Implications of urban development on escarpment instability

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Abstract: The town of Penarth, South Wales, owes its development to major industrial expansion experienced during the 19th Century. Penarth Dock was constructed at the foot of a 30m high escarpment between 1859 and 1865 primarily to assist Cardiff in receiving coal mined in South Wales via railway for transhipment abroad for export. In addition to this, quarrying of limestone from the escarpment for use in cement manufacture was also commonplace. During the late twentieth century, and after many years of neglect, redevelopment work commenced at Penarth Dock. The docks area was partially infilled and the rail tracks and sidings removed. A marina with high quality residential and commercial buildings was constructed in its place. This redevelopment has brought about the need for car parking and a boatyard in close proximity to cliffs of marginal stability in areas of enhanced public access. The escarpment, which comprises sediments of the Mercia Mudstone Group overlain by deposits of the Penarth Group, has suffered a number of slope failures and rockfalls over recent years; the most recent occurring in January 2004 after heavy rainfall resulting in the partial closure of the car park servicing the marina. It is considered that excavation of a portion of the escarpment toe, haphazard infilling of an old quarry at the crest of the escarpment and poor drainage has contributed significantly to the failures on the escarpment. Geological controls, including faulting and possible relict instability features have also markedly influenced stability. This paper presents the findings of a desk study, a risk assessment based upon roped access surveys and an intrusive ground investigation. The factors, including the industrial legacy, which led to instability, are discussed together with the resulting necessity for mitigation measures to secure public safety.

Résumé : La ville de Penarth, au sud du Pays de Galles, doit son développement à d'importantes expansions industrielles qui se sont déroulées au cours du 19ème siècle. Le Port de Penarth fût construit au pied d'un escarpement de 30 mètres de hauteur entre 1859 et 1865, principalement afin de soutenir la ville de Cardiff à exporter vers l'étranger le charbon extrait des mines du sud du Pays de Galles arrivant par voies ferroviaires. En outre, l'extraction de calcaire sur l'escarpement était une pratique courante pour alimenter l'industrie de la cimenterie. A la fin du 20ème siècle, et après de nombreuses années de négligence, des travaux de réaménagement commencèrent au Port de Penarth. La zone portuaire fût partiellement comblée et les voies ferrées et d'évitements furent retirées. Un port de plaisance, des bâtiments de résidences et des centres commerciaux de qualités y furent construits. Ce réaménagement entraîna le besoin de parking et d'un chantier de construction navale à proximité de falaises de faibles stabilités dans des zones publiques de plus en plus fréquentées. L'escarpement, qui comprend des sédiments du Groupe Mercia Mudstone recouverts par des dépôts du groupe Penarth, a subit de nombreux décrochements et éboulements au cours des dernières années ; la plus récente a eu lieu en janvier 2004 suite à de fortes précipitations qui ont provoqué la fermeture partielle du parking entretenant le port de plaisance. On suppose que l'excavation d'une partie du pied de l'escarpement, un remplissage mal organisé d'une vieille carrière au sommet de celle-ci et un mauvais drainage ont considérablement contribué aux failles sur l'escarpement. Des contrôles géologiques, incluant des caractéristiques de défectuosité et un passé possiblement caractérisé par d'instabilités, ont aussi nettement influencé les instabilités présentes. Ce document présente les conclusions d'une étude basée sur une recherche en bureau accompagnée d'une étude sur terrain via une inspection de l'escarpement par voies d'escalades ainsi que d'un sondage des sols. Les facteurs, y compris l'héritage industriel qui ont mené aux instabilités, sont traités avec le besoin cohérent de mesures d'atténuations afin de sécuriser les accès publics.

Keywords: Slope Stability, mudstone, surface water, failures, risk assessment, case studies.

INTRODUCTION

The Penarth Escarpment is located to the north of Penarth Town in the Vale of Glamorgan, South Wales. The escarpment runs in a west to east direction with the cliff-like slope facing to the north. It extends for about 650m in length and ranges in height from approximately 20m to 40m. The slope is heavily vegetated and varies in angle from about 15º to the horizontal to near vertical. The slope overlooks a car park and boatyard which serves the modern Penarth Marina, located on level ground at the foot of the escarpment.

