

Welsh Office

A Selection of Technical Reports Submitted to The Aberfan Tribunal



London : Her Majesty's Stationery Office 1969

A Selection of Technical Reports submitted to the Aberfan Tribunal

Foreword

In our Report* published last year we said that as soon as we were constituted as a Tribunal we arranged for a series of scientific investigations to be started under the general direction of Professor A.W. Bishop, London University. The National Coal Board brought in expert members of its own staff and also independent experts and the Aberfan Parents' and Residents' Association likewise engaged independent expert advisers. In addition certain other investigations were put in hand on behalf of some of the parties who appeared before the Tribunal. In view of their scientific interest, we thought it right to arrange for the separate publication of seven of the reports submitted by these experts to the Tribunal, and they are reproduced here with exactly the same text as was originally submitted. Most of the original drawings were unsuitable for reproduction within the size of this publication and many have been re-drawn. In some cases there was sufficient similarity between the drawings used by different experts to make it possible to use one drawing here without detracting from the information given in the original report.

Certain of the written reports submitted to the Tribunal were required simply as formal evidence and these have not been reproduced in this publication.

The task of preparing this volume for publication has been performed by Mr A.D.M. Penman with assistance from the authors of the reports and others. We acknowledge our debt to him and to all who helped him.

EDMUND DAVIES
HAROLD HARDING
VERNON LAWRENCE

R. LLOYD THOMAS, *Secretary*
November 1968

*H.L. 316
H.C. 553

Contents

- Item 1. Geotechnical Investigation into the Causes and Circumstances of the Disaster of 21st October 1966
by A.W. Bishop, J.N. Hutchinson, A.D.M. Penman
and H.E. Evans p. 1
- Item 2. Report on the stability of Aberfan Tip No. 7
by J.K.T.L. Nash p. 83
- Item 3. Inquiry into the Aberfan Disaster
by G.M.J. Williams p. 91
- Item 4. Geological Report on the Aberfan Tip Disaster of
21st October 1966
by A.W. Woodland p. 119
- Item 5. Geological Report on the Tipping Site and its
Environs at Merthyr Vale and Aberfan
by L.R. Moore p. 147
- Item 6. Report on Mining Subsidence
by K. Wardell and R.J. Piggott p. 187
- Item 7. Meteorological conditions relating to the Aberfan
Inquiry
by A. Bleasdale p. 207
- Item 8. Interpretation and analysis of photography covering
the Aberfan area carried out by Fairey Surveys Ltd.
(Bound separately)

Geotechnical Investigation into the Causes and Circumstances of the Disaster of 21st October, 1966

Alan W. Bishop MA PhD DSc(Eng) MICE, Professor of Soil Mechanics in the University of London, Imperial College

John N. Hutchinson BSc PhD AMICE FGS, Senior Lecturer in Soil Mechanics, Imperial College, University of London

Arthur D. M. Penman MSc AMICE, Member of the Council of the Institution of Civil Engineers, Principal Scientific Officer at the Building Research Station

Haydn E. Evans BSc PhD FGS, Lecturer in Civil Engineering, University College of Swansea, University of Wales

Contents

- 1 Introduction
- 2 Some earlier slips in South Wales and their relevance
- 3 Geology of the site in the immediate vicinity of the tip and soil properties of the natural strata
- 4 Ground water conditions
- 5 Properties of tip material
- 6 Pore pressures observed in tip material
- 7 History of Tip 7
- 8 Discussion of mechanism of failure
- 9 Conclusions

Appendices

- 1 Summary of paper 'Landslides in South Wales' by Professor George Knox
- 2 Press reports of Abercynon slip
- 3 Details of soil tests, piezometer readings, etc
- 4 Stability analyses
- 5 Model tests
- 6 Evaluation of quantities involved in the history of Tip 7

Recommendations

References

1 Introduction

In preparing this Report we have attempted to give a concise summary of those aspects of our investigation which appear to be directly relevant to the four questions posed by the Chairman at the opening session of the Tribunal:

- (1) What exactly happened?
- (2) Why did it happen?
- (3) Need it have happened?
- (4) What lessons are to be learnt from what happened at Aberfan?

Details of tests are given in appendices, together with information which appears at this stage to be of marginal relevance to the four questions, but which may be of value to future studies in this field. In this latter connection we would draw attention to the present lack of information on the engineering properties and behaviour of tip materials and on the seasonal variations in water pressure within tips and the strata on which they are founded. It will be one of our recommendations that some of the observations and investigations begun during this present Inquiry should be continued, under the sponsorship of the National Coal Board, the Science Research Council or the National Environmental Research Council, by the Institute of Geological Sciences, the Building Research Station and appropriate University Departments of Civil Engineering and Mining Engineering.

A rigorous scientific investigation involving precise calculations of the factor of safety of the structure has been particularly difficult in this case. The structure with which the Inquiry is concerned, though comparable in magnitude with our major road or reservoir embankments (the height from toe to crest being about 200 ft) is a colliery rubbish tip, and the stages of its construction and its shape immediately prior to the slip of October 1966 are not well documented. The internal water pressures in the foundation and the tip were not measured and have since been substantially modified. Most of the relevant material from the tip has moved many hundreds of yards down the mountainside.

Our conclusions therefore depend not only on the measurement of the properties of the foundation strata and the tip material, but on a careful examination of the behaviour of the tip in the years preceding the ultimate collapse. In this examination we have enjoyed the co-operation of the Ordnance Survey, the Royal Air Force, Hunting Surveys Ltd, the Department of Photogrammetry and Surveying of University College London, and the Meteorological Office. The programme of boreholes has been planned jointly with Dr A.W. Woodland, of the Institute of Geological Sciences, and co-ordinated with work initiated by the National Coal Board. Borehole logs have been agreed by the geologists of the I.G.S. and the N.C.B. Some 80 boreholes have been completed and are shown on Fig. 1.1 (folded drawings are contained in the wallet).

The National Coal Board have co-operated most willingly in the provision of offices, heavy plant to facilitate the site investigation, and where necessary photographic and surveying services, often at very short notice. Some difficulties have arisen in carrying out our investigation due to safety requirements and due to the problems involved in handling heavy plant and carrying out large-scale earth-moving operations under the prevailing weather conditions. Very significant data about the nature of the slip under the southern section of the tip, only began to be available to us on 8th February 1967 and the area immediately uphill of the spring revealed by the October 1966 slip has not been cleared at the date of writing this Report.

In examining the data on which this Report is based it has become apparent to us that all the events contributing to the disaster cannot be associated with a single cause. Several factors were involved, which separately could have caused a slip, though not necessarily a disastrous one. Our conclusions depend on the general agreement of data from a

number of sources, and are not dependent on the precise measurement of particular properties or dimensions.

Evidence given during the course of this Inquiry indicates that it is necessary to clarify the distinction between an unsafe and a safe structure. The fact that a structure is standing at the time of inspection is, by itself, no indication that it will not collapse the following day. A discussion of the engineering concept of 'factor of safety' is outside the scope of this Report, but is presented most lucidly in Chapters 11, 12 and 13 of a short book by Sir Alfred Pugsley entitled *The Safety of Structures* (1966).

2 Some earlier slips in South Wales and their relevance

It is relevant to the four questions posed by the Chairman of the Tribunal to examine the background of earlier slips in the Welsh valleys against which the present disaster is to be seen. An exhaustive survey has not been attempted, but the following information is considered to be useful.

(I) *A paper on 'Landslides in South Wales Valleys' by Professor George Knox, FGS, MIME, read and discussed in 1927*

This paper was read and discussed in Cardiff on 29th March 1927, with further remarks and discussion on 28th April 1927. This is published in full in the *Proceedings of the South Wales Institute of Engineers*, Vol. 43, pp. 161–247 and 257–290. A critical summary is given in Appendix 1.

This paper is of importance because of the great interest which it aroused at the time in landslides, including slides involving colliery refuse. Though Knox's understanding of the physical mechanism and applied mechanics of the slide is now considered inadequate, he correctly emphasised the over-riding importance of water in causing landslides. He also recognised that in the area of South Wales under discussion most of the water concerned in a landslide is derived from percolation from the joints of the Pennant sandstone rather than from direct rainfall on the slide area.

Knox recognised that the most generally effective measure for remedying landslides was adequate drainage of the seat of the slide. In the discussion reference was made to preparatory drainage of sites selected for tipping. The hope was expressed that 'mining engineers would make a more careful investigation of so-called suitable ground for colliery tips'.

(II) *The Abercynon slide on 5th December, 1939*

This slide is described in the following documents :

- (a) An unsigned Powell Duffryn report dated December 1939. This is accompanied by two survey drawings dated 8th January 1940.
- (b) A report prepared by Mr W. Brynmor Davies entitled 'Rubbish Tip Slide, Cilfynydd Common, on 5th December 1939'. This includes photographs of the slide and was presented in February 1940.
- (c) Report in the *South Wales Echo* on 5th December 1939.
- (d) Report in the *Western Mail* on 6th December 1939. This report is included as Appendix 2.
- (e) A text-book for mining engineers by Professor J. Sinclair entitled *Ground Movement and Control at Collieries* and published in 1963.

The reports are in general agreement in their description of the slide. The slide occurred at about 1.40 p.m. on 5th December about one week after a period of unusually heavy rainfall (details of which are given in evidence from the Meteorological Office). The slide travelled down the mountainside for about 1430 ft, 'at a terrific speed' according to the Press accounts, blocked the roadway for 585 ft with rubbish to a depth

of 8 ft, breached the canal and blocked the River Taff with rubbish to a depth of 15 ft.

This slip, which is the nearest parallel in its speed and destructive effect to that at Aberfan and could have resulted in a similar disaster had inhabited property lain in its path, was visited briefly by the senior author of this Report in 1940 and left a lasting impression.

The slip is relevant to the present investigation in several respects :

- (i) It took the form of a destructive flow slide although accompanied by no significant outflow of water. A comparison of the sections of the slides at Abercynon and at Aberfan in 1966 (Fig. 1.2 in wallet) shows that over much of its path the former slide had a flatter gradient.
- (ii) The material did not include tailings of the type tipped at Aberfan from February 1962.
- (iii) It was an active tip, placing of material at the relevant section having taken place shortly before the failure. The photographs accompanying the report by Mr Brynmor Davies (for example, Fig. 1.3) suggest that the original cross-section indicated on his survey is nominal and is dissimilar to the actual profile of the remaining sections of the tip immediately adjacent to it.
- (iv) An 'ominous move' of the tip on the day before the final slip is referred to in the Press reports. The survey plan included in the Powell Duffryn reports suggests that the toe of the tip had bulged at this section at an earlier date.
- (v) The original version of the Powell Duffryn Report entitled 'The sliding of colliery rubbish tips' was dated December 1939 and, it may be inferred, was a consequence of this event.

The various reports are not in agreement as to the initial cause of the slip, and differ from the explanation given to the senior author in 1940. In the absence of a detailed investigation we can only suggest that several of the factors found to have been operative at Tip 7 at Aberfan would be of significance in this case also :

- (a) The Geological Report by Dr A.W. Woodland indicates that the tip lay across the probable spring line of water emerging from the Daren-ddu sandstones and over a seepage point of water from the Cefn-Glas sandstone.
- (b) The material was loosely dumped, the outer part by over-tipping. For the material to be in a loose state is a pre-requisite of flow slides.
- (c) Some prior movement occurred.
- (d) The foundation consisted of Head and Boulder Clay, which can have a lower angle of internal friction than tip rubbish, sloping steeply towards the valley. Excess pore pressure below the boulder clay was likely in periods of heavy rainfall.

