

A LEGACY SLOPE FAILURE IN PENLEE QUARRY - A WARNING TO OTHERS

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Penlee Quarry has a 90 m high slope which is 50-60 years old and is showing increasing signs of instability with two significant collapses in 2010 and 2011. The latter collapse gave rise to a possible flow slide at the toe and a significant air blast. This paper presents details of the underlying joints controlling ground movements, the investigation of these joints and proposals for remedial works. There are implications for other similar slopes elsewhere in England.

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INTRODUCTION

Penlee Quarry is a large quarry in West Cornwall that has been in operation since the late 1880s. It was a major producer of aggregate, but since 2003 under new ownership, quarry operations have concentrated on maintenance and preparatory works for the recovery of armourstone and the eventual construction of a marina.

The western face of this quarry was excavated between the 1950s and 1970s and is akin to other legacy slopes found at several older British quarries. The slope is up to 90 m in height, has little benching and has shown increasing signs of instability since 2005. Initially instability was evidenced by rockfall and more recently by serious collapses that have indicated the need for appropriate geotechnical design of a new replacement slope.

This paper sets out background and historical data and then considers investigations into the underlying mechanisms and rock structures that have contributed to instability and are relevant to the design of measures to overcome the potential for future significant ground movements. Methods to assess remotely the controlling joint sets are discussed and the rationale behind the stabilisation measures to facilitate future workings is outlined.

High, over-steep rock faces with limited, ineffective benching and excessive bench heights that may be found in some older quarries, as at Penlee, are likely to become a matter of increasing concern. In addition the potential for major air blast or flow slide phenomena needs further investigation in these legacy slopes some of which are present in South-West England.

SETTING

Penlee Quarry lies on the southern side of Newlyn, in West Cornwall. Located within the metamorphic aureole of the Land's End Granite it is comprised of metadolerite, a metabasic igneous rock, which intrudes into the surrounding Devonian metasediments (Figure 1). The quarry covers an area of

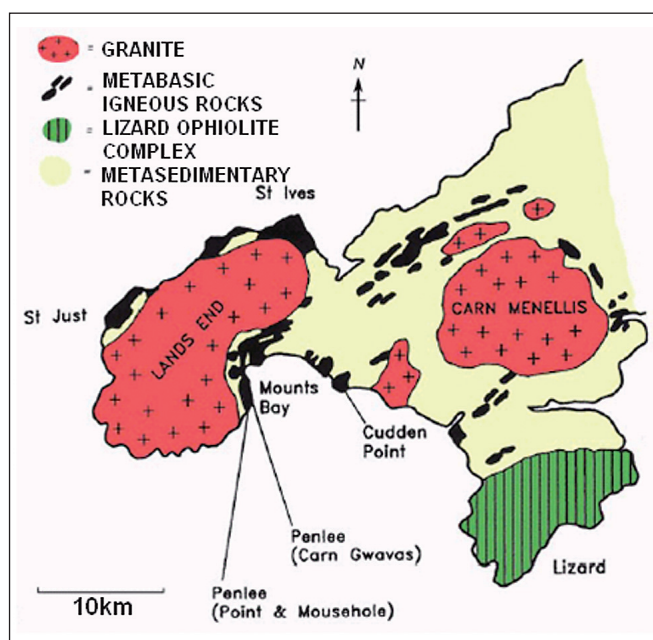


Figure 1. Geological map of West Cornwall showing the location of the metabasic igneous rocks and the general location of Penlee Quarry at Carn Gwavas. After Denby (2004).

approximately 23 ha and is roughly oval in shape with an irregular boundary. It is excavated to a maximum depth of 130 m with the lower 25 m being flooded to Ordnance Datum (Scott and Walton, 2010).

The western highwall has its toe at *c.* 10 m A.O.D., is about 90 m high and has a single debris choked bench at *c.* 45 m A.O.D. The slope runs parallel to the site boundary, immediately beyond which lies a public footpath and arable farmland (Figure 2).



Figure 2. Location of Penlee Quarry showing the generalised slope ornamentation for the western highwall and the quarry pond.

HISTORY

Excavation works began at Penlee Quarry in the late 1880s and continued well into the 1990s. The stone was predominantly used as roadstone, but also for a limited amount of armourstone and for making concrete blocks (Stanier, 2005). Reportedly all quarry records have been lost in fires or through storm damage, however much information can be obtained from old aerial photographs (Scott and Walton, 2010). The benching of operational faces began in the 1950s and much of the western highwall was excavated between the late 1950s and the mid 1970s. The rock is very strong with a crushing strength of 475 MPa and a density of 2.95 t m⁻³, hence large explosive charges were used which resulted in significant blast vibrations causing extensive fracturing and break-back of the bench crests. The blasting was poorly regulated with abandoned misfires and significant damage to the resulting quarry faces, which have irregular profiles in plan and section, and the opening of near-surface joints. This and associated blast hole deviation is apparent from face inspection.

