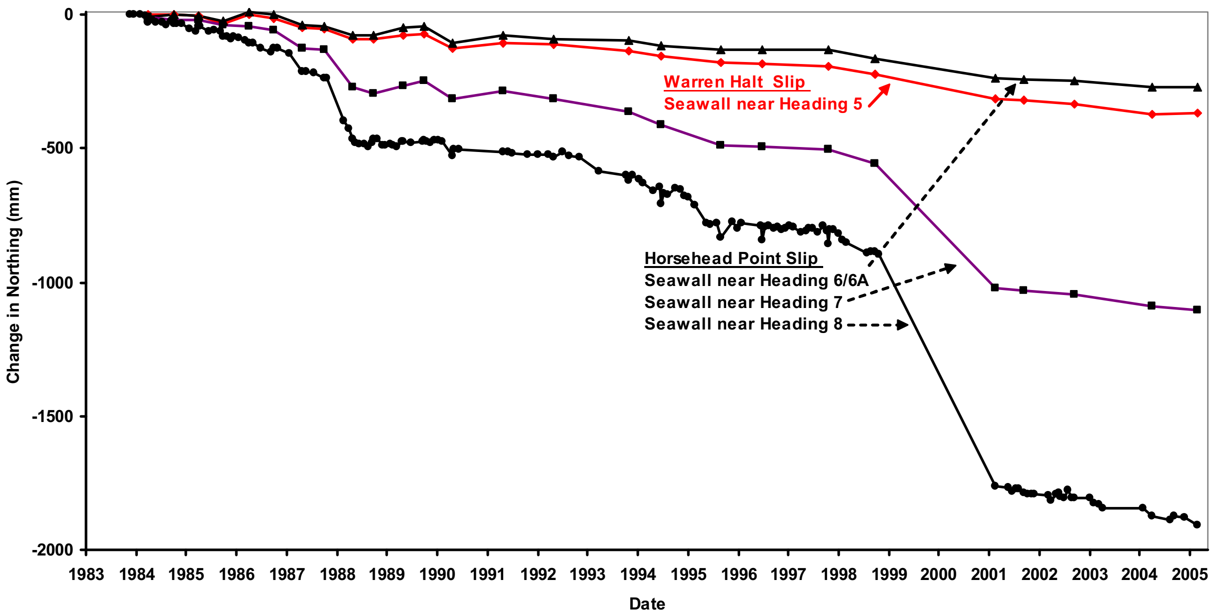


**Figure 6.** Movement of selected points at Warren Halt and Horsehead Point

## *Management strategy*

For many decades the coast defences at The Warren were maintained and repaired by a dedicated team based at Warren Halt. However, this luxury was lost in the late 1990’s and repairs were carried out as required by specific contracts. This continued up to the winter of 1996 when part of the high wall at Warren East End collapsed. Emergency works, comprising reconstruction and rock revetment, were then undertaken to repair this section of wall. This collapse raised a number of issues concerning the long term approach to maintaining the existing sea wall and coastal stabilisation measures and consequently a ten year strategy was developed. The strategy required a fresh ’holistic’ overview of the landslide processes, existing monitoring regime and maintenance strategy. This led to a rationalisation of the routine monitoring arrangements at the Warren;

- Hazard assessment to focus efforts on zones of high risk to railway safety

- Surveying of ground movement along the railway formation and the sea wall
- Condition surveys of the high wall and apron
- Inspection of headings - movements and water flows
- Monitoring of fissure systems behind the crest of the High Cliff
- Installation of electrolevels on the tracks
- Selected piezometers fitted with data loggers and monitored remotely by modem
- Automated weather station at Warren Halt
- Extension to the ‘chalk fall’ detection fence
- Long-term monitoring of cliff face de-stressing alongside Abbotscliffe and Shakespeare Tunnels
- Annual ‘expert eye’ walkover and update of geomorphological mapping

The routine inspections, condition surveys and ground deformation mapping are used to determine deterioration trends which generate the maintenance priorities for the ensuing years.

The remote monitoring of groundwater, weather and track deflections is aimed at providing ‘real time’ information on actual conditions on the ground and, thus, early warning of potential instability.