The escarpment adjoining Penarth Marina has suffered at least three previous slope failures (BarKonsult Ltd 2000a and 2000b) in recent years. The most recent slope failure occurred in January 2004 after a period of heavy rainfall. A summary of past slope failures known to have occurred is given in Table 1.

Table 1. Summary of Past Slope Failures at Penarth Escarpment

Date	Summary of Known Failures within the Escarpment
1995	Block of mudstone fell from the face of the escarpment and damaged a car
1997	Shallow sliding failure of weathered bedrock and organic soils resulting in approximately 10 tons of over burden sliding into the escarpment over a length of 30m.
2000	A minor landslip/surface slip, similar to and immediately west of the 1997 slip. Tension cracks in the footpath at the crest of the escarpment were identified near a public open space/playground area.
2004	Shallow slope failure resulting in material sliding into the car park, damage to a wire fence and the blocking of the escarpment toe drain after a period of heavy rainfall (most recent failure).

Following the 2004 failure, fallen slope debris material collected behind an existing chain-link fence located along the length of the car park/boat yard. During investigation of the slope failure, water was observed discharging from the base of the failure plane and the slope toe drain was seen to be intermittently blocked with debris. Scouring of the slope failure scar from surface water was also evident.

After consultation with the Vale of Glamorgan Council a phased study was implemented to assess the causes of the localised slope failure and to appraise the potential risk to existing development along the escarpment. This involved a desk study to review the published geology and assess the site history and field investigations using roped access surveys. Site mapping by an engineering geologist enabled the escarpment geometry to be measured and signs of instability to be determined. This data was collated into a risk assessment, which was used to specifically target intrusive ground investigation to assess possible remedial options in areas of high risk. The results of these phased investigations are discussed in the following sections.

GEOLOGICAL SETTING

Published geological mapping (British Geological Survey, 1989) shows that the escarpment comprises sub-horizontal sedimentary rocks from the Triassic and Jurassic Periods. The full sequence of strata encountered near Penarth is illustrated in Table 2.

Table 2. Geological Setting of Penarth (Lawrence & Waters, 1987)

Period	Group	Formation	
Jurassic	Blue /Lower Lias	**Porthkerry Mudstone** Consists of regular alternations of fossiliferous grey, very fine grained subordinate limestones and blue grey mudstones.	
		St Mary's Well Bay Formation *(Crest of Penarth Escarpment)* Consists of regular alternations of fossiliferous grey, very fine grained limestones and blue grey subordinate mudstones.	
		Ammonite Marker Bed: *Psiloceras planorbis*	
Triassic	Penarth Group	**Listock Formation**	**Langport Member** Thinly bedded basal micritic shelly limestone. Fossils include bivalves, echinoids, ostracods and corals
			Cotham Member Green grey mudstones with thin calcareous siltsone and sandstone ribs.
		Westbury Formation *(Bulk of Penarth Escarpment)* Black pyritic, fissile, shales with thin beds of limestone and sandstone. Fossils include gastropods, bivalves, echinoid and a bone bed at the base.	
	Mercia Mudstone Group	**Blue Anchor Formation** (*Base of Penarth Escarpment)* Greenish grey calcareous / dolomitic mudstones with subordinate limestones and scattered beds of gypsum nodules). Unfossiliferous.	
		Red Mudstones *(Keuper Marl)* Massive, monotonous, red brown mottled green, silty, gypsiferous (as veins or nodules), calcareous or dolomitic mudstones, which pass laterally into marginal or littoral facies of breccia/conglomerates, commonly dolomitised. Unfossiliferous.	

Published geological mapping (British Geological Survey, 1989) indicates that the main strata exposed in the escarpment comprise the Mercia Mudstone Group at the base of the escarpment, the Penarth Group in the middle sections of the slope and the Lower Lias at the crest of the escarpment.

At the location of the 2004 slope failure a distinct change in the colour of the beds of the exposed sediments was evident. The extent of the slope failure can be seen in Figure 1.