It is inferred from aerial photographs of the late 1950s that the upper 10 m of the western highwall was excavated without blasting, and from photographs during the 1960s with blasting in which narrow benches were formed at 45 m A.O.D. and locally, rudimentary discontinuous small benches at other levels. The western highwall is approximately 200 m in length at its crest, but less than 50 m in length at the toe. At the northern end of the western highwall backfill was tipped over the contiguous northern face, it is not known if this was to support a failing slope or merely to dispose of unwanted rock. In 1999 the owners obtained planning permission to extend and deepen the quarry. This was to be achieved by increasing the height of the western highwall by a further 100 m at a gradient of 62°.

SLOPE MOVEMENTS

In 2003 in the absence of any quarry records and prior to any significant site works being undertaken for the proposed development, initial geotechnical inspections of the western highwall indicated that there may have been some previous rockfall although none had been reported. Rockfall was apparent from vegetated scree piles observed along sections of the narrow 45 m A.O.D. bench. As a consequence all access to the western face was prohibited and inner and outer barriers constructed. There was however no evidence of recent rockfalls (Figure 3a). In 2005 a rockfall occurred near the centre of the slope with a resulting pale coloured collapse scar and some debris collecting on the 45 m bench (Figure 3b). Further movement occurred in 2007 which could be described as a high angle debris slide (Figure 3c) and again in 2009 at four locations (Figure 3d) resulting in material choking the 45 metre bench.

On 25 January 2010, a more significant failure occurred involving a high angle wedge of rock weighing approximately 2,000 t which fell from just below the crest of the highwall (Figure 4). Debris from the face choked the 45 m bench and then fell onto the quarry floor 35 m below. This material also formed a debris scree pile, but stayed within the inner exclusion zone demarcated by a 2 m high bund. Further precautionary measures were established since potential for distinct wedge and toppling failures was identified. However early the following year, a more significant collapse occurred.

In January 2011 hairline cracking (0.5 mm wide) was identified during routine daily checks along the boundary road immediately behind the edge protection at the crest of the highwall. This cracking continued into February and lengthened to more than 85 metres (Figure 5). At 05:30 hours on 22 February 2011, a collapse of 7-8,000 t occurred leaving a large scar with several clear discontinuity surfaces (Figure 6a). The collapse may have been assisted by extensive freezing and thawing of the face over the winter, followed by heavy rainfall just prior to the collapse. Although the collapse was expected, the nature of the resulting ground movements was not. As noted, the slope toe was significantly less in length than the slope crest and the debris landed in a confined area at the 10 m level. From the resulting piles and spreads of material (Figure 6b) it is apparent that rock fragments and debris travelled large distances from the toe of the slope. A buoyancy aid on the crest of the slope down to the quarry pond, 90 m from the toe, had 5 mm fragments of rock embedded within it (Figure 6c) and the surrounding ground with an area of *c.* 1.0 ha up to a level of 35 m A.O.D., was covered in a thick layer of dust. Two distinct ridges of small rock debris (<10 kg) were formed on either side of what appears to have been a possible flow slide although there is little doubt that much of the finer debris was dispersed by the air blast.

The plan and cross-section in Figure 7 show the extent of the collapse scar and debris pile, highlighting the debris pile with a shallow gradient of 7°. The positions of the choked 45 m bench, the buried inner exclusion barrier (2 m high bund) and position of the buoyancy aid are indicated. The collapse scar extended 35 m along the perimeter road, but the cracking extended more than 85 m along the road in places more than 10 m behind the crest of the slope. Subsequent calculations have shown that a further 40-60,000 t of rock could imminently collapse in relation to the discontinuity patterns that had become apparent. In the context of what occurred on the morning of 22 February there appeared to be some potential for even more significant flow slide/air blast phenomena and as such the event was reported under RIDDOR (Anon, 1996) as clearly this was a dangerous occurrence of relevance to this and other operations.

Additional protection measures were imposed including the closure of the quarry roads at the western crest, access to all ground in front of the highwall was prohibited, and steps taken to close the public footpath and advise the landowner beyond the site boundary accordingly. Detailed investigations were put