Threshold levels, based on track geometry criteria, are set on the electrolevels (Red, Amber and Green), which allows swift remedial action to be taken in the event of significant ground movements, Figures 7 and 8.

**Figure 7**. Tiltmeters measure real-time deflections.

**Figure 8.** Tiltmeter locations at Warren Halt.

## *Process mapping*

The density of undergrowth within the Warren Undercliff precludes comprehensive geomorphological mapping to a consistent level of detail throughout the Warren. However, there are a variety of stereo aerial photographs available dating back to the earliest RAF sorties in 1947, which have been used to determine the ground morphology from ‘snap shots’ in time. A further means by which the morphology is revealed, albeit in a transient way, is the occasional clearance of selected areas of scrub to maintain the habitat for a rare species of moth, the fiery clearwing (Bembecia chrysidiformis), which is found only at Folkestone Warren. It is the latter clearance behind Horsehead Point that revealed the existence of graben features bounded by opposite facing normal faults, or ‘antithetic’ faults, to accommodate the principally lateral nature of the ground movement, Figures 9 and 10.

**Figure 9.** Severed concrete apron at Horesehead Point in 2001.

**Figure 10.** Graben feature at Horsehead Point in 2001.

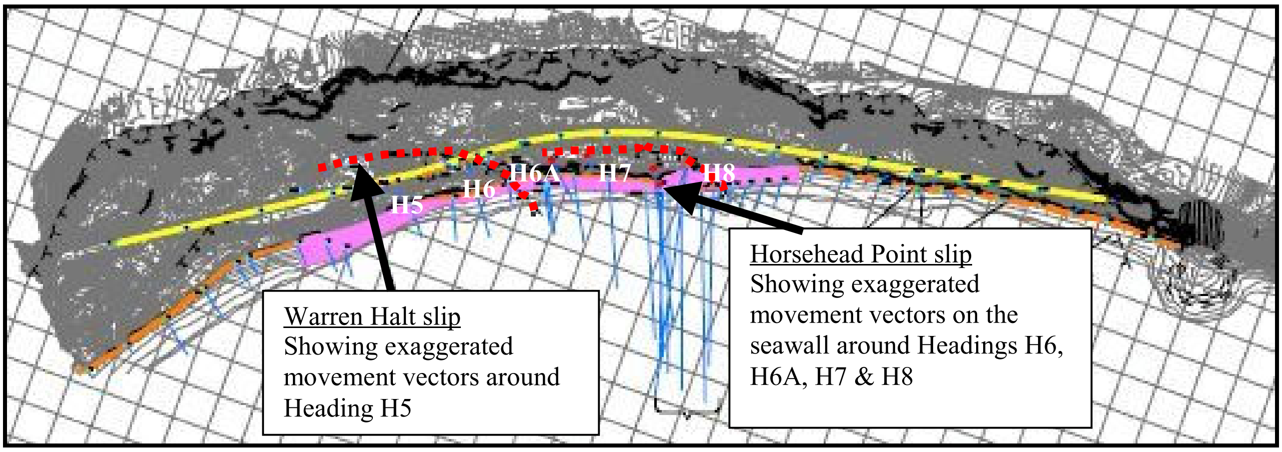
Archive research has revealed photographs from earlier periods of ground movements which provide insight into the nature of the movements we see today. A notable observation is that the ‘fresh’ ground movements observed over the winter of 2000/2001 are a re-activation of the same failure surfaces associated with the last major phase of ground movements in 1915. Indeed, the process rates had accelerated to the point where, if it had not been for the drainage and weighting works put in place following the 1915 events, we could well have seen similar catastrophic failures.

In terms of process rate there has been a good correlation observed between the Met Office calculations of Soil Moisture Deficit (SMD) and landslide activity. It is not so much the rainfall on the Warren itself which drives the activity, but the longer duration build up of groundwater within the Folkestone – Dover Chalk Block and this build up is mirrored by periods of low SMD.

Outside of the Warren are a number of processes which become active in response to prolonged periods of rainfall and associated low SMD. These are movements of portions of the Warren Highcliff and failures of the adjacent cliffs to the east of The Warren. Such features can be detected many decades in advance of collapse by settlements adjacent to the cliff crest described as ‘sets’ (Hutchinson, 1969). The falls can involve many hundreds of tonnes of chalk which, under certain circumstances, can develop into flow slides with run-out distances in excess of the cliff height (Hutchinson 2002).