At the base of the escarpment there are alternating red and greenish-blue beds of the Blue Anchor Formation exposed in a near vertical face approximately 6m high from car park level. Above this horizon the shales of the Westbury Formation are exposed in a slope of approximately 50° to the horizontal. Thus the change in colour and slope angle is coincident with the stratigraphic change from the Blue Anchor Formation to the Westbury Formation and correlates precisely with the results of published mapping. At the crest of the escarpment it is believed that limestones of the St Mary's Well Bay Formation (Lower Lias Group) are present. It is known that this limestone was extensively quarried at the end of the 19^{th} Century and the early part of the 20^{th} Century for use in cement manufacture (Lawrence & Waters, 1987) and thus exposures would be difficult to examine due to disturbance by man's activity.

Figure 1. 2004 Slope Failure at Penarth Escarpment

The sequences of strata within the length of the escarpment are also controlled by geological structure. The NW to SE trending Penarth Fault traverses to the south behind the escarpment crest. Several smaller subsidiary faults are also known to be preset above the escarpment crest from geological mapping (Lawrence & Waters (1972), British Geological Survey (1989)). Thus, changes in elevation between the formations occur both along the escarpment and potentially laterally within it.

SITE HISTORY AND LEGACY OF THE PAST

Jenkins (2005) has shown the importance of dock developments at Penarth being closely linked to the development of the port at Cardiff. Initially Cardiff port grew in the early part of the 19th century based on the need to export iron manufactured along the Heads of the South Wales Valleys. By the 1850s onwards, however, coal was extensively exploited resulting in 2million tons of export through the port at Cardiff in 1862. Pressure on the port facilities led to rival docks opening in Penarth in 1865 and neighbouring Barry in 1889. By 1913 coal exports peaked at 10.7 million tons. Although shipping expanded and peaked after the First World War, oil become more important and a depression developed in the 1930s resulting in falling coal exports. As a result of this fall in exports, use of the docks at Cardiff, Penarth and Barry decreased significantly and never really recovered, even though coal exports did not cease until 1964.

A series of historic maps clearly show that a railway shunting yard or railway sidings, which served the heavily industrialised docks (now the existing Penarth Marina), was well developed to the immediate north of the escarpment from the mid 19th Century to at least 1947 (Landmark Information Group, 2004). These maps illustrate the changes in land use were linked to the legacy of the coal exporting business. During the late 1990's the yard/sidings were replaced with a car park and boat yard constructed immediately in front of, and below the escarpment. Simultaneously a new road was constructed linking the new Marina residential development to the existing road network in the area of the previous railway line.

Quarries, used to extract limestone for cement manufacture (Lawrence & Waters, 1987), together with associated tramways and limekilns, were prominent at the crest of the escarpment until 1922. Aerial photographic evidence shows that the crest was "pock-marked" with scars estimated to be almost 60m wide as a result of quarrying until at least 1942 (NAfW, 2004). At least one large quarry was evident on the crest above the existing car park. However, during the 1960's, the aerial photographs show that the quarries had been in-filled. Thereafter the area was shown as rough pastures and allotment gardens in historic plans. The Prince Charles Court complex, a series of flats, was constructed on the crest of the escarpment during the late 1960s and early 1970's and is present today, but in a state of disrepair.

WALKOVER/ROPED ACCESS SURVEY AND RISK ASSESSMENT

Following agreement with the Vale of Glamorgan Council, an engineering geological walkover survey, including a series of roped access surveys, was carried out on the escarpment to determine the risk of further failure of the escarpment and to assess engineering options to remediate the slope. The surveys included a measured slope profile of each survey line and an engineering geological assessment of the condition of the escarpment.

The surveys noted an area of ponding and pooling of surface water evident on the slope crest above the car park area as a result of poor drainage. During periods of heavy rainfall this standing water is known to exceed the natural ponding capacity and cascade down the slope.

The survey also revealed that a large back scar of an historic rotational slope failure was present directly upslope of the 2004 slope failure. This back scar, obscured by thick vegetation and not visible from car park level, extended approximately 40m along the upper third of the escarpment. Rotated blocks and ribs of the subordinate competent mudstone and marl within the Westbury Formation were also evident within the 2004 failure scar, providing further evidence of a larger, older rotational failure than that indicated by the most recent, shallower failure.