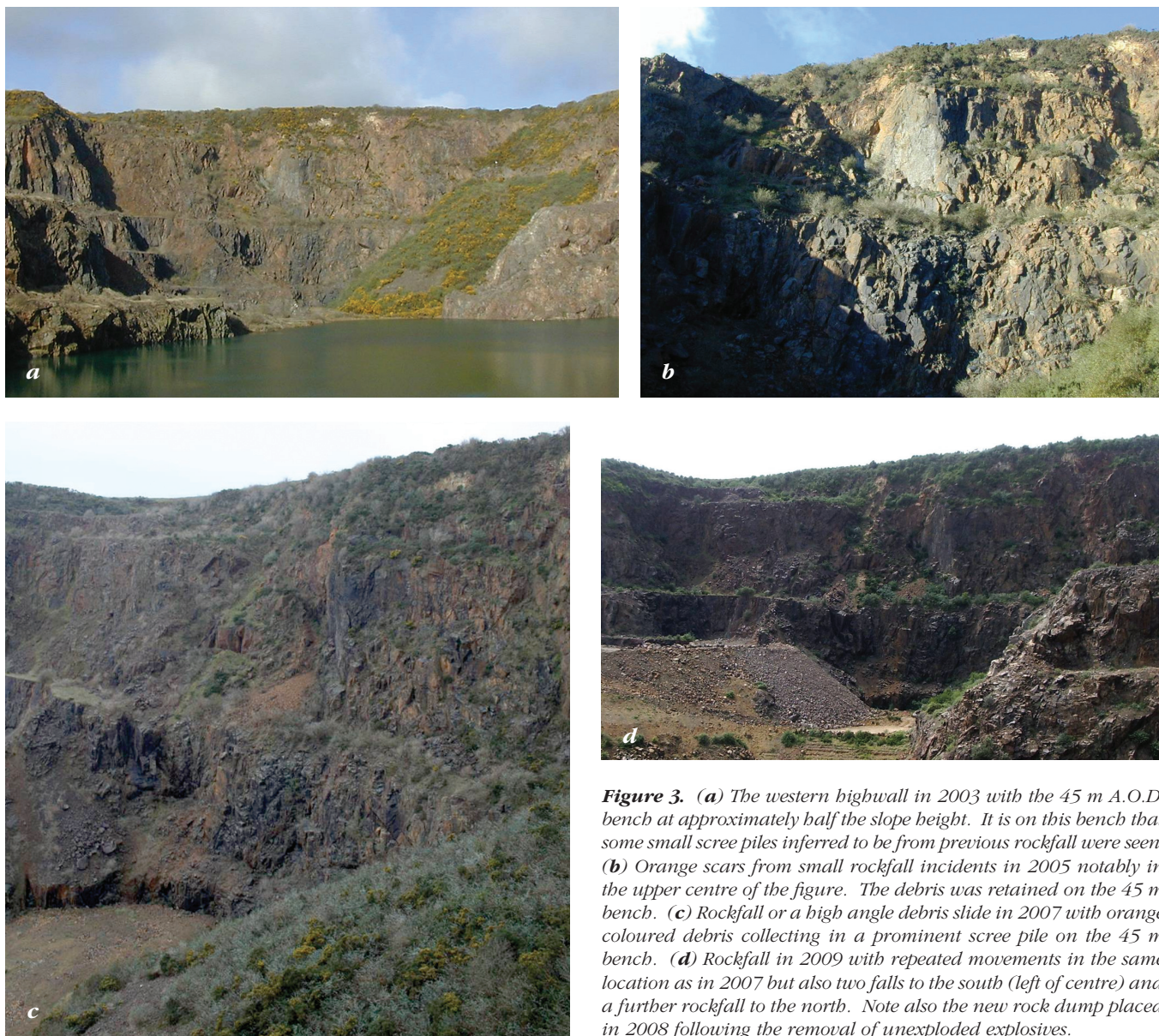


Figure 3. (a) The western highwall in 2003 with the 45 m A.O.D. bench at approximately half the slope height. It is on this bench that some small scree piles inferred to be from previous rockfall were seen. (b) Orange scars from small rockfall incidents in 2005 notably in the upper centre of the figure. The debris was retained on the 45 m bench. (c) Rockfall or a high angle debris slide in 2007 with orange coloured debris collecting in a prominent scree pile on the 45 m bench. (d) Rockfall in 2009 with repeated movements in the same location as in 2007 but also two falls to the south (left of centre) and a further rockfall to the north. Note also the new rock dump placed in 2008 following the removal of unexploded explosives.

in hand and following this a replacement slope was designed as outlined below.

INVESTIGATIONS

The first investigations in 2004 included the collection of basic geotechnical data on joint sets and their continuity. This was primarily based on rock face data from the southern, eastern and northern faces as access to most of the western faces was prohibited. It indicated some potential for steep angled wedge failures and some toppling, but nothing of great significance on the western face; these findings were consistent with the rockfall and debris slides seen in the 2000s.

Following the observed cracking in January 2011, and the subsequent collapse on 22 February, it was decided to evaluate the geotechnical parameters controlling the slope using laser scanning methods. This is a widely used method of remotely characterising discontinuity characteristics and identifying potential failure modes within the extractive industries (Poulton *et al.*, 2006; Sturzenegger and Stead, 2009). A Leica HDS 3000 was used for its surveying accuracy (point accuracy of ± 6 mm, distance accuracy of ± 4 mm, and range capability of 1-100 m) and field of view range (360° horizontal and 270° vertical) (Leica Geosystems, 2011). The scanner transmits and collects laser pulses reflected off the surface of the slope which are recorded as a series of points with x, y, z coordinates and can be

displayed together as a 3D image known as a point cloud. Despite the scanners field of view and range allowing it to scan the face in one set up (Fekete *et al.*, 2010), irregular slopes such as the highwall at Penlee Quarry contain surfaces which will remain oblique to the scanner; this prevents reflections from these surfaces being recorded and results in ‘shadows’ occurring in the point cloud image. Three separate scans were therefore undertaken at different locations with different orientations and elevations to limit these ‘shadows’ occurring (Coggan *et al.*, 2007; Sturzenegger and Stead, 2009); the scanner locations are numbered 1 to 3 in Figure 8. The three scans were merged together and georeferenced using a global positioning system (GPS) and then converted to an ASCII format for analysing using the Split FX software (Split Engineering LLC, 1997-2011).