(III) *The slide at Tip 4 at Aberfan on 21st November 1944*

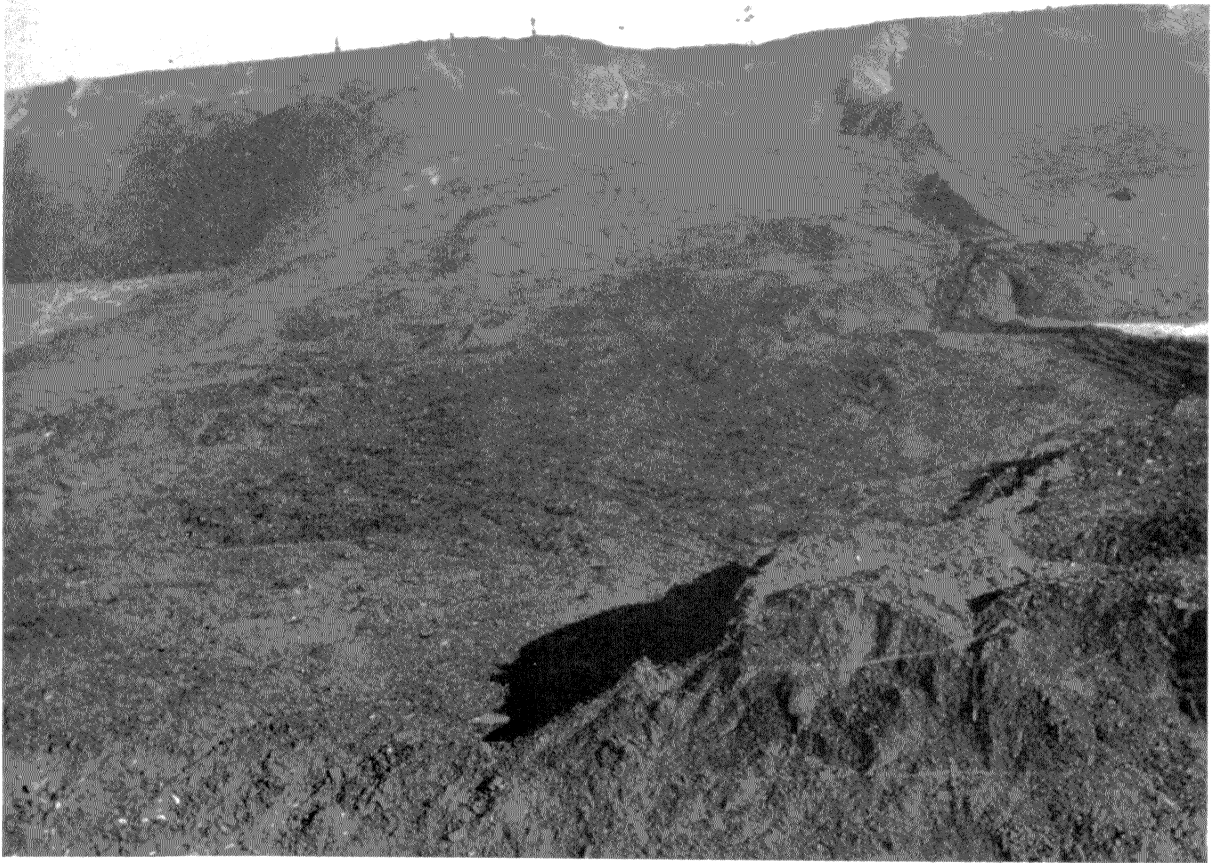
The slide is described in the evidence before the Tribunal. It is also described in the following documents :

- (a) Photographic Interpretation Report of the Joint Air Reconnaissance Intelligence Centre (U.K.) (J.A.R.I.C.), and of Fairey Surveys Ltd. Photography of 3rd August 1945 (their Fig. 1 *et seq.* see Item 8).
- (b) Interpretation and Analysis of Photography covering the Aberfan Area by Fairey Surveys Ltd (their Fig. 1 *et seq.*).
- (c) Ordnance Survey Map dated 1957.

A major rotational slip took place accompanied by a flow slide on a rather narrow front reaching to within 550 ft of the disused canal above the school.

The slip is relevant to the present investigation in several respects :

- (i) It took the form of a potentially destructive flow slide, although accompanied by no significant outflow of water. The gradient on which it flowed is much the same as at Tip 7 at Aberfan in 1966. The developed sections are compared in Fig. 1.2.



1.3 Flowslide at Abercynon, December 1939.

- (ii) The material did not include tailings of the type tipped at Aberfan from February 1962.
- (iii) It was an active tip, placing of material having continued until the final failure.
- (iv) Some sliding of the tip had occurred before the final failure.

This is supported by statements made in evidence before the Tribunal. It is also supported by our interpretation of the spurs extending from the tip to the south-west on either side of the slide and particularly on the southern side. These appear on J.A.R.I.C. Fig. 1, and rather more clearly on their Fig. 4 (photography of 12th October 1951). The interpretation by Fairey Surveys Ltd supports this view and on their Fig. 1, note 108, indicates the estimated outline of the southern base of Tip 4 prior to the slide. Similar but smaller spurs may be seen on the Powell Duffryn plan of the Abercynon slip. A detailed examination of this slip has not been carried out, but attention is drawn to several features :

- (a) The Geological Report by Dr A.W. Woodland indicates that the tip lay across the outcrop of a thin mudstone, possibly at the horizon of the Brithdir Rider. The 'rise' of stream on the Ordnance Map surveyed in 1898 approximates to this position.
- (b) The material was loosely dumped, which is a prerequisite of a flow slide.
- (c) Some prior movement occurred, probably of large magnitude. Detailed evidence in quantitative terms is difficult to obtain on this point due to the absence of earlier low-level aerial photography.
- (d) The preceding rainfall was heavy but not unusual and corresponded closely to that at Aberfan prior to the October 1966 slip. Details are given in the evidence to the Tribunal from the Meteorological Office.

(IV) *The slide at Tip 7 at Aberfan, 1963*

Further reference to this slip will be made in section 7 (p. 21). Evidence before the Tribunal suggests that a significant rotational slide accompanied by a small flow slide occurred in the second half of October or the first half of November 1963.

This is supported by evidence given by the tipping gang, by the interpretation of aerial photography (for example, J.A.R.I.C. and Fairey Surveys Ltd, Fig. 8, notes 55 and 56), and by the evaluation of quantities (Appendix 6). It is also consistent with the nature of the slip surface discussed in section 8 (p. 30) and with the lack of forward progress of the crest of the tip indicated by the cross sections (Fig. 1.4a).

(V) *The failure of the tip at Tymawr in 1965*

From the information available to us it appears that this breaching of the tip was different in character from the slides mentioned in sections 2(II), 2(III), 2(IV) and from the final slip at Aberfan in October 1966.

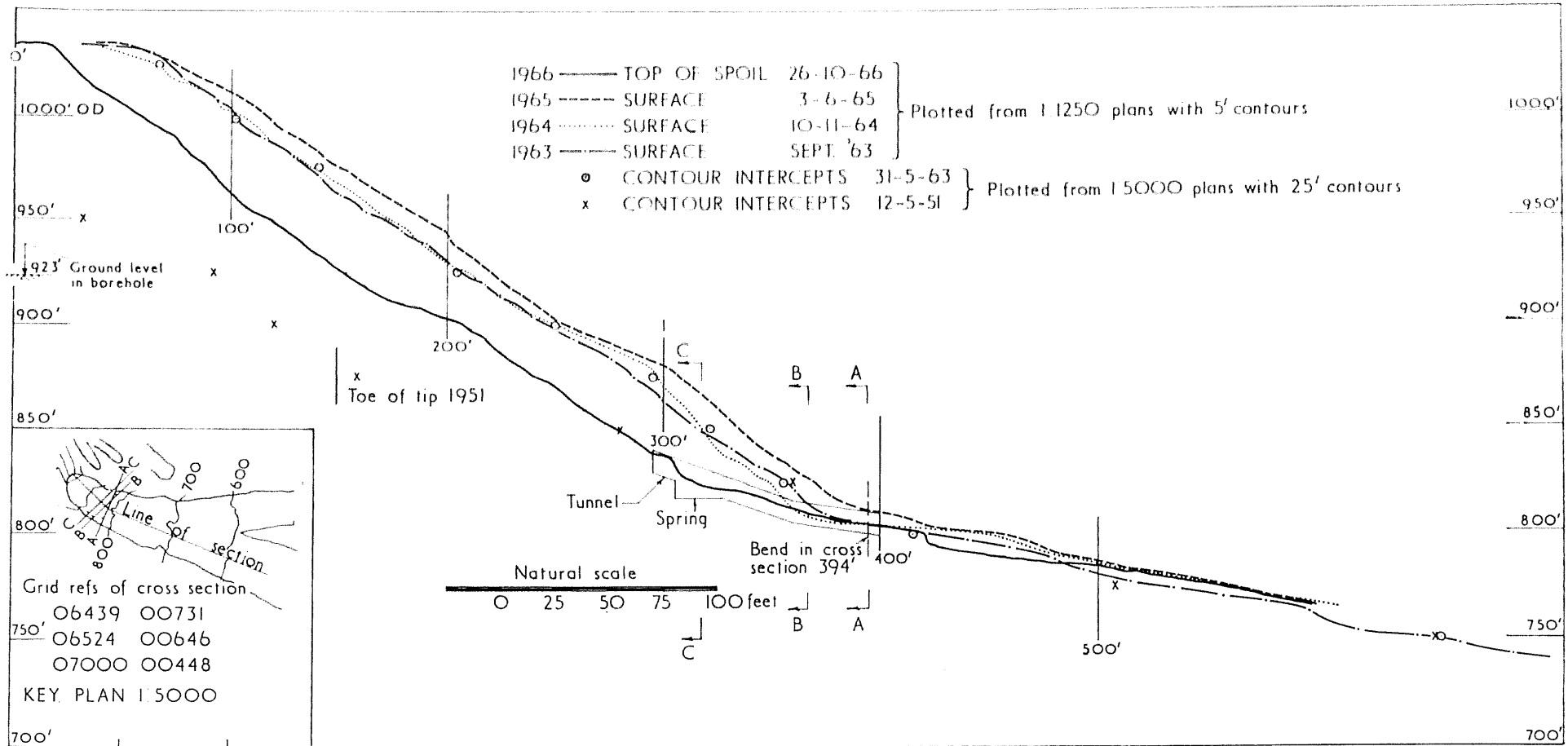
It is of interest to the present Inquiry in two respects :

- (a) It occasioned the circulation of the Powell memorandum dated 12th April 1965 requesting the inspection of tips.
- (b) It illustrates that damaging failures can occur under conditions quite different from those at Aberfan. Another example is the collapse of a slurry pond on 24th March 1966 at Williamthorpe Old Dirt Tip, which covered an adjacent road to a maximum depth of 10 ft and closed it for 10 days.