A variety of risk assessments systems have been used to assist with assessment of rock slope instability. An initial categorisation of rock slopes (McMillan & Matheson, 1997) was developed using a two stage field assessment approach. This requires an initial rapid field assessment followed by a detailed assessment on a priority basis to examine risks in a 50km highway corridor in Scotland. More comprehensive risk assessments, involving complex mathematical formulae, have also been successfully used in Australia (Ko Ko, Flentje & Chowdury, 2003). For the South Wales site, taking into account time and access constraints, it was decided to adopt a simplified semi-quantitative risk assessment approach for the slope, based upon the results of the desk study and walkover/roped access survey. The assessment was compiled following the guidelines displayed within governmental publications on managing geotechnical risk (DETR, 2001). The approach assesses the potential type of hazard of instability and then derives the risk as the product of the likelihood that the hazard occurring as an undesirable event and the consequence of damage to property, personal injury or death to individuals in the vicinity of the slip or escarpment.

Potential hazards were recorded during the site work and included:

- loose material,
- lack of vegetation,
- evidence of poor drainage,
- animal burrows,
- seepage of groundwater,
- the presence of weak geological strata,
- steep slope angles,
- changes in slope morphology across the escarpment,
- evidence of relict and recent slope failure,
- evidence of intermittent erosion.

Undesirable events considered in the risk assessment included:

- rock falls from wedge or toppling failure,
- rock slides,
- failure of weathered material by rotational movement,
- zones of debris accumulation on the escarpment,
- loose debris falling on to modern infrastructure such as the car park/boat yard.

The potential consequence of each of these undesirable events was considered, and zones of assessed risk were assigned across the extent of the site. It was found that the areas at greatest risk from further slope failure were located around the recent failure, the historic rotational failure and in the same location as the poorly drained ground at the crest of the slope.

INTRUSIVE GROUND INVESTIGATION

Following the risk assessment an intrusive ground investigation was carried out at the crest of the slope in the area above the recent slope failure and the area of the former quarry. The investigation, comprising cable percussion and continuously cored boreholes to 30m depth, was carried out to ascertain the ground profile. Standpipe piezometers were installed to monitor the groundwater regime within the slope. The ground conditions encountered are summarised in Table 3.

Table 3. General Summary of Ground Conditions

Variably soft to firm and stiff dark brown and grey sandy CLAY with gravel of mudstone and limestone. Fragments of brick, coal slag and concrete were also recovered. **(Fill/Made Ground)**
Firm to very stiff red brown CLAY with gravel sized fragments, interpreted as lithorelicts of mudstone. **(Weathered Westbury Formation)**
Weak thinly laminated light and dark grey to near black calcareous MUDSTONE with rare strong limestone bands. Recovered material is closely and very closely fractured both sub horizontally and sub vertically. **(Westbury Formation)**
Moderately weak to moderately strong predominantly grey, green and red calcareous MUDSTONE. Locally strong and very strong. **(Blue Anchor Formation)**

Made Ground, up to 6.5m thick was interpreted as being associated with the backfill material to the old limestone quarries identified on the historical maps. The upper 1m to 4m of the Penarth Group is weathered to a firm to very stiff clay and there are approximately 20m of unweathered Penarth Group Mercia Mudstone Group strata beneath. Groundwater was observed in standpipes as being perched at two levels within the escarpment: at a level associated with the base of the backfilled quarry material and at the level of the interface of the Westbury and Blue Anchor Formations. These measurements correlate with observations of seepage on the escarpment face.

The lithological boundary between the Westbury Formation and the Blue Anchor Formation logged in cored boreholes from the ground investigation was found to be approximately 10m higher that the same stratigraphic boundary observed in the rock outcrop from the car park level. It was considered that the most likely explanation for the difference in level is the probable presence of a significant structural feature between the face of the escarpment and the boreholes positioned approximately 30m to 40m back from the toe of the escarpment. This could be in the form of a fault with a down throw to the north. It was suspected that the observation of the back scarp representing a previous deep seated rotational failure could also be interpreted as being coincident with a line or zone of faulting. Such a zone of fractured and sheared strata, derived from tectonic disturbance, could be a factor in reducing shear strength and hence aid the development of rotational shear and tension cracking given sufficiently high pore pressures and a critical geometry. Such conditions could have provided the mechanism for the formation of the back scarp which is now visible as a remnant of the instability that has previously occurred. A second inspection of the slope, following the ground investigation, could not positively identify the presence of faulted strata in the outcrop of the back scar. However, the presence of potential faulting would be a factor in designing further investigations for a remedial design, should this be required at some stage in the future.