Figure 9 shows a photograph and point cloud image of the 2011 failure scar on the upper region of the western face. The point cloud data were analysed using Split FX to identify the dip and dip direction of identified surfaces that represent individual discontinuities within the rock mass. These surfaces or ‘patches’ were manually identified rather than relying on automated routines. This involved rotating the point cloud until it was perpendicular to the identified plane before the patch is inserted to ensure the correct orientation of the patch. It should be noted patches cannot be inserted on shadows on the point cloud as these areas have no points. By representing this



Figure 4. The January 2010 wedge failure showing the scar below the crest of the highwall and debris clogging the 45 m bench, with some spillage onto the face below. The release surfaces creating this wedge have been identified using the stereoplot in Figure 10 as Set 2 and Set 4.



Figure 5. Cracks in the western quarry access road being marked out in January 2011 to aid the identification of further movements.

orientation data on a stereoplot four dominant joint sets were identified, as shown in Figure 10. Kinematic analysis of the data suggests that Joint Set 1 forms potential planar failure surfaces or basal planes for direct toppling, in addition to the potential wedge failure from intersections of joint sets identified previously. It is unclear whether the 2011 collapse was a result of planar failure (Set 1) or toppling failure (Sets 2

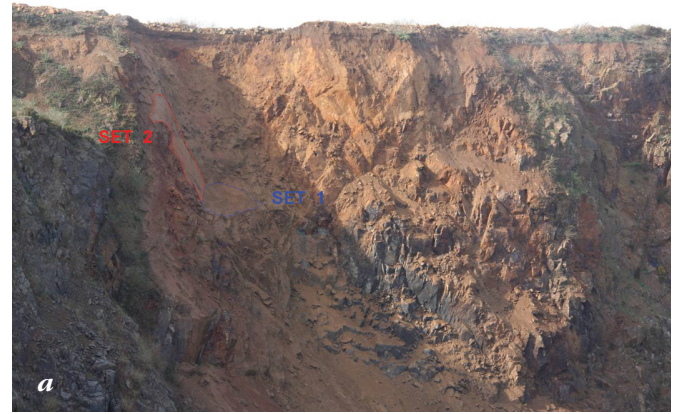


Figure 6. (a) Scar of collapse in February 2011 showing discontinuities inclined out of the highwall (Set 1) and release surfaces similar in alignment to those of the 2010 collapse (Set 2). Figure 10 shows the stereoplot derived from the laser scan of this face with allocation of the discontinuity sets. (b) The debris pile at the toe of the February 2011 collapse. Photograph taken from Laser scan position 3 (see Figure 8). (c) A buoyancy aid at a distance of 90 m from the toe of the highwall with 5 mm rock fragments embedded from the resulting air blast following the collapse. Figure 7 shows the location of the buoyancy aid in relation to the slope face.

and 3) or a combination of both (with Set 1 forming the basal plane); however the risk of further failure was apparent with movements extending beyond the site boundary behind the crest of the slope. The Split FX analysis primarily focussed on identifying the orientation characteristics of the discontinuities although it is also possible to establish other parameters such as persistence and spacing of the respective sets.