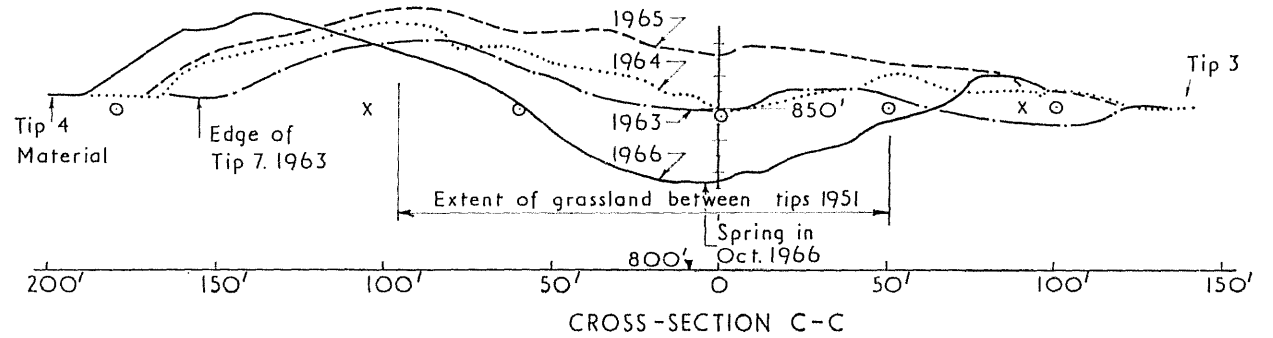
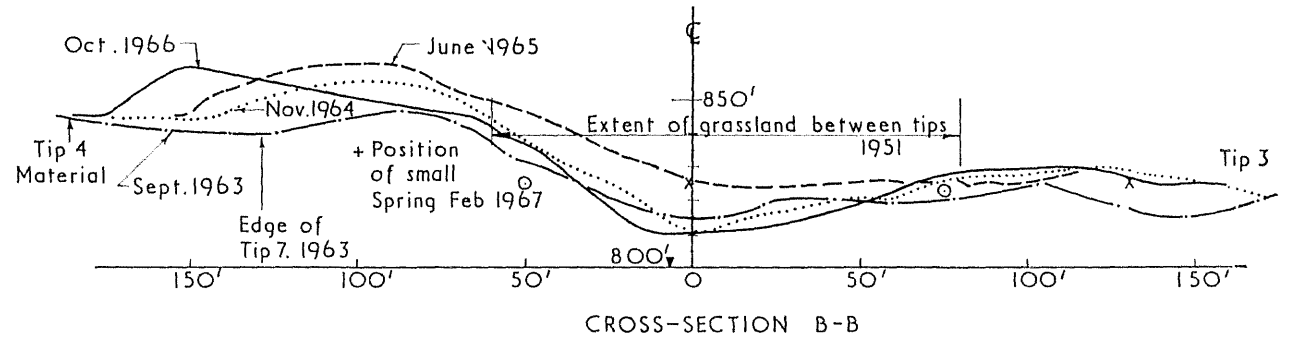
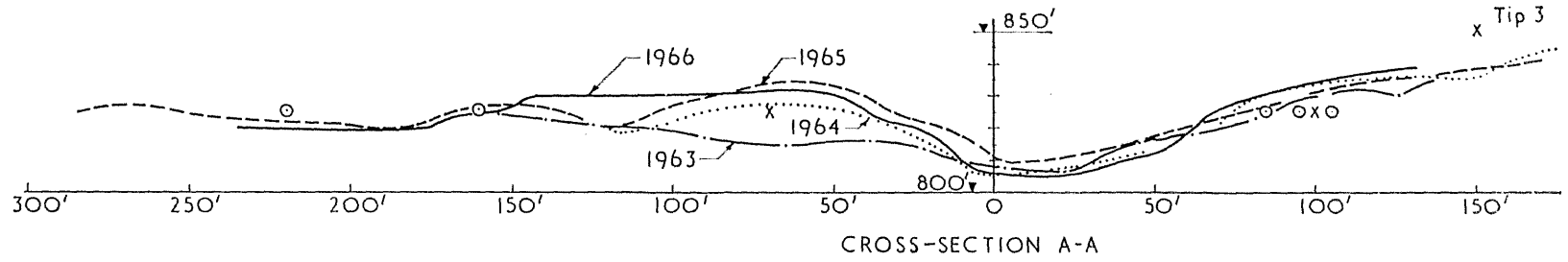
3 Geology of the site in the immediate vicinity of the tip and geotechnical properties of the natural strata

Aberfan is situated in the valley of the River Taff on the northern limb of the broad structural basin of the South Wales coalfield. In this vicinity the Taff runs in a southerly direction and is incised over 1000 ft

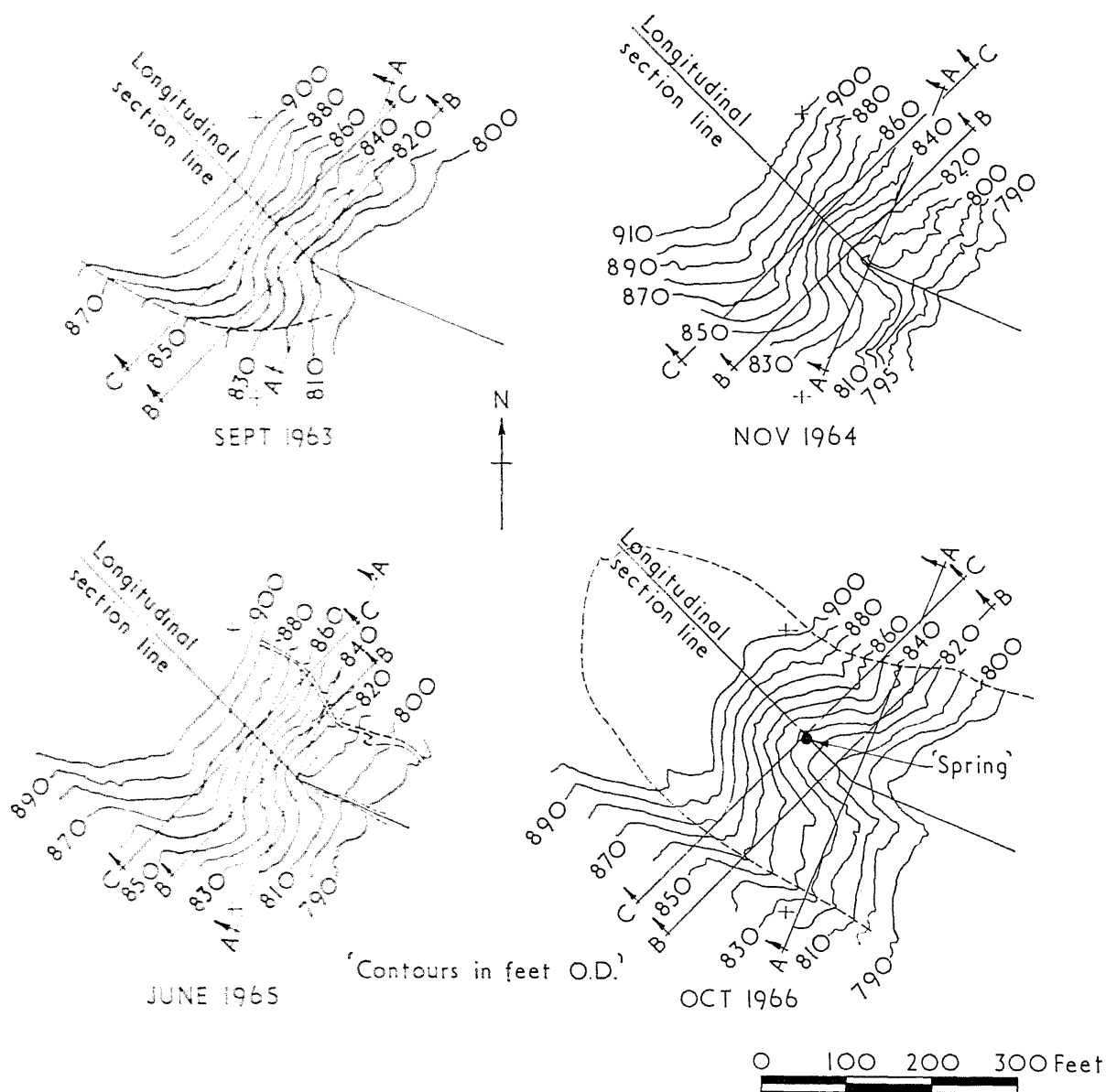
¹ This is a relative term. While small compared with the October 1966 slide, its volume probably greatly exceeded that of the Tymawr failure in 1965. (See Appendix 6.)



1.4a Agreed sections of Tip 7 for the years 1963–1966. Section through crest.



1.4b Agreed sections of Tip 7 for the years 1963-1966. Cross-section of toe.



1.4c Agreed sections of Tip 7 for the years 1963–1966. Contours of toe.

below the surface of the rolling plateau of Pennant Measures which forms the interfluvies. The complex of tips of colliery waste above Aberfan rests on the western slopes of the Taff valley. These slopes have an average inclination of approximately 12° (1 in 4.7) and extend from about $+450$ ft to -1450 ft O.D.

The solid geology of the tipping area has been described by Dr A.W. Woodland in the Geological Report of the Aberfan Tip Disaster (Item 4). It is illustrated, in relation to the various tips, on the agreed Aberfan Geological Plan (H9) and its accompanying Horizontal Sections (H 10A and H 10B) (see notes on p. 103). The above documents also give a general indication of the character of the local superficial deposits.

The whole of the hillside in the vicinity of the Aberfan tip complex is mantled by a layer of drift deposits. The greatest proven thickness of these is 77 ft in borehole L11. The average thickness of drift beneath the tips is probably rather less than half this, and locally in the vicinity of the 'spring' the thickness is much less. The extent and nature of this drift mantle is relevant to the current investigation in two ways. Firstly, as in general much of the drift is of lower permeability than the underlying jointed rock masses, it exerts a major influence on the magnitude and distribution of the ground-water pressures acting within the mountain. In the second place, as the drift mantle underlies all the tips, its strength as a foundation material is of importance.

The stoniness of much of the Aberfan drift has rendered it difficult to sample effectively using soft ground techniques. On the other hand the content of uncemented material is usually such that poor cores are obtained by rotary drilling methods. These factors, in conjunction with the inherent variability of the drift mantle, have considerably hampered its investigation.

Available evidence on the geology in the immediate vicinity of Tip 7 is summarised in Figs. 1.5 and 1.6. These show respectively sections down-slope and cross-slope through the position of the spring which was exposed beneath Tip 7 after the disaster of October 1966. The sub-surface detail is based on the results of rotary borings, shallow excavations, trial pits and soft ground borings. The surface profiles are taken from appropriate photogrammetric and tacheometric surveys. The lines of these two sections are shown on Fig. 1.7.

Tip 7 is sited over the outcrop of the Brithdir Beds, which consist locally almost entirely of Pennant sandstones. At the base of these is the Brithdir coal, which outcrops beneath the drift some 50 to 100 yards downslope from the toe of the tip. This coal seam is underlain by about 70 ft of predominantly mudstone strata which rest on further beds of sandstone. In this vicinity the solid strata dip at about 5° (1 in 12) to the south-south-east. Their component of dip towards the valley is about 4° (1 in 15).

The layer of drift lying between the base of the tips and undoubted rock-head comprises broadly three components :

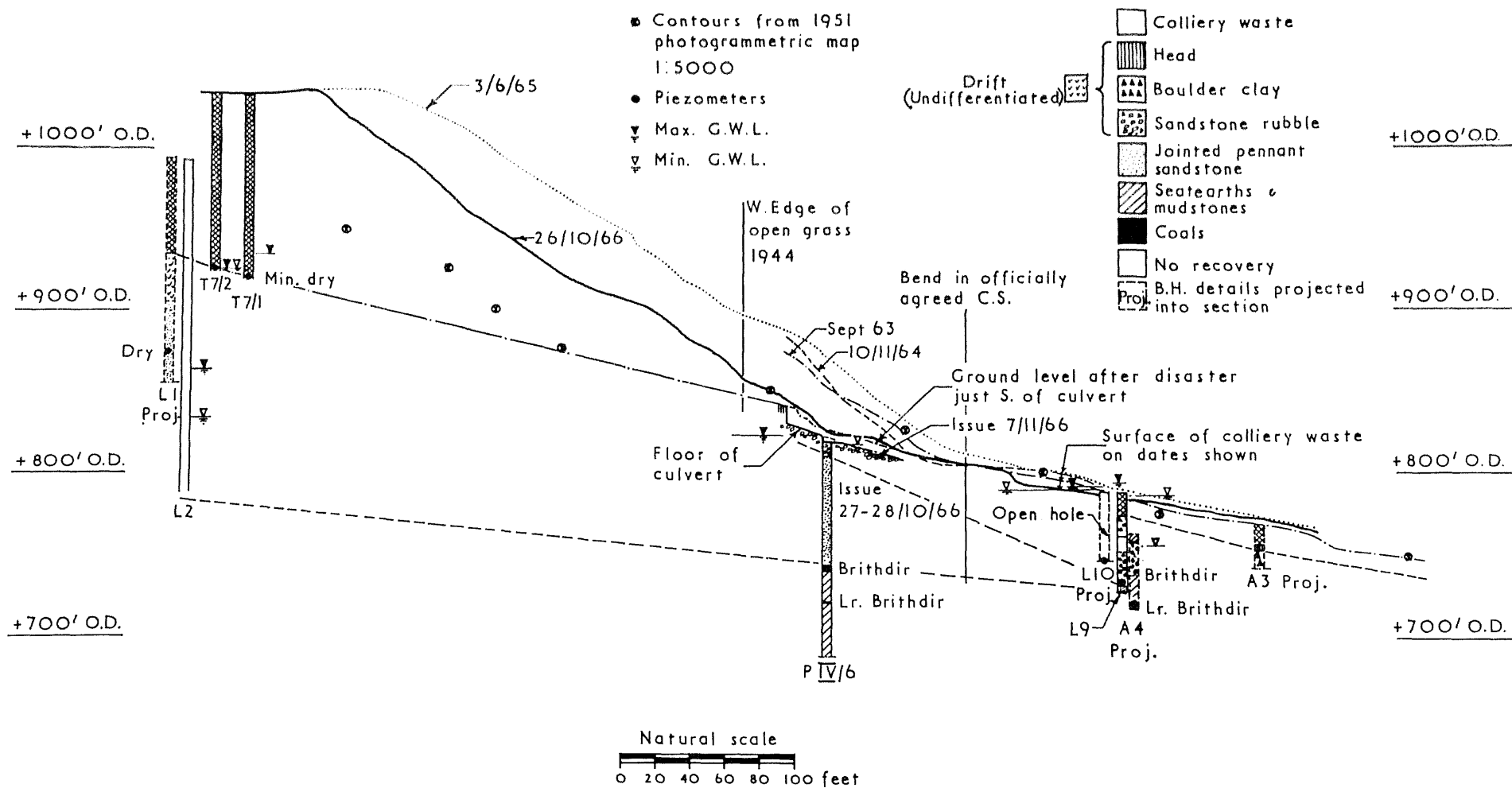
(i) An uppermost, ubiquitous mantle of Head. This is made up of solifluction, scree, hill-wash and superficial creep deposits which have presumably accumulated during the Late- and Post-Glacial period. The character of these deposits reflects their derivation from the slopes directly above their present location. On the slopes immediately below Tip 7, the Head consists typically of a thin spread of buff, somewhat silty, fine sand (presumably hill-wash) overlying some feet of yellow sandy clay which contains stones that are predominantly of Pennant.