This interpretation of faulted strata verified the published geological information for the area, which suggests that the escarpment represents the fault scarp of the Penarth Fault.

DISCUSSION

The desk study, walkover/roped access surveys, ground investigation and risk assessment have showed that the causes of the most recent 2004 slope failure are complex and that there is likely to be a combination of natural influences and human influences.

Natural Influences

Natural influences are complex at this site and relate to many factors including lithology, tectonic activity, sea erosion processes, weathering and hydrogeology. Several specific contributory factors are considered to have resulted in the 2004 failure, although other factors may also have had an effect:

- differing rates of weathering for differing lithological units within the Westbury Formation resulting in the exposure of thin competent beds of mudstone,
- structural influences originating from the east-to-west-trending wrench fault (Penarth Fault),
- sea erosion processes,
- natural surface erosion from precipitation and surface water runoff,
- changes in pore pressures associated with complex groundwater conditions.

Clearly the geometry of the slope is at least partially formed by sea erosion prior to human influences and industrial development, but would have been modified by mans activity as a result of historical developments.

Historical Human Influences

The artificial steepening of the escarpment was especially likely to have occurred at the slope toe for the construction of the rail sidings used to serve the Penarth Docks. This would have undercut the escarpment resulting in a steepened slope gradient. Haphazard infill of former quarries at the crest of the slope, as observed during the ground investigation, may have raised the natural ground surface profile at the crest of the escarpment. Both influences tend to destabilise the slope. Backfilling of disused quarries could have altered the groundwater regime at the crest, as suggested by the perched groundwater noted at this level. Surface water ponding and runoff across the escarpment, possibly associated with the location of the backfilled quarries, could result in water ingress along preferential pathways, increasing pore water pressures within the slope.

A combination of natural and historical human influences affecting Penarth Escarpment has contributed to the 2004 slope failure. However, the historical rotational failure, the back scarp of which was noted immediately upslope of the 2004 failure, has undoubtedly influenced the stability of the escarpment in this area, and is very likely to have had a significant influence on the 2004 slope failure. The position of this older failure may be related to geological faulting (the Penarth Fault) and it's occurrence may also have been affected by human activities such as changes in slope geometry from steepening of the slope during the construction of the rail sidings at the toe of the slope. Rotated blocks and beds of the subordinate competent mudstone observed within the 2004 failure scar during the roped access surveys, confirm that the recent failure is simply a small section of a much larger historic failure. Figure 2 summarises the main factors influencing the failure.