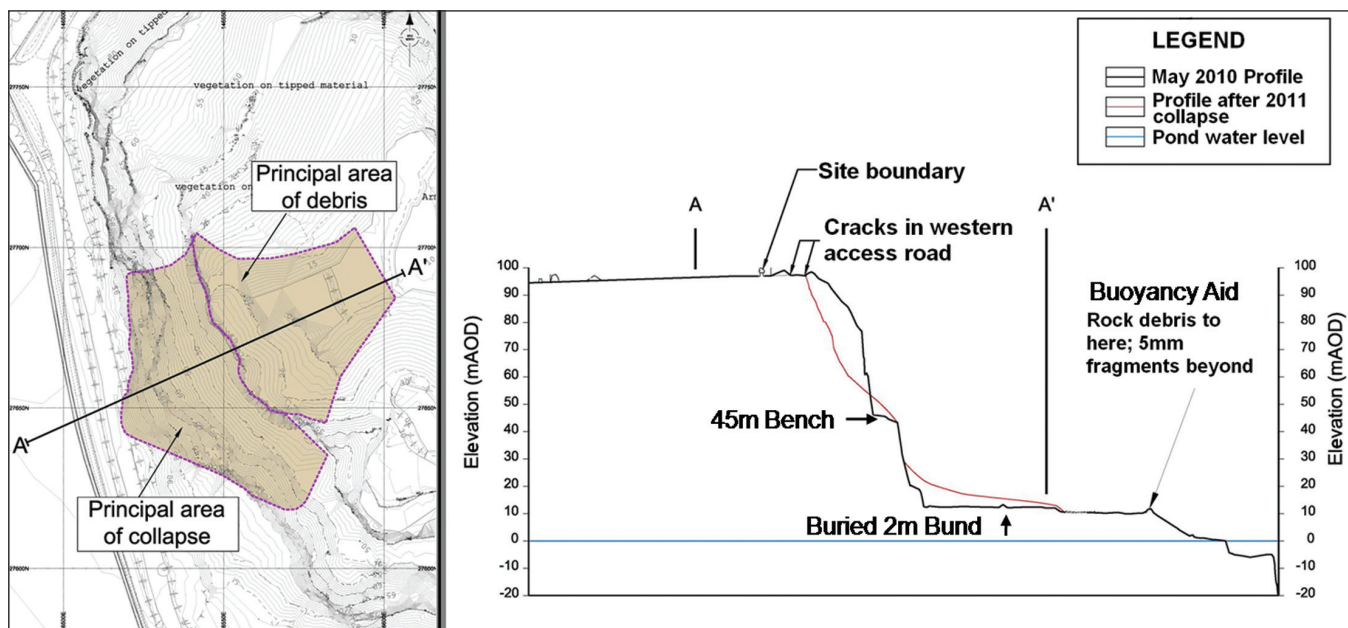


Figure 7. A plan and cross-section of the 2011 collapse showing movements in relation to the site boundary and the western quarry access road.



Figure 8. The set up for the laser scanning survey (left) and the Google image of the quarry showing the 3 survey set up positions (right). The illustrated set up is in position 2; the Google image of the quarry dates from before the collapse.

PROPOSED STABILISATION WORKS

The aim is to use the quarry to produce armourstone for export and arrange the after-use of the quarry for residential and commercial development with a marina. Both activities depend upon the ability to operate safely during extraction and construction and require safe long-term slopes needing minimal maintenance. With the limited area of land beyond the crest of the highwall, and that land subject to further movements, and with the risk of rockfalls and flowslides preventing access to the slope, stabilisation was a difficult issue. No system of support works could safely and practicably be considered feasible.

Projections of discontinuity Set 1, assuming a worst case scenario, as shown in Figure 11 indicate that movements could extend beyond the boundary of the quarry into the land to the west depending on the inferred discontinuity persistence. In

consequence it was agreed to purchase sufficient land for a viable scheme to achieve the short- and long-term objectives for the quarry.

Remedial work such as anchoring, bolting and face netting cannot be achieved safely within the context of the likely scale of any active movements and the only practical long-term solution within the context of the proposed site development was to flatten and buttress or reprofile the overall slope. The proposal was therefore to acquire the land to the west and to excavate a series of benches commencing with working to the rear of the landslip and raising a buttress at the toe of the slope using excavated material. A small part of this buttress has already been formed from material excavated during the removal of old unexploded explosives in 2008/9.



Figure 9. Split FX software point cloud image of the upper region of the western face from the 2011 scanning survey (right), and a photograph of the same slope (left). Figure 10 shows the stereoplot derived from the laser scanning of this face.