(ii) In certain areas of the lower slopes of the hillside the Head is underlain by a layer of Boulder Clay, presumably of Weichselian age. Although somewhat variable, this till seems to consist typically of a matrix of firm to stiff, grey-brown silty clay containing rock debris up to boulder size. Its suite of erratics is consistent with deposition by a glacier moving down the Taff valley from a source in the neighbourhood of the Brecon Beacons.

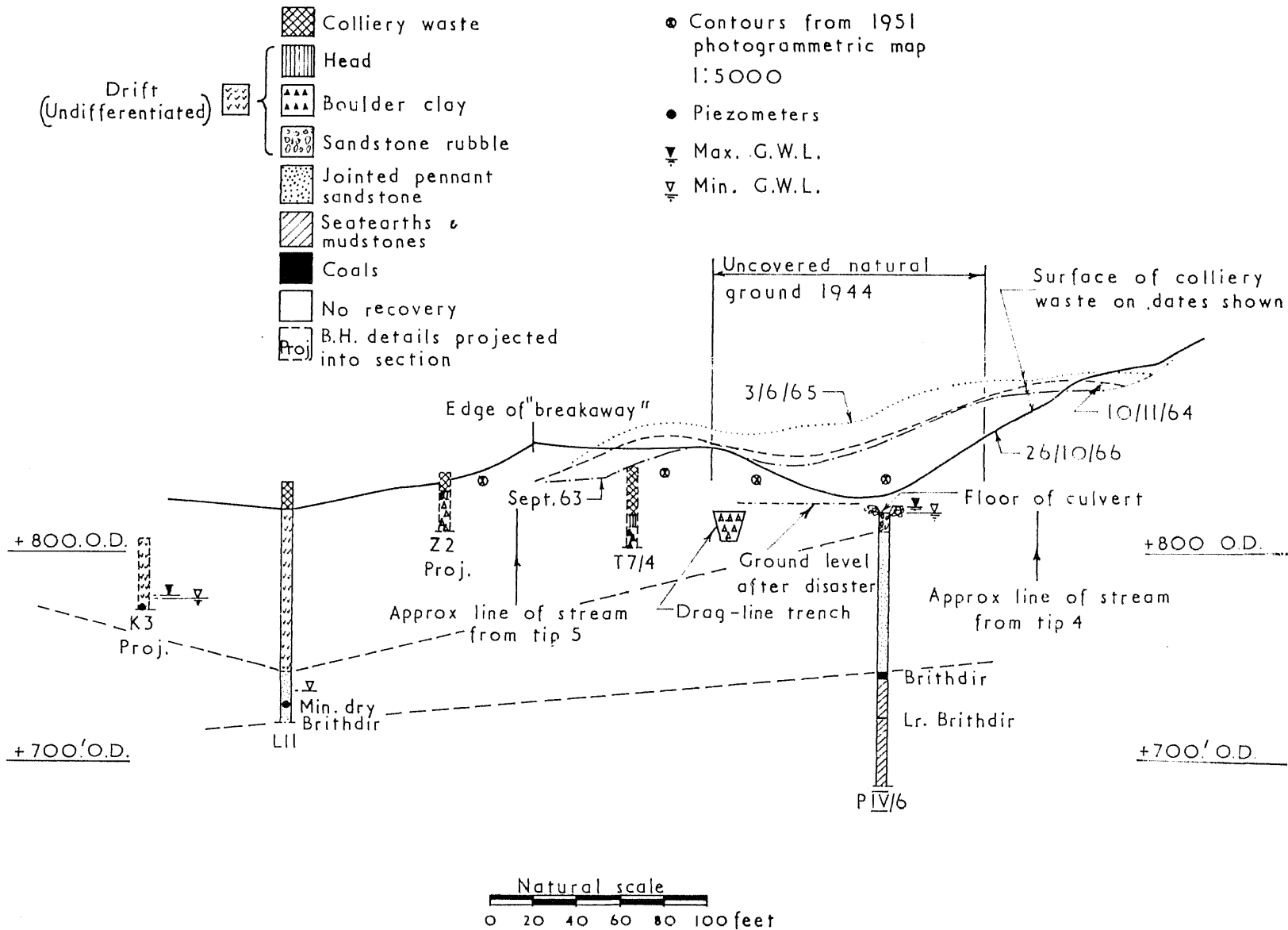
(iii) In an area immediately downslope from Tip 7 the base of the drift is occupied by a layer of Pennant debris. The high, rather random dips observed in particularly the upper part of this layer suggest that it has been subjected to some degree of movement. The lower part of the layer appears to consist of weathered rock-head, virtually *in situ*. Both types of debris contain interstitial sandy clay. They will be referred to jointly as Sandstone Rubble.

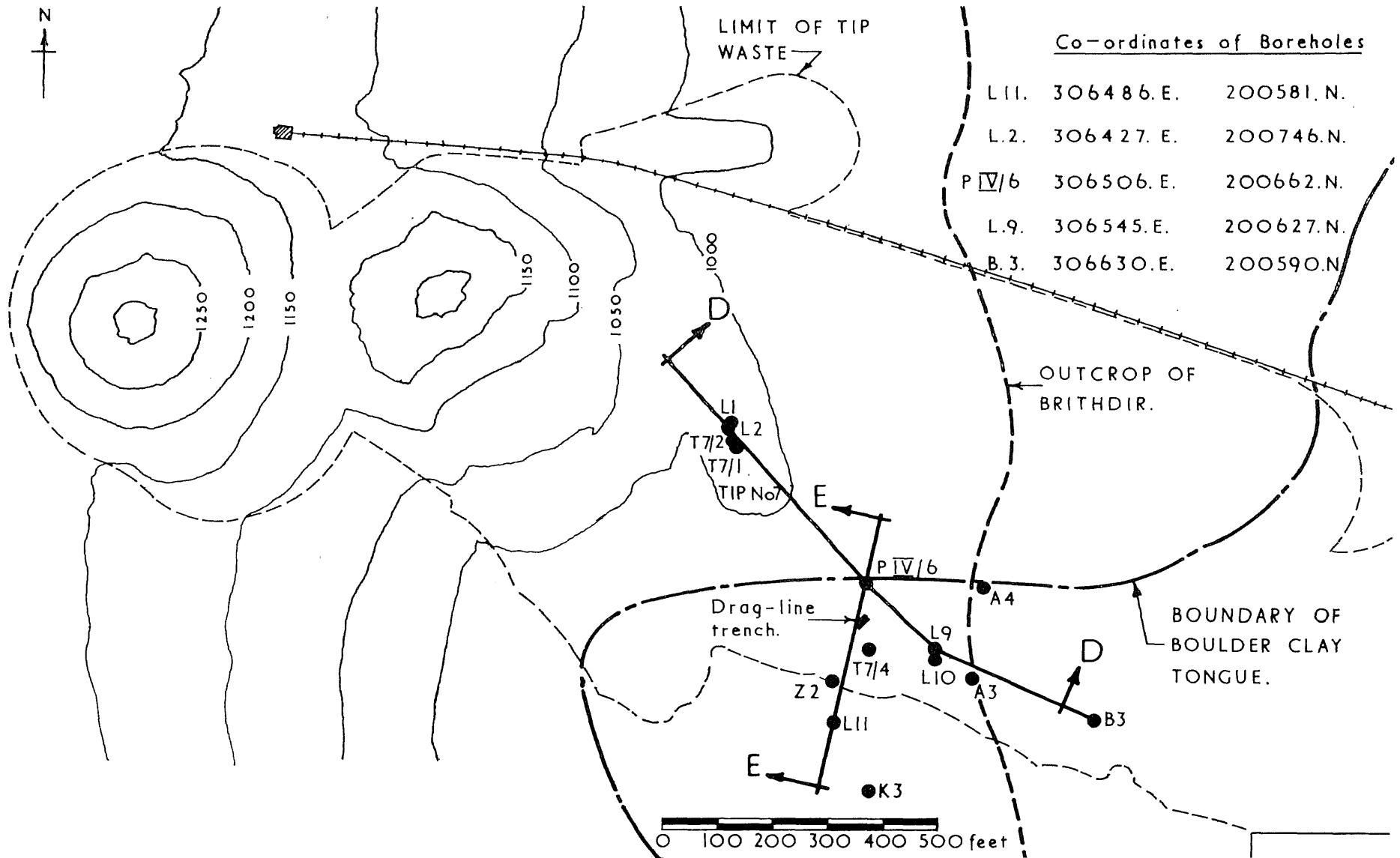
The approximate extent and thickness of these three components of the drift in the immediate vicinity of Tip 7 are indicated on the sections shown on Figs. 1.5 and 1.6. While the boundaries shown must generally be regarded as tentative, the broad pattern is reasonably well established. The uppermost layer of Head is everywhere present and appears to vary in thickness from about 4 to 10 ft. The underlying tongue of Boulder Clay is confined to the shallow embayment in the valley side to the south of the lower part of the tip complex, as shown by the Aberfan Geological Plan, Fig. 4.2 (in wallet). The northern edge of this tongue extends under the southern part of the top of Tip 7, feathering out on a generally east-west line in the neighbourhood of the spring by borehole PIV/6. The available detail of the location of the Boulder Clay in the vicinity of this feather edge is shown on Figs. 1.5 and 1.6.

The upper surface of the layer of Sandstone Rubble is exposed in the uppermost 70 ft of the floor of the arched culvert.



1.5 Down-slope section D-D through 'spring' at borehole PIV/6.





1.7 Part of agreed geological plan showing locations of sections D-D and E-E.

been obtained chiefly from laboratory tests on about 30 samples. These have been taken from between depths of about 1 and 20 ft in boreholes and trial excavations located in the vicinity of the seat of failure below Tip 7. The majority of the samples were taken by open-drive samples of 4-in. nominal diameter (U4 samples). The remaining samples were taken either by driving a 1½-in. diameter metal tube (U1½ samples) or by cutting a block of soil by hand. Locations of the samples tested and details of the results obtained are given in Appendix 3.

The impracticability of defining accurately the boundary between the Head and the Boulder Clay usually prevents firm allocation of the test results to one deposit or the other. A summary of the properties determined for the upper drifts¹ in the area below the toe of Tip 7 is given in Table 1. These properties have been measured on the finer matrix of the drifts,² either from ½ in. down or from sieve 7 size (c. 1/10 in.) down. They are typical of a lean, inorganic, over-consolidated clay. Drained triaxial tests show that in terms of effective stresses the material has zero cohesion intercept and an angle of internal friction which ranges from 29° to 40°. The magnitude of the latter parameter tends to decrease as the clay content of the soil increases. The residual shear strength has been measured on one sample of the drift and is not significantly lower than the peak shear strength. There is some indication from the laboratory tests (Appendix 3) that the bulk density of the matrix of the Head is distinctly lower than that of the Boulder Clay; of the order of 125 lb/ft³ as compared with 135 lb/ft³.