## *Topographic surveys*

Whilst 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 11. These linear 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 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 provided sufficient targets are permitted within the SSSI.



Warren Halt slip
Showing exaggerated movement vectors around Heading H5

Horsehead Point slip
Showing exaggerated movement vectors on the seawall around Headings H6, H6A, H7 & H8

**Figure 11.** Movement summary for 1998 to 2005, showing exaggerated vectors (blue lines) for selected points.

## *Capital works*

The combination of long term monitoring and future strategy leads to the execution of remediation works commensurate with commercial aspirations for the route’s viability. Current and future capital works include;

- Rock revetments
- Seawall and concrete apron maintenance
- Enhanced drainage by probe hole arrays
- Enhanced drainage by directional drilling
- Drainage interceptor galleries

The recent phases of rock revetment work have been the single most positive contribution to maintaining the coastal defences which, in turn, protect the railway, Figures 12 and 13. The rocks are supplied by quarries in Carboniferous Limestone in Nord-Pas-de-Calais, just across the channel from Folkestone Warren. The rocks, which weigh between 4 and 8 tonnes each, are selected for their durability, prismoidal shape and light grey to brown colour.

The rocks are shipped via the ports of Dover or Boulogne in loads of 1,500 tonnes and transferred into smaller barges which unload the rocks within specific drop zones at high tide. The rocks are placed during low water to a designed profile and specification that requires a five point contact in order to achieve the required placed density of 1.87 tonnes per cubic metre.

The revetment design provides the following key benefits;

- Physical support to the sea wall

- Breaks up the destructive wave energy
- Traps sediment which reduces erosion
- Adds toe weighting against rotational slip surfaces
- Blends in well with the local colours
- Meets environmental approvals

**Figures 12.** Rocks are off-loaded at high tide.

**Figure 13**. Rocks are placed at low water.

# FUTURE OPPORTUNITIES

## *Coastal monitoring*

In recent years a wealth of coastal process data has been gathered by the Strategic Regional Coastal Monitoring Programme to which Network Rail have access on a data exchange basis through associate membership of the South East Coastal Group. The principal data streams are;

- LiDAR surveys of the coastline
- Ortho-rectified digital aerial photography
- Automated Beach Monitoring Surveys (ABMS) – beach profiling
- Shoreline And Near-shore Data System (SANDS)
- Offshore wave and tide monitoring

These data streams represent a considerable improvement on the previous techniques used for monitoring beach sediment migration and long-term trends in beach level especially relevant to the positive effects of toe loading and negative effects of scour in front of the apron and seawalls. Additional benefits are in establishing a long-term survey of coastal change and impact of particular storm events.

## *Satellite interferometry*

Folkestone Warren has been 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 800 km. Any difference in reflectance between successive images can represent ground deformation, which is displayed as interference fringes to which values can be assigned. Whilst 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

The use of satellite interferometry can help with the geomechanical understanding of ground movements but practical considerations, notably the image processing time, preclude this as a system for real-time detection of ground movements.

# CONCLUSIONS

The paper demonstrates the importance of looking at a wide range of sources in the investigation and understanding of landslide processes, in particular, it is important to ensure a balance between the geotechnical investigations and the geomorphological observations.

The application of modern technology has allowed the rationalisation of an unwieldy monitoring regime and the use of developing technology shows promise in enhancing the overall understanding of the ground movement mechanisms. In particular, the use of SMD as a forecasting tool and of satellite interferometry for ground deformation mapping, have been key developments in the monitoring and management of the landslide complex.

Given the current speculations on climate change, it is becoming increasingly important to have a monitoring strategy which, on the one hand builds on the established long-term history and, on the other hand optimises the best of the developing technology such that we can continue to operate a safe, punctual and dependable railway service.

**Acknowledgements:** The authors are indebted to Network Rail for permission to reproduce data and photographs and to the European Space Agency for funding the ground deformation mapping trial. We are grateful to Alastair Galt for his linguistic skills.

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