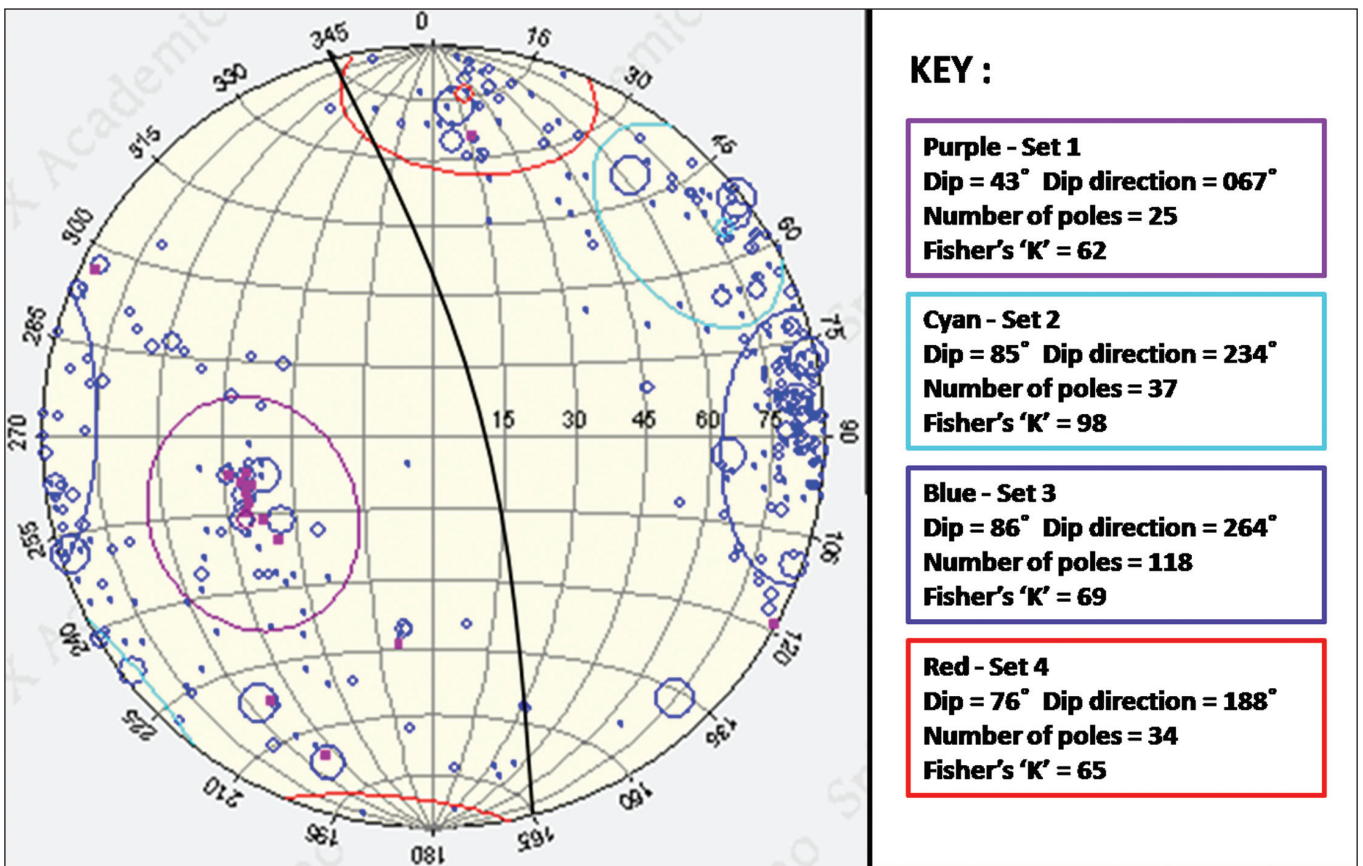


Figure 10. The stereoplot based on manually inserted 'patches' onto the point cloud image shown in Figure 9 for the 2011 collapse. Joint Set 1 with a general dip of 43° in the direction of 067° was found to be a significant structural element to be accommodated in the proposed remedial works.

The excavation proposed shown in Figures 11 and 12 extends from the western limits of the proposed armourstone quarry in the south east to the northern end of the western highwall. This aims to provide access and space for ramps, a safe replacement road behind the landslip area and haul roads down to the proposed buttress area incorporating the existing buttress from the 2008/9 works.

The proposed benching system comprises benches at the 45, 60 and 75 m A.O.D. levels and a minor 'rockhead bench' at 90 m A.O.D. The bench heights are 15 m and the basic bench widths nominally 25 m wide. This configuration ensures that the lowest angled adversely orientated discontinuities within

the rock mass, as identified in the investigations following the 2011 collapse, are only undercut at bench level and not by multiple benches. The levels and configurations of benching are modified at the northern and southern ends of the excavation to accommodate existing ground levels. Bench faces are assumed to be 1 to 3 (horizontal to vertical) but would be modified by face dressing, especially at the crest, and by debris placed at the toe of each bench reaching up to a third to half the bench height. Benches would have 2 m high outer edge protection and would be covered with roughly sorted material generally of less than 300 mm. Allowing for break-back and dressing slope crests, this would give a bench