Table 1
Geotechnical properties of the upper drifts in the area
of the toe of Tip 7

Description	Unit	Magnitude			
		Min.	Max.	Average	
Bulk density, γ	lb/ft ³	118	140	130	
Natural water content, w	%	10	36	16	
Liquid limit, w_L	%	14	42	24	
Plastic limit, w_P	%	13	29	16	
Plasticity index, I_P	%	2	13	8	
Clay content ($< 2\mu$)	%	3	25	13	
Activity	—	—	—	0.6	
In terms of effective stresses	Cohesion intercept, c'	lb/ft ²	0	0	0
	Angle of internal friction, ϕ'	degrees	29	40	36
	Permeability (from falling head tests)	cm/sec	4×10^{-6}	5×10^{-5}	3×10^{-5}
Specific gravity of particles	—	2.55	2.60	2.58	

The permeability values given in Table 1 have been obtained from falling head tests on piezometers installed in the drift, and must be regarded only as a rough indication of the actual permeabilities. The locations and results of the various falling head tests made are detailed in Appendix 3. One laboratory permeability determination has been made on a 4-in. long, 4-in. diameter sample of Head taken from immediately below the exposed slip surface in Tip 7 at the location 306485E, 200635N (c. +837 ft O.D.). The test was carried out in an oedometer under a vertical load of about 60 lb/in.² and at a constant temperature of 70°F. The measured permeability was 4.1×10^{-8} cm/sec.

Little is known of the mechanical properties of the layer of Sandstone Rubble. It is clearly stronger than the overlying drifts and neither it nor the underlying solid rocks was involved in the shear failures beneath

¹ That is, the undifferentiated Head and Boulder Clay. The Sandstone Rubble layer is not included in the table.

² Boulders several feet across have been found in the Boulder Clay.

Tip 7. A sample of the interstitial clayey material, taken from the artificially cut face a few feet above the borehole PIV/6, had a water content of 13% and liquid and plastic limits of 16 and 15% respectively. No direct measurements of the permeability of this layer have been made but general observation of the material in the floor of the culvert suggests that its permeability is relatively high. Some support for this view is provided by the readings of ground-water levels at boreholes PIV/6 and L9.

4 Ground-water conditions

An analysis in general terms of the ground-water conditions existing in the mountain beneath the tip complex is contained in Dr A.W. Woodland's Geological Report and the Appendix by Mr D.A. Gray (Item 4).

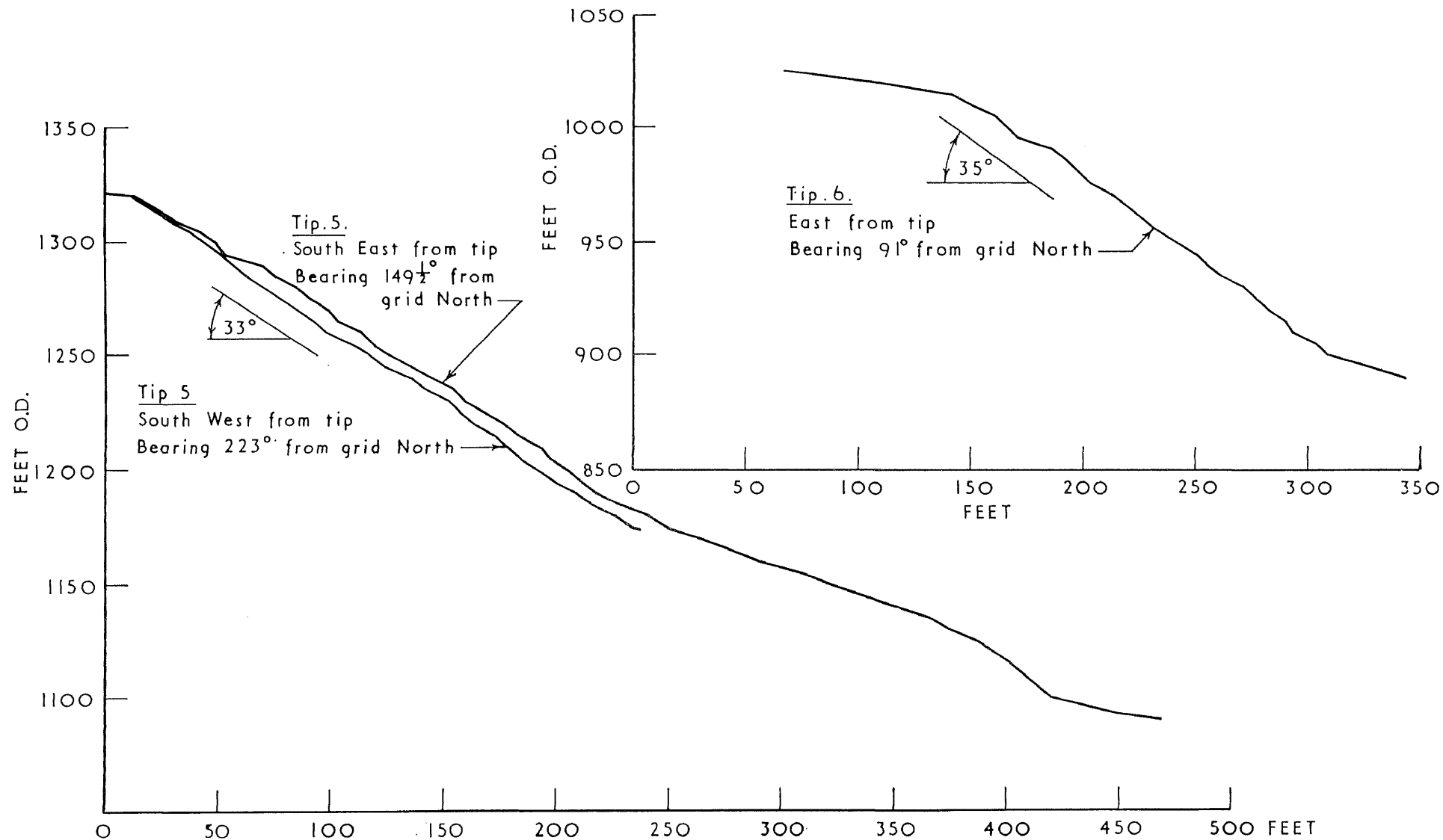
The ground-water conditions in the Brithdir Sandstone, which underlies that part of the hillside upon which Tip 7 is sited, have been explored by means of a number of piezometers. These are installed in a line of boreholes which follows approximately the dip direction of the solid strata and passes through the position of the spring at borehole PIV/6. This line coincides closely with the centreline of Tip 7.

A section along this line of piezometers is given in Fig. 1.8 (in wallet), on which the highest and lowest water levels so far recorded are shown. In general, observations are available from February 1967. In most cases the lowest piezometric levels were observed on or about 16th February and the highest on or about 1st March. Comparison of these observations with the rainfall data confirms that changes in ground-water level in the Brithdir Sandstone lag about two days behind changes in rainfall.

The section of Fig. 1.8 shows that at borehole R6 on the upper slopes of the hillside the ground-water levels in the Brithdir Sandstone fluctuate between extremes of about 75 and 145 ft below ground level. From these the free ground-water surface falls at an average slope of about 1 in 12 to meet the ground surface in the vicinity of the 'spring' at borehole PIV/6. Most of the piezometers on the hillside below the spring are installed either in the layer of Sandstone Rubble, which appears to be in direct hydraulic communication with the Brithdir Sandstone, or in the sandstones below the Brithdir seams. These piezometers generally indicate artesian pressures, the less permeable upper drift mantle providing a confining layer.

The conditions immediately downslope from the 'spring' are shown in more detail on the section of Fig. 1.5. Of particular interest is piezometer L9 which is installed at the base of the Sandstone Rubble and indicates an artesian ground-water pressure, with respect to the interface between the tip rubbish and the drift, which ranges from about 12 to 20 ft (–785.9 to –793.6 ft O.D.). Prior to the discharge of water associated with the disaster of October 1966 the ground-water pressures at this point are likely to have been greater than any pressures measured subsequently. The maximum piezometric level observed since the disaster, of –793.6 ft O.D., may be taken as a reasonable lower bound for the piezometric level immediately before the disaster at the position now occupied by piezometer L9.

An upper bound for this pressure may be arrived at as indicated below. The 1951 air survey indicates that the natural ground level at L9 before any tipping took place on the hillside was approximately 10 ft above the present broken surface of the drift (Fig. 1.5). As this drift-covered hillside had remained stable through the years before tipping started, it can be concluded that the ground-water pressures in the underlying Sandstone Rubble had never, in all this time, reached a high enough value to cause the drift mantle in this vicinity to slide off. The piezometric level required to produce such a failure could be taken as the upper bound for the pressure immediately before the disaster, were it not for the possibility that the placing of the tips on the hillside has altered the hydrological conditions in the mountain, for instance by



1.9 Slopes of Tips 5 and 6.

restricting previous points of ground-water discharge. The calculation is carried out, therefore, for the latest pre-disaster conditions for which photogrammetric data is available, i.e. 3rd June 1965. This indicates that the maximum piezometric level in the Sandstone Rubble at the location of L9 that could be sustained by the overlying mantle of drift and tip rubbish existing at that date is about +796 ft O.D. The latter figure would of course require to be increased if the profile of the tip immediately before the disaster was higher local to L9 than that surveyed in June 1965.

Similar calculations at the position of the 'spring' indicate the lower and upper bounds of the pre-disaster piezometric level at that point to be about -822 and -836 ft O.D. This latter figure represents a pore-water pressure equal to only about 20% of the weight of overburden, mostly tip rubbish, above this point on 3rd June 1965. This value forms a useful comparison with the values of r_u considered in the stability analyses of Section 8 and Appendix 4.

5 Properties of tip material

Tip 7 is formed of colliery rubbish of which shale, probably derived chiefly from the Lower Coal Measures, is the predominant and most significant component. The tip contains some coal and also general rubbish including some boiler ash, pit props, steel cables, pieces of reinforced concrete, etc. In spite of these hazards, the taking of samples by soft ground techniques has proved surprisingly successful, though some disturbance and density change in the 4-in. diameter samples must be accepted.

In certain zones tailings are encountered almost unmixed with other rubbish and their properties are treated separately.

Details of the mechanical properties of the materials tested are given in Appendix 3, and only the principal features are summarised here.

(a) Density

This is expressed as either the bulk density, i.e. the total weight of solid material and water (in lb) per cubic foot of volume, or dry density, i.e. the weight of solid material less the water (in lb) per cubic foot of volume. The latter value is more relevant in comparing the relative looseness or denseness of material, in which the degree of saturation may vary.

Considerable variations in density were encountered in the boreholes. *In situ* values of density by the sand replacement method gave an average value of bulk density of about 110 lb/ft³ and of dry density 100 lb/ft³.

The Proctor (or B.S.) Optimum Dry density for Tip 7 material was 121 lb/ft³. This is the density produced by normal field compaction equipment. It is relevant to note that a minimum of 95% of this value is usually specified for embankment work and this gives 115 lb/ft³ in this case. This illustrates the relative looseness of the tip material.

The average of two *in situ* density tests in an undisturbed area of the slipped material not far from the canal (coords 20064mN-30691mE)¹ gave a dry density of 111 lb/ft³. This is consistent with the view that the flow was associated with a collapse of the granular structure which became denser after shear.

During the investigation a shallow 'mud-run' occurred on Tip 7 following heavy rain. Water content and specific gravity measurements on the moving material enabled its dry density to be determined (on the assumption of full saturation). A series of eight tests gave values ranging from 97 lb/ft³ to 106 lb/ft³ under virtually zero identical stress. The dry density at which saturated material will flow under higher stresses is substantially greater (on the basis of published data). It must be inferred therefore that the tip material was placed at a density

¹ See Reports & Spec. a. Plans, Sheet 2, Ordnance Survey, November 1966 (in wallet).

at which shear displacements could lead to flow slides in saturated or even partly saturated material.

The looseness of the tip is also confirmed by the low values given by the Standard Penetration Test. Values in the upper part of the tip lay in the range 3 to 36 (see Appendix 3). Loose material is generally considered as lying below a value of 10.