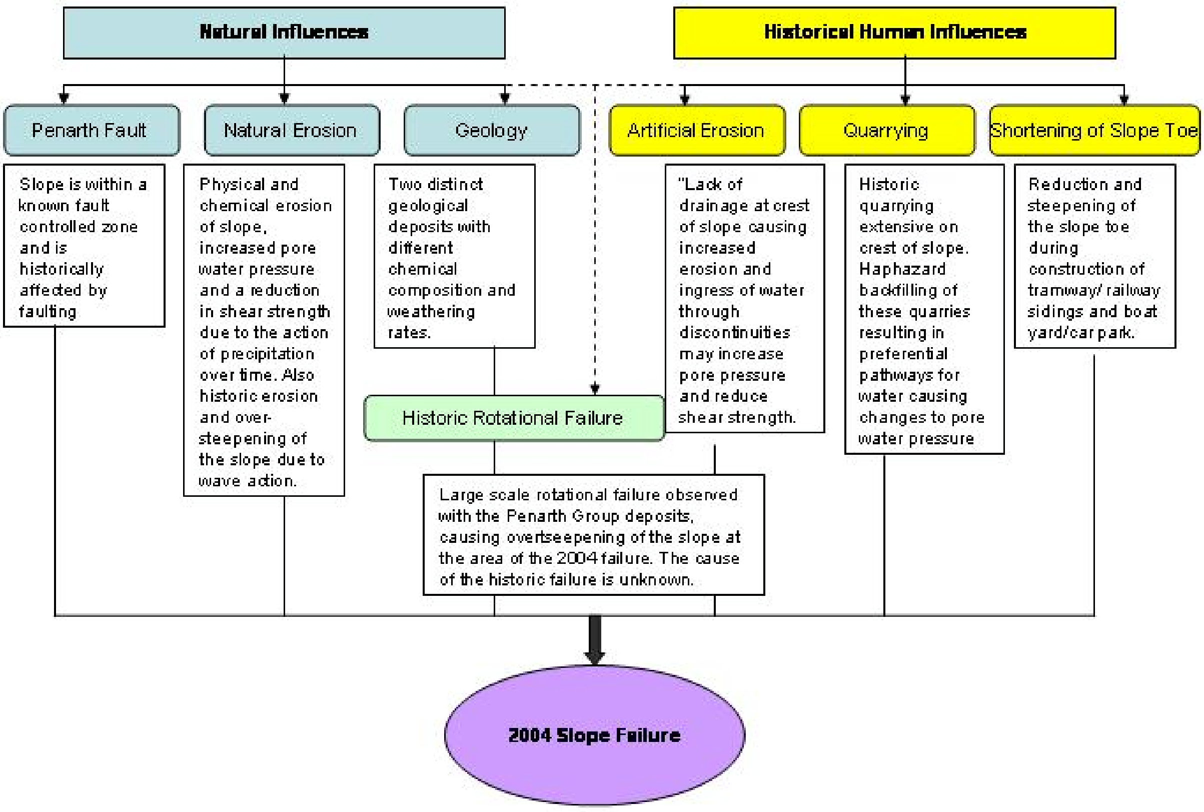

Figure 2. Factors Influencing the 2004 Slope Failure on Penarth Escarpment

A simplified sketch explanation of the slope failure is given in Figure 3 and clearly shows that the 2004 slope failure at Penarth Escarpment resulted from a combination of natural influence and human influence, as well as the position of an older, pre-existing slope failure.

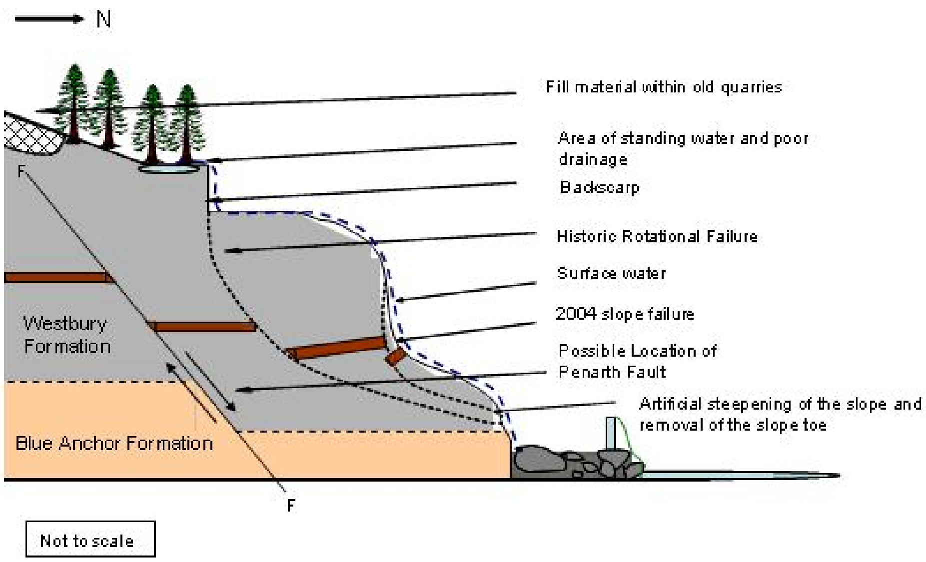

Figure 3. Simplified Explanation of the 2004 Slope Failure

SUMMARY

A section of the escarpment overlooking Penarth Marina suffered a slope failure in January 2004 after a period of heavy rainfall. The slope had suffered at least three previous failures in recent years. The escarpment, comprising mudstone and marls of the Blue Anchor Formation underlying fissile shales with subordinate marl or mudstone beds of the Westbury Formation, is steep and generally heavily vegetated. The results of a desk study, walkover/ roped access survey and subsequent risk assessment confirmed that the failure was caused by a combination of natural influences and historical human influences. The site combines a complex interaction between natural geological conditions, superimposed upon recent human activity, which has created a hazard in terms of stability and restricting current land use.

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