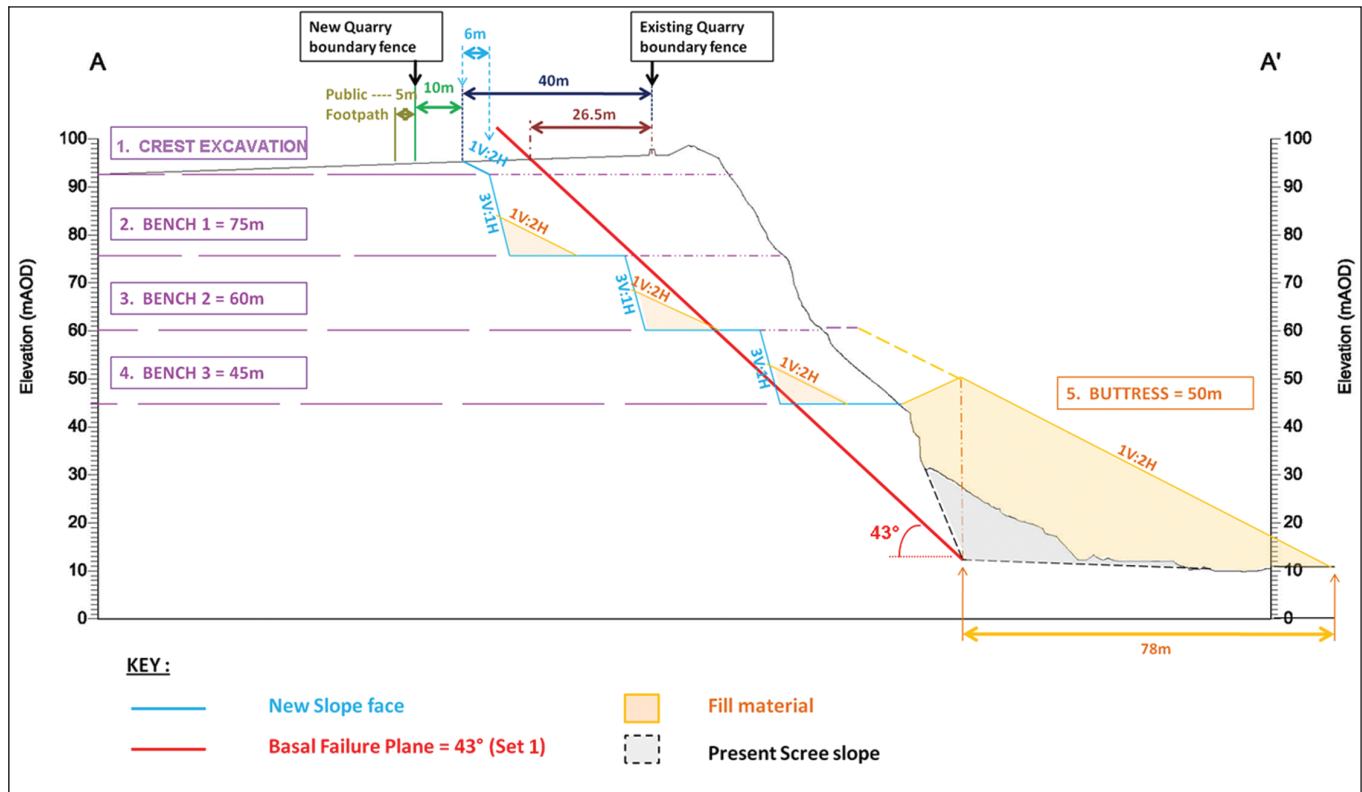


Figure 11. A cross-section showing the proposed stabilisation works using bench excavation and buttressing up to 45 m A.O.D. and buttressing of each excavated bench. (N.B. this cross-section is along line A-A' in Figure 12, but extends c. 90 m to the SW and c. 30 m to the NE).