It must be noted that these values of *in situ* density were measured in what remained of the tip. The front portion which slipped may well have been of even lower density.

A sample of fine material, apparently tailings, located near the crest of Tip 7 was found to have an initial water content of 18.2% and a liquid limit of 26.5%. Its constituent particles have an average specific gravity of 1.92. In the semi-fluid state (i.e. at its liquid limit), therefore, its bulk density would be 100 lb/ft³, dry density 79.3 lb/ft³, and as sampled (if full saturation is assumed) 105 lb/ft³ (dry density 88.9 lb/ft³).

(b) *Strength*

This is expressed as the angle of internal friction, ϕ' , measured in terms of effective stress. This angle varies somewhat with pressure and where this variation is of importance, attention will be drawn to the stress range. Details of the tests are given in Appendix 3.

The samples taken from the boreholes through the crest of Tip 7 gave average values ϕ' of $39\frac{1}{2}^\circ$ in drained tests and of $41\frac{1}{2}^\circ$ in undrained tests after allowing for excess pore water pressure. These tests are of only a few hours duration and make no allowance for long-term effects. The comparison given below with the shale fill used in two important embankment dams shows that the Aberfan material has a higher angle of internal friction than that found satisfactory in major water-retaining structures. The latter were designed as structures with due regard to slope angle and drainage.

	ϕ'	<i>In situ</i> dry density lb/ft ³	Height (ft)	Average downstream slope
Burnhope Dam (1936)	35°	107	131	19.4°
Balderhead Dam (1965)	34.5°	119	157	19.7°
Aberfan Tip No. 7	39.5°	99	1220	136.0°

1 June 1965

The fact that the older tips at this site have remained stable for considerable heights at slopes of 33° to 35° (Fig. 1.8) indicates that long-term effects may be limited in magnitude or delayed in operation.

The tailings, under fully drained conditions, show a measured value of angle of internal friction, ϕ' , in the range 31°–33°. The difference in their behaviour is due principally to their low permeability and inability to drain freely.

A most significant feature of the strength characteristics of the tip rubbish is the large reduction in angle of internal friction which occurs on surfaces on which large shear displacements have occurred. Evidence of this phenomenon only became available when the slip surface south of the 'spring' was exposed on 8th February 1967 and a detailed study of its cause is still in progress. However, the following facts can be reported.

The lowest values of the residual angle of internal friction, ϕ_r' , on the slip surface were $18\frac{1}{2}^\circ$ on a disturbed sample and $17\frac{1}{2}^\circ$ on a prepared sample of the smear of fine material immediately adjacent to the slip surface, which was polished and striated (for example, Fig. 10). When the excavation exposing this area was made, the removal of toe support caused a renewal of movements in the remaining tip material above the old slip surface. Stability analyses of this mass gave an average

value of ϕ' of 26° , on the assumption of zero excess pore pressure in the tip material (see Section 6).

The origin of the layer of fine material associated with the slip surface is almost certainly connected with the degradation of the shale under shear strains (a similar degradation of the much stronger quartz particles in a sand occurs under high pressures, see Bishop 1966).

Freshly ground shale particles less than 2 microns showed a residual angle of internal friction of 26.7° but had a very low plasticity index (4.4%). This suggests that comminution alone is insufficient to produce the low value of residual shear strength and that it must be accompanied by some process of weathering¹ or hydration of the clay minerals in the shale, on the actual shear surface. The orientation of the clay particles on the slip surface is clearly also of importance since samples of material adjacent to the surface showed appreciably higher strengths if sheared other than along the previously formed surface.

The residual angle of internal friction of the tailings has been found to be almost the same as its peak angle of friction, i.e. about 32° . This suggests that the layer of fines associated with the slip surface does not consist of a layer of tailings as placed, although the possibility of the degradation of the shale content of tailings at very large strains and after weathering cannot be ruled out.

(c) *Permeability*

The permeability of the tip material is variable but on the average the tip is shown by the piezometer readings to be relatively free-draining. A representative sample of tip material gave a permeability of 6.6×10^{-2} cm/sec.

A representative sample of the fine material adjacent to the slip surface gave a permeability of 1.8×10^{-9} cm/sec. This indicates that large shear strains² have an important influence on the permeability of the colliery rubbish.

The permeability of the tailings obtained from consolidation tests was found to be between 2.34 and 1.27×10^{-7} cm/sec (average of six tests 1.73×10^{-7} cm/sec).

(d) *Sizing analyses*

The grading characteristics of the tip rubbish and the tailings are given in Appendix 3. It is of interest to note that the percentage of fines passing the 200 sieve averaged about 10% for samples taken from the undisturbed tip material. The percentage of fines passing the 200 sieve determined by the same method for samples from the flow slide, however, are as follows:

Mid-way between Tip 7 and the schools	19%
Near the senior school	18%

(e) *Mineralogy of tip material*

The mineralogy of the tip material has been examined at the Building Research Station and the results are given in Appendix 3.

6 Pore pressures in the tip material

Instruments for the measurement of pore-water pressures (piezometers) have been installed in Tips 3, 4 and 7. Details of the observations in these and the other piezometers are given in Appendix 3.

Shallow piezometers of special design were driven, between 12th and 14th November 1966, into the face of Tip 7 left by the failure. These penetrated generally about 20 ft below the surface of the tip. None of them indicated any water pressure. Most of these piezometers were destroyed by shallow slides and 'mud-runs' in early December 1966.

Casagrande type piezometers were installed in boreholes T7/1 and

¹ Possibly accelerated by the generally acid environment.

² Together with the other factors leading to degradation of the shale particles.

T7/2 in Tip 7 at approximately the interface between the tip material and the natural ground (Figs. 1.1, 1.5 and 1.8). Typical observations in these piezometers are given in Table 2. They indicate that in general the phreatic surface in Tip 7 is situated close to the surface of the underlying natural ground, although transient rises in pore-water pressure may occur after heavy rain.

Table 2
Observations in piezometers in Tip 7

Date	Rainfall	Ht. water above natural ground level	
		T7/1	T7/2
21st November 1966	0	Dry	
23rd November 1966	0	4 ft 2 in.	
27th November 1966	0.42 in.	4 ft 2 in.	
28th November 1966	0.13 in.	4 ft 6 in.	
1st December 1966	1.69 in.	14 ft 10 in.	1 ft 7 in.
2nd December 1966	0.14 in.	Dry	1 ft 11 in.
3rd December 1966	0.03 in.	Dry	1 ft 11 in.
4th December 1966	0.01 in.	Dry	2 ft 0 in.

A Casagrande type piezometer installed in borehole T3/1 (Fig. 1.1) at approximately the base of Tip 3 has remained dry since its completion on 1st December 1966.

Two Casagrande type piezometers have been installed in boreholes 9 and 14 (Fig. 1.1) which are sited on the slipped material near the back of the 1944 failure. Both piezometers are located at about the interface between tip material and natural ground. They indicate the piezometric level in this vicinity to fluctuate with rainfall from zero to a maximum of about 3 ft above the natural ground surface at piezometer 9. This piezometer is located on the course of the stream which is shown by the earlier Ordnance maps to have originated on the site now occupied by Tip 4.

The above piezometer observations indicate that the pore-water pressures in Tip 7 since the disaster have been low, the phreatic surface rarely rising more than a few feet above the level of the underlying natural ground. The slight seepage from the lower few feet of the tip into the excavation made south of the culvert in February 1967 was entirely consistent with these observations. The fact that the face of Tip 7 left by the disaster of October 1966 stood at an overall inclination of about 35°, little below the average ϕ' value of the tip rubbish, suggests that relatively low pore pressures also obtained within Tip 7 behind and above the position of the 'spring' at the time of that failure.

7 History of Tip 7

Basic information covering the history of Tip 7 is provided by the aerial and other photographs, by maps made from these photographs and by evidence given to the Tribunal. Reference may be made to the Report 'Interpretation of analyses of photography covering the Aberfan area' carried out by Fairey Surveys Ltd (Item 8).

Tip 7 was begun around Easter 1958. Initially the Tip 7 rubbish was placed over a small tip that had been sited between Tips 3 and 4 and used for a short time in 1944. The height of this small tip is uncertain but can be estimated to have been about 50 ft in the vicinity of the south-south-east extremity of the top of Tip 7, having had a top surface level of about +975 ft O.D. The top surface of Tip 7 was fixed at a level of +1050 ft O.D. near the inclined tramway and sloped gently to a level of +1035 ft O.D. at its south-south-east extremity. Thus, at this point, the top of Tip 7 was some 60 ft above the top of the small tip and about 115 ft above the natural ground.

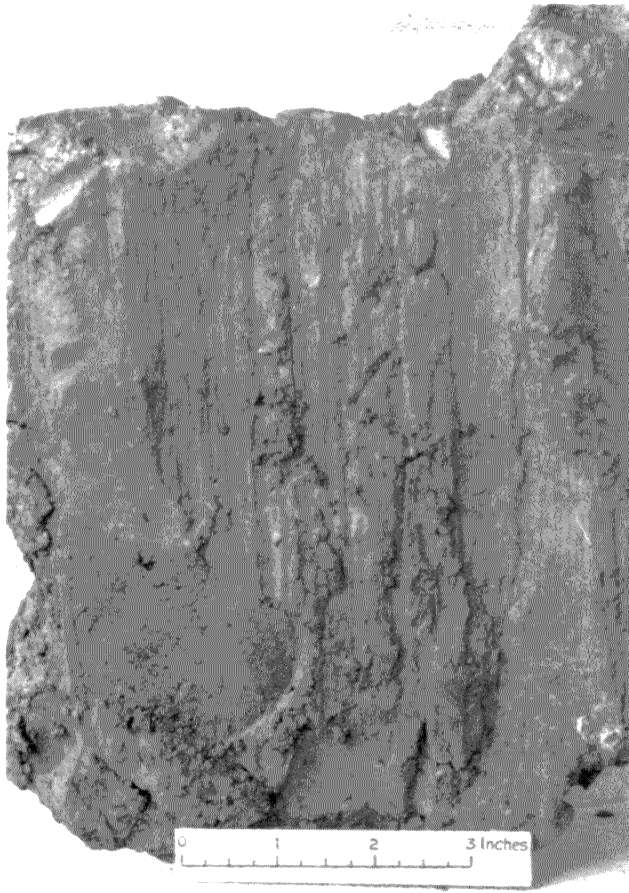
By April 1960, Tip 7 had advanced beyond the end of the small tip and had begun to encroach on to the clear ground beyond it. This clear ground, which is described in Fig. 2 of Fairey's report (Item 8), was tongue-shaped, its southern edge being outlined by the material from the flow of Tip 4 and its northern edge running along the toes of Tips 1, 2 and 3. The width of this tongue was about 130 ft and it sloped downhill. At this stage, the height of Tip 7 was, very approximately, 150 ft, i.e. a little in excess of the height of Tip 6, and the aerial photography (Fig. 5, Fairey Surveys Ltd) indicates no signs of instability.

By May 1963 (Fig. 6, Fairey Surveys Ltd), the condition of the tip had changed radically and a large depression, evidently caused by back-sapping, had appeared in the toe of the tip (Fig. 6, Fairey Surveys Ltd). This is shown even more clearly by Fairey Surveys Ltd, Fig. 7, which is the photograph of 14th September 1963. Both these aerial photographs have been used by the Ordnance Survey to produce photogrammetric contour maps. The contours on these show this depression and also indicate that a significant bulge had already been formed in the south-eastern toe of the tip.

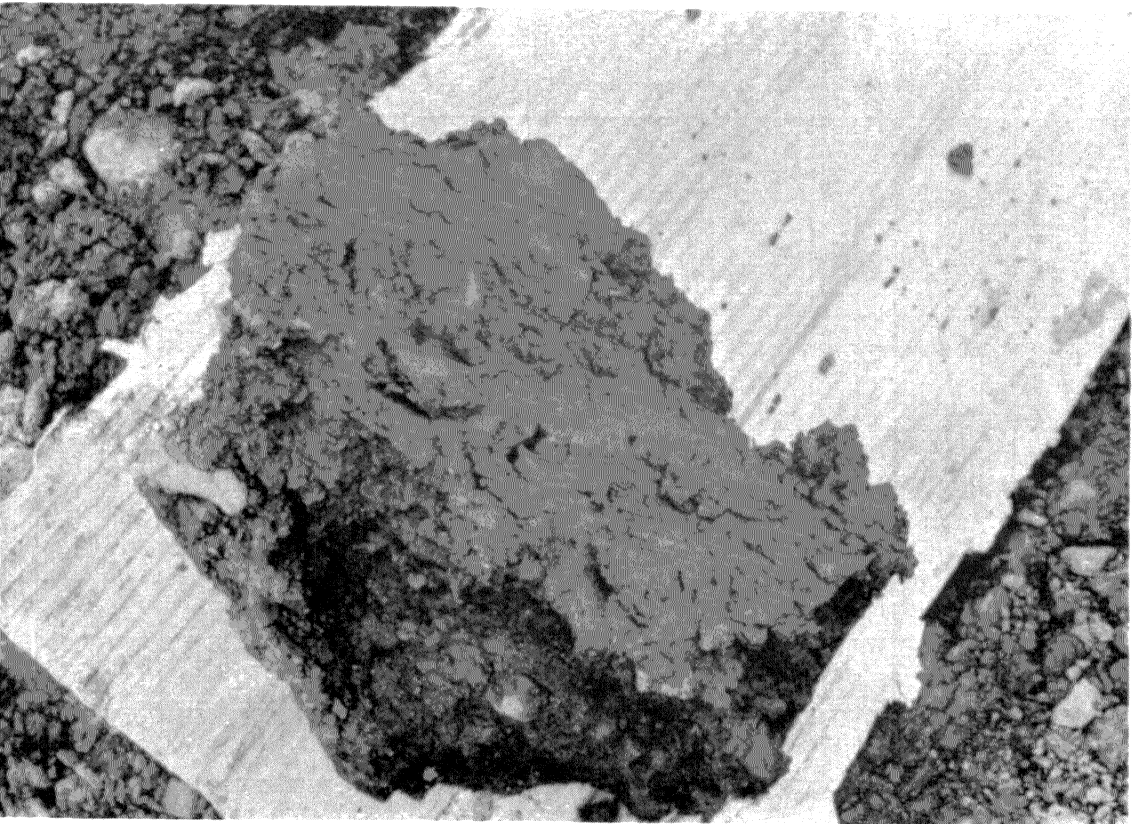
At this stage the back-sapping had already created a steepened face some 70 or 80 ft in height. The source of water causing back-sapping would appear to lie on a line between the issue of water shown on the 1957 Ordnance Survey to the south-east and final position of the spring to the north-west. It may be significant that the line joining the 1957 issue of water and 1966 spring lies parallel to the contours of mining subsidence illustrated in the reports by Wardell and Piggott (Item 6) and is thus in the direction across which tensile strains would be at their maximum. This also coincides approximately with one of the principal joint directions of the Pennant sandstone. The effect of tensile strains on a clay-covering of low plasticity over a jointed rock containing water under pressure is difficult to predict, but recent work on the cracking of the clay cores of earth dams suggests that open cracks may be caused by relatively low tensile strains (e.g. G.A. Leonards and J. Narain, 1963).

Evidence of a significant slip in the latter part of 1963 has been given to the Tribunal by the tipping gang. This slip appears to post-date the September 1963 photograph and probably occurred in the second half of October or the first half of November 1963. A major settlement of the front 30 ft of the crest of the tip is reported as having taken place at this time. The aerial photography supports the view that a significant movement of rubbish took place between September 1963 and November 1964 when the next low-altitude aerial photography was taken (Fig. 8, Fairey Surveys Ltd). From quantities evaluated by Hunting Surveys Ltd from the photography of September 1963 and November 1964 it appears that about 30,000 cubic yards of material had moved down on to the mountainside below the nominal toe of the tip between these dates (see Appendix 6). This estimate is approximate but clearly indicates that during this period the movement of material was more than a small run or slide of tailings.

During the period November 1964 to June 1965, little new material appears to have reached the by then extended south-eastern toe (or claw) of Tip 7. Hunting Surveys Ltd have been able to identify a number of reference objects on these two successive air photographs and have plotted some of their positions in November 1964 and June 1965. Their displacements in the seven-month period which elapsed between these photographs are given on Fig. 1.11. It will be seen that these displacements form a consistent pattern and indicate a general down-slope movement of the order of 20 ft in this seven-month period (an average of approximately 1 in. per day). The directions of these movements are found to correspond to the general direction of the striations observed on the slip surface exposed in this area in February 1967. The directions of the striations are plotted on Fig. 1.12. It may be noted that a large, flat-faced boulder of hard sandy siltstone, which was

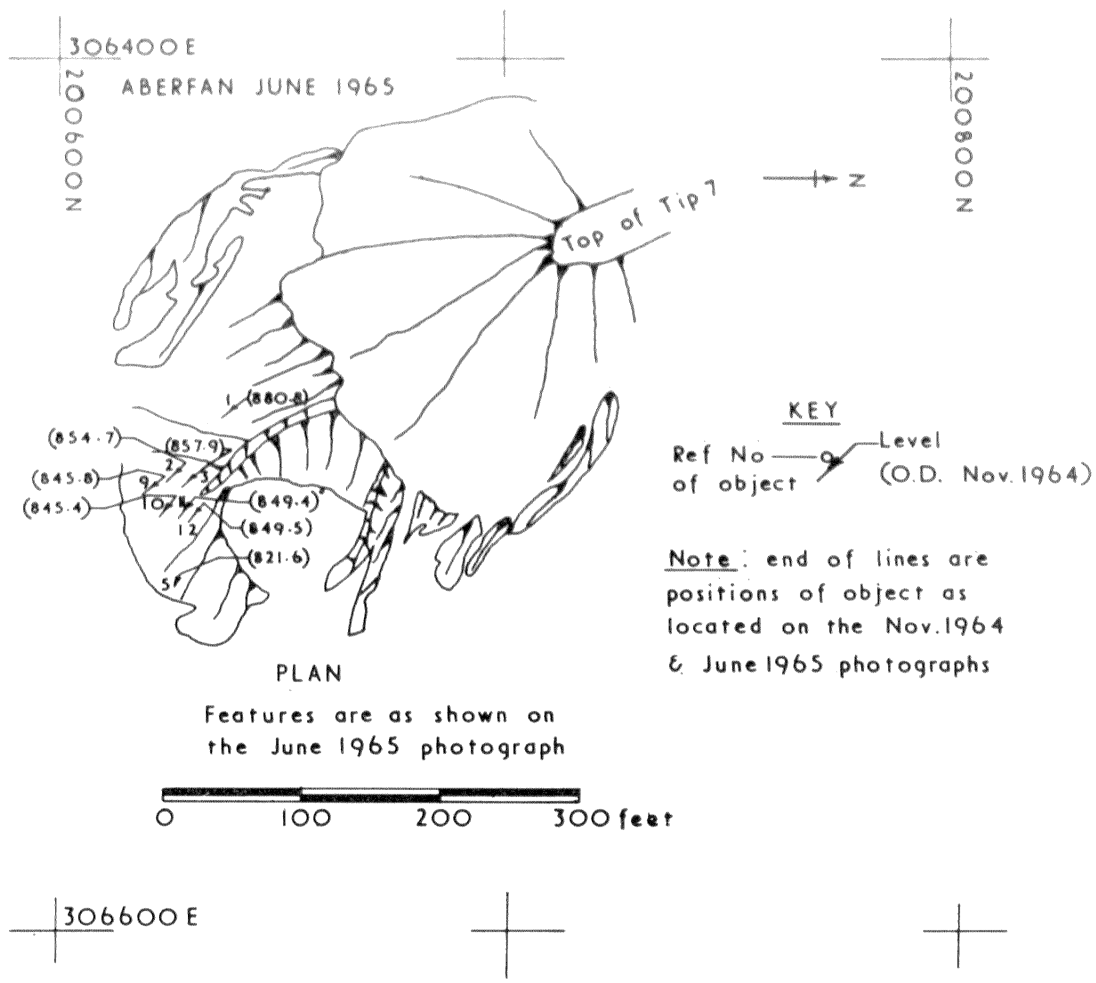


1.10 Photograph of samples showing polished and striated slip-surface.

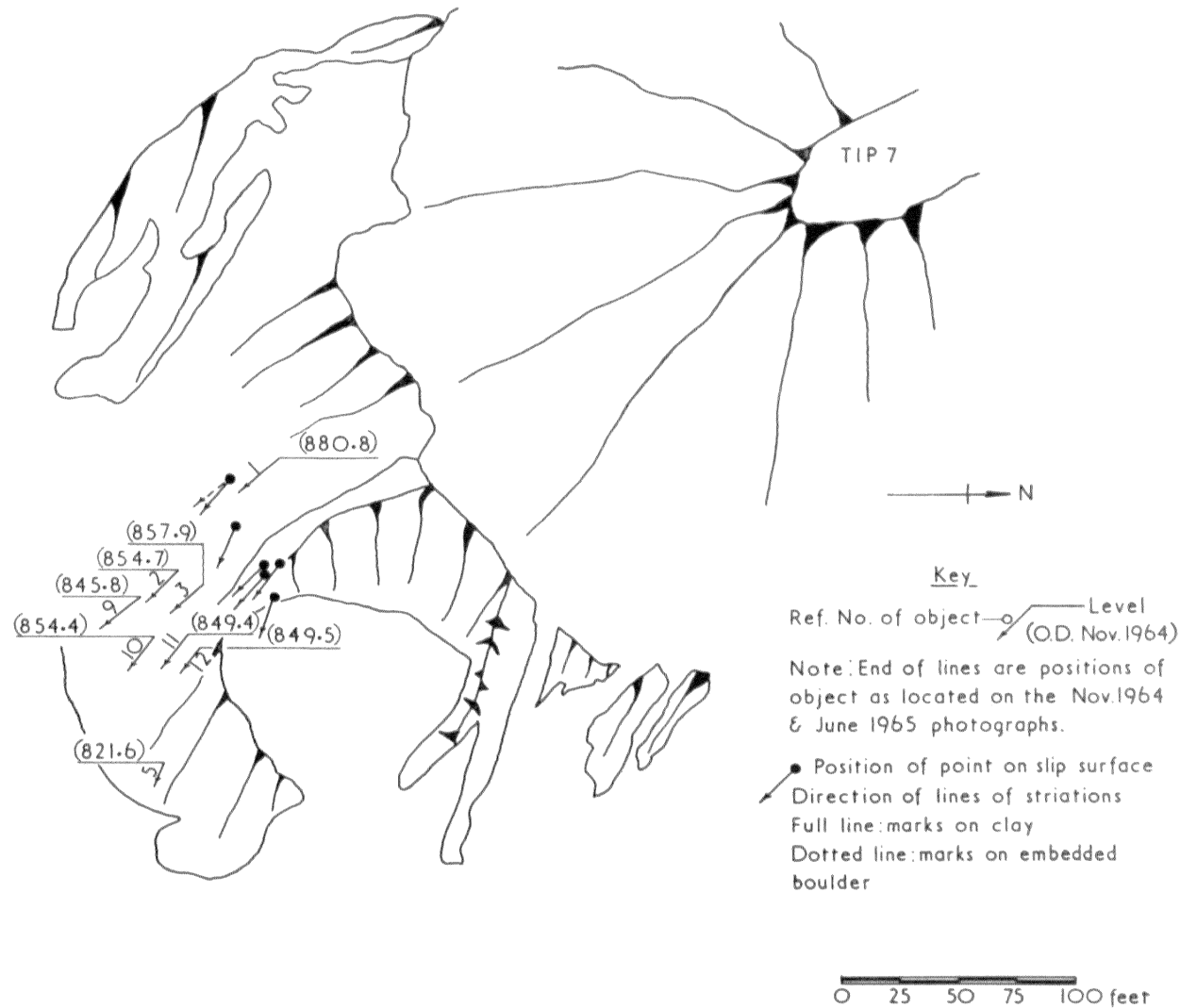


Colour transparency of a sample removed from above slip plane showing striations.