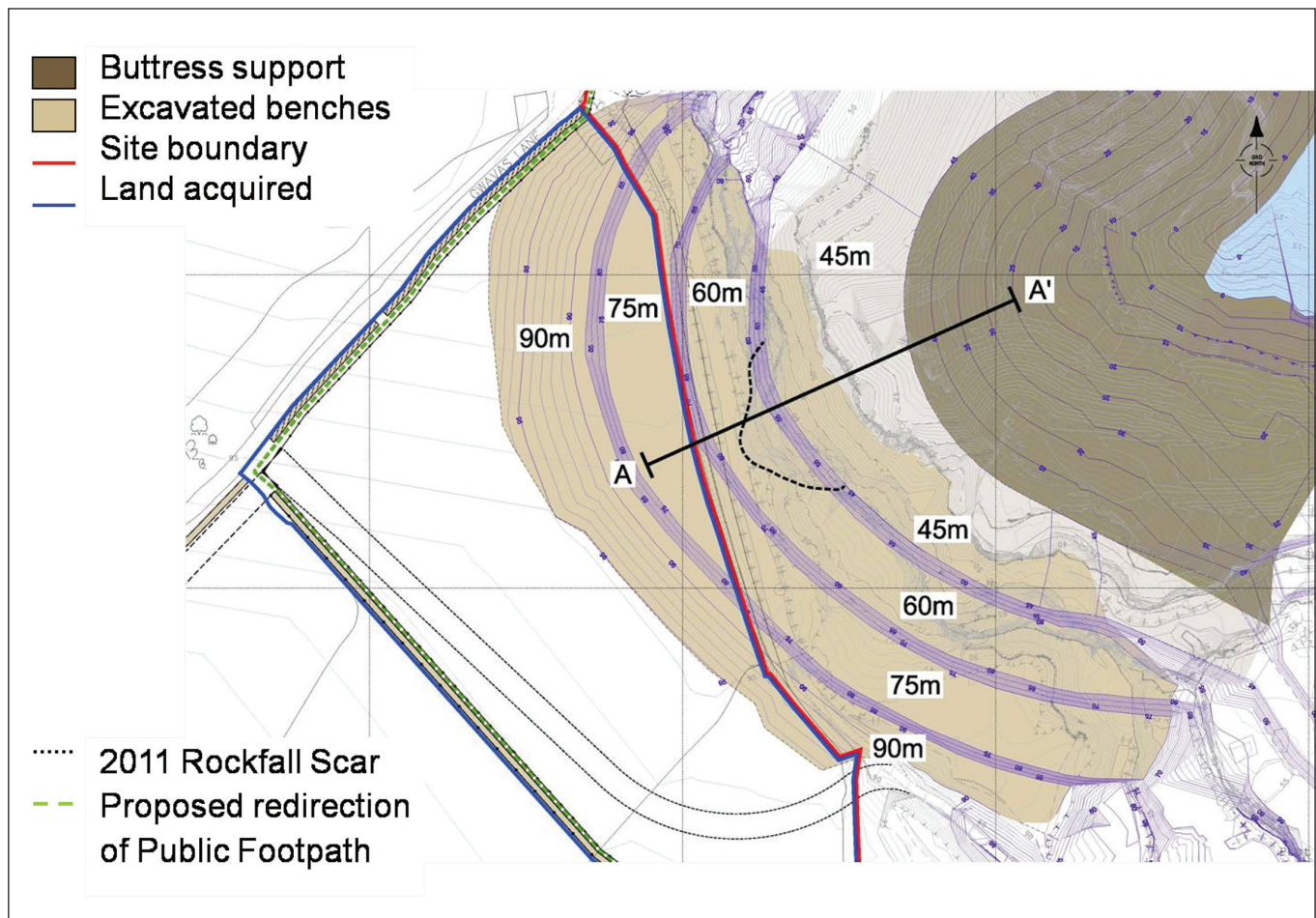


Figure 12. A plan showing the proposed excavation benching, buttressing and the likely diversion of the public footpath. (N.B. the cross-section for line A-A' is shown in Figure 7).

between the edge protection and the buttress material of about 5 m for a 20 m-wide basic bench. Limited rock excavation would occur between the 60 m and the 45 m level, but a significant buttress bench would be formed of excavated material at the 45 m level. The total excavation volume of material to form the overall benching would be 346,000 m³.

As designed, this system of benching and buttressing allows for excavation to commence at the southern/south eastern end of the relevant area and to progress into and behind the landslip area where there is active cracking. Excavated material would be hauled via temporary ramps to the existing buttress, which would be progressively raised and extended to form the buttress shown in Figures 11 and 12.

The excavation would be undertaken with controlled blasting, possibly with some pre-split blasting of final faces. The equipment employed would be a 25-30 t shovel and small articulated dump trucks (up to 30 t). The upper level above 90 m could in part be excavated without blasting or without significant blasting.

CONCLUSIONS

There are several findings of importance beyond their relevance to this site:

- 1) Legacy slopes can be potential long-term hazards and although difficult to undertake, their geotechnical assessments need to cover the underlying geotechnical constraints. In 2003, the long-term hazards were far from clear although in hindsight the indications were there. There was some evidence of previous rockfall which may be an early indicator of potential large-scale failure. Kinematic analysis of remote scanning data highlighted the potential for further discontinuity-controlled failure in the western face at Penlee Quarry, where Joint Set 1 may form potential planar failure or basal planes for direct toppling. It is considered that remotely captured data is an essential part of geotechnical assessment where access to the face is restricted or considered dangerous for legacy slopes.
- 2) High level collapses on steep high slopes with minimal benching will not necessarily produce a 'standard' scree-type debris pile. There have been no previous reports in Britain of such flow slide/air blast movements from excavated slopes in quarries. However, collapses of aggregate stockpiles in quarries ending in flow slides have been known since the 1960s. It is possible that the confined space into which the debris fell assisted in the mechanism. Larger volumes of rock could have travelled much further, perhaps several hundred metres. Fortunately this part of the quarry was only occasionally visited after close inspection, although it was a stocking ground for armourstone. In other operational situations the consequences could have been critical. There are many working quarries in Britain with slopes of similar size or with higher slopes as well as some restored to other uses. This slope is only 50 to 60 years old. These other slopes of a similar age should be checked to eliminate the potential for similar events.
- 3) The inner barrier in front of the toe was not a protection against larger slope movements. Designing barriers on the basis of standard rockfall programs is not sufficient if high level slope failures may occur. If these are possible a much larger area should be cordoned-off. The possibility of high level failures not being retained on benches should always be considered. Benches are generally intended as protection against rockfall and consequential damage as well as the means to achieve the appropriate overall slope gradient. Unfortunately a

common view in mining and quarrying operations in the 1950s and 60s was that such slopes only needed to be marginally secure for the life of the operation. Moreover the maximisation of mineral recovery was often a prime objective and the need for long-term stability was seldom assessed in detail. Benches are now often seen as restoration features, but their underlying design function remains important. Mistaken approaches to previous quarry slope design should never be forgotten especially when these slopes remain in the upper part of existing operations.

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