Object No	Grid bearing of direction of move	Horizontal movement	Scaled limits $\pm 1'$ Vertical movement taken from levels: limits $\pm 6''$
1	140°	23'	5'
2	136°	21'	3.4'
3	133°	20'	3.4'
5	109°	12'	1.4'
9	140°	23'	6.4'
10	127°	20'	4.5'
11	127°	21'	4.5'
12	127°	20'	4.0'



1.11 Plan showing movements of reference objects between November 1964 and June 1965.



1.12 Plan showing movements of reference objects between November 1964 and June 1965 and showing direction of striations on slip surface exposed by excavation, February 1967.

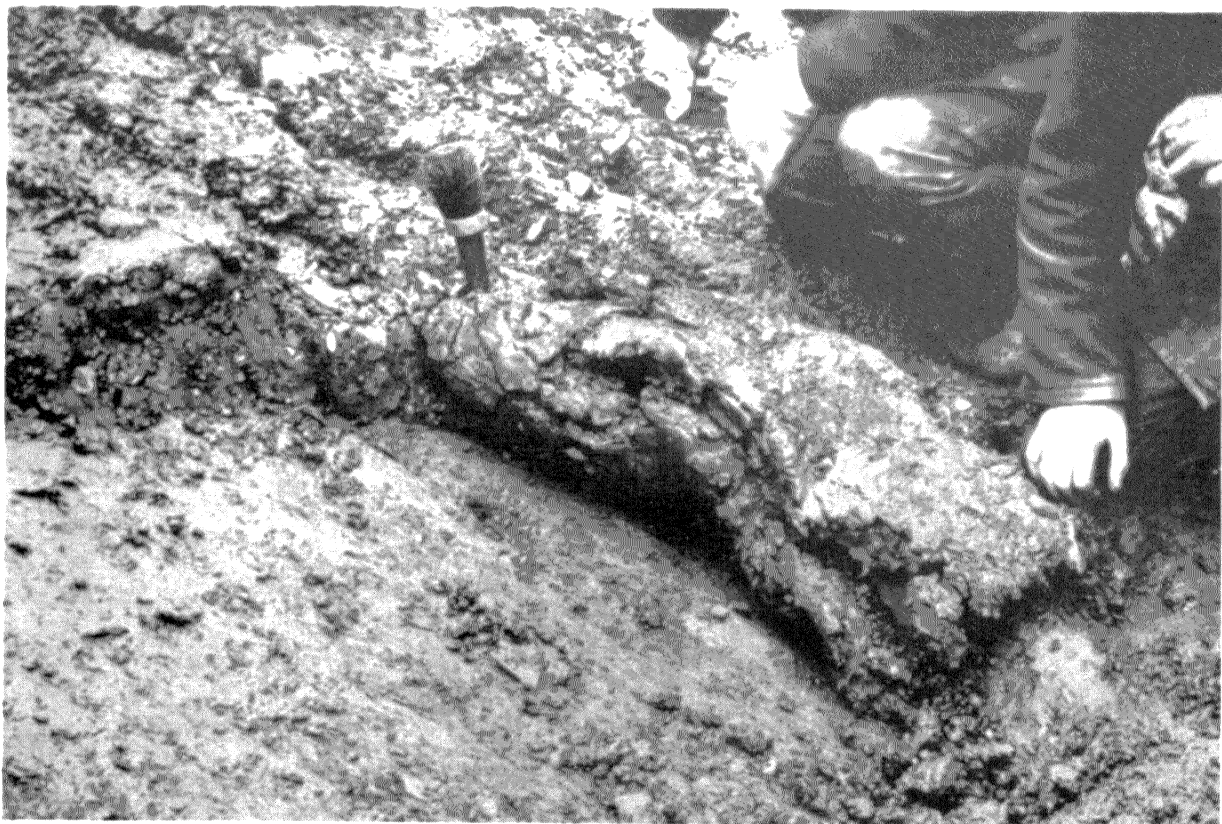


1.13* Colour transparency showing the embedded boulder with red pencil giving direction of striations.



1.14* As Fig 13 with red pencil showing direction of striations on adjoining slip surface.

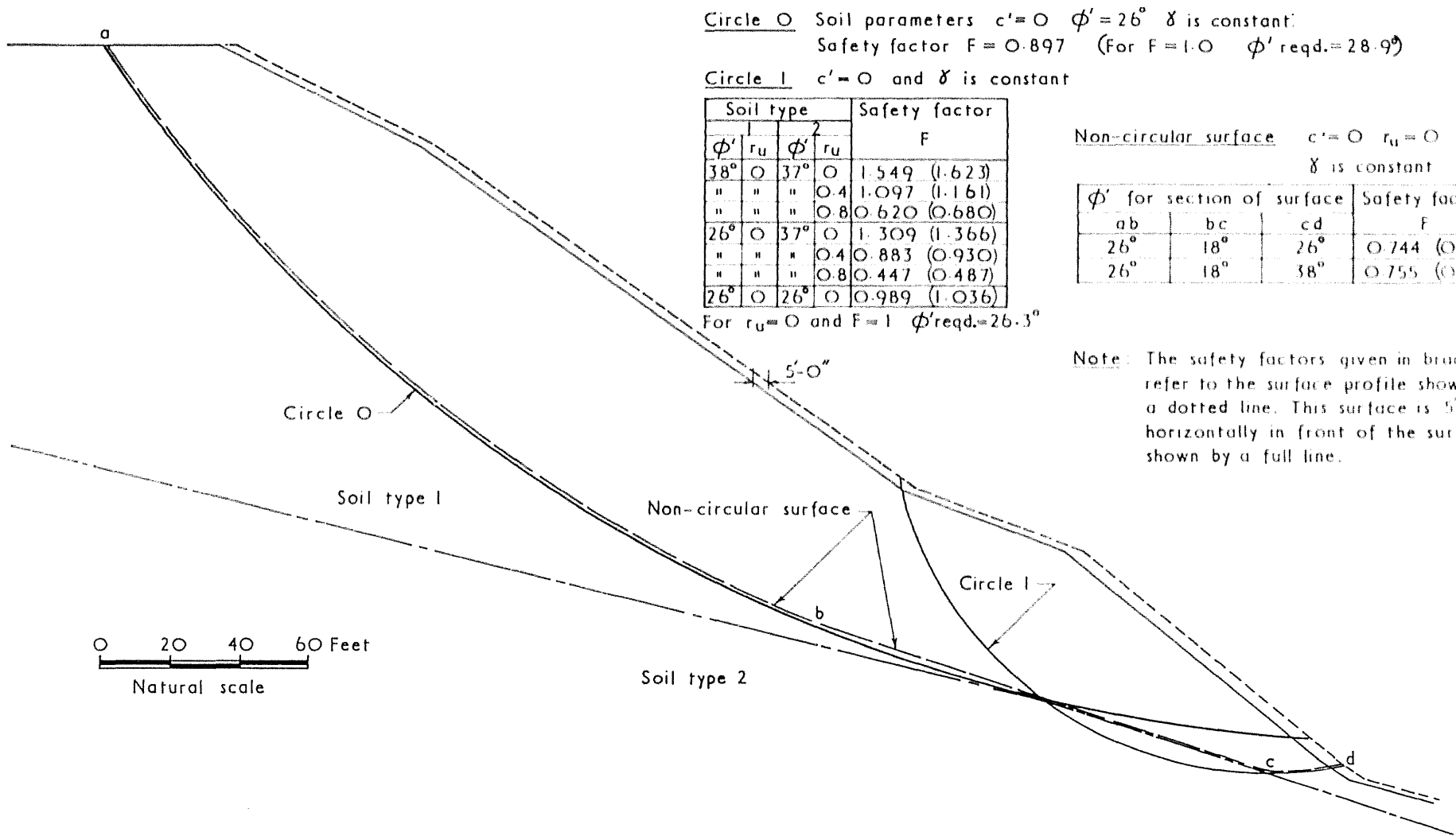
*Reproduced here in black and white.



1.15* Colour transparency of slip plane exposed by rolling back material above it.



1.16* As Fig. 1.15.



Circle O Soil parameters $c'=0$ $\phi'=26^\circ$ δ is constant.
 Safety factor $F=0.897$ (For $F=1.0$ ϕ' reqd. = 28.9°)

Circle I $c'=0$ and δ is constant

Soil type				Safety factor	
ϕ'	r_u	ϕ'	r_u	F	
38°	0	37°	0	1.549	(1.623)
"	"	"	0.4	1.097	(1.161)
"	"	"	0.8	0.620	(0.680)
26°	0	37°	0	1.309	(1.366)
"	"	"	0.4	0.883	(0.930)
"	"	"	0.8	0.447	(0.487)
26°	0	26°	0	0.989	(1.036)

For $r_u=0$ and $F=1$ ϕ' reqd. = 26.3°

Non-circular surface $c'=0$ $r_u=0$
 δ is constant

ϕ' for section of surface			Safety factor
ab	bc	cd	F
26°	18°	26°	0.744 (0.754)
26°	18°	38°	0.755 (0.775)

Note: The safety factors given in brackets refer to the surface profile shown by a dotted line. This surface is 5'-0" horizontally in front of the surface shown by a full line.

1.18 Failure surfaces assumed for the stability analyses of Tip 7.

embedded firmly in the matrix beneath the slip surface at about 306483mE, 200635mN, had well-developed striations parallel, within observational error, to the 1964–65 displacement of the nearest reference object. The depth of fill at this point was of the order of 25 to 30 ft during this period and its slope was relatively flat compared with the face of the tip behind it, so that surface creep was likely to be small. The evidence suggests, therefore, that the 1964–65 movements resulted mainly from shear displacements on the well-defined slip surface exposed by the excavation of February 1967.

Profiles of the face of the tip at the various dates for which photogrammetric maps are available are plotted on Fig. 1.4. Critical parts of these profiles are shown in relation to the local geology in Figs. 1.5 and 1.6. From Fig. 1.5 it is apparent that by 1964 the surface of the tip material, in the depression formed by back-sapping, already lay some distance below the probable original ground level in that locality. As the thickness of the tip material at that point is not known, the depth of drift removed by 1964 cannot be determined accurately. It is clear, however, from Fig. 1.5 that much, and possibly all, of the drift overlying the Sandstone Rubble at that position had already been removed.

Further evidence in support of this is provided by the excavation of a trench, running some 150 ft downhill from the area of the 1966 spring, in which the contact between the tip material and the underlying drift was exposed. It was observed that, immediately over the broken surface of the drift, lay a deposit of fine-grained black material, generally several inches thick. This is similar in nature to the band of fine-grained black material found associated with the slip surface exposed at the foot of Tip 7 and probably also consists chiefly of degenerated shale of the type discussed in Section 5. It can be inferred from this that the removal of the original ground surface had taken place some years earlier, thus allowing this accumulation to form.

In 1965 it should be noted that the cliff behind the area of back-sapping still had a height of 80 to 90 ft, but was in a more forward position than at any previous time for which we have cross-sections. Its position prior to the disaster in 1966 is subject to some uncertainty but the examination by the Department of Photogrammetry and Surveying of University College, London, of a photograph taken in March 1966 suggests that the top of this cliff is still at much the same level, i.e. about 780 O.D., but that some further bulging of the tip has probably occurred, possibly of the order of 7 ft in magnitude in the plane of their observations.

A description of the events immediately preceding the disastrous slide on 21st October 1966 has been given in evidence and we would draw attention only to a few of the significant features. By the time the first members of the tipping gang reached the top of the tip at about 7.30 a.m. in the morning the crest had already sunk about 10 ft over a distance of 30 to 40 ft back from its edge. By approximately 8.30 a.m. this settlement had increased to around 20 ft. At about 9.10 a.m. the toe of the tip was observed to start moving forward and this movement continued for some minutes before the rapid flow of material down the hillside began. It should be noted from the cross-sections that an observer on the crest of the tip would probably have his view of the toe of the tip in the back-sapping area obscured by the top of the cliff at the back of this area and might well report movement of the top of this cliff as movement of the toe of the tip.

The subsequent flow of material down the hillside is described graphically in the evidence and its apparent fluidity is clear both from the evidence and from the manner in which it is shown by the photographs (Figs. 1.19, 1.20 and 1.21) to have spread across the hillside.

In the final slip some 140,000 cubic yards of rubbish were deposited on the lower slopes of the mountainside and in the village of Aberfan. The amount actually crossing the embankment is estimated, very approximately, to have been about 50,000 cubic yards.

approximates to the amount of rubbish dumped in the period September 1963 to October 1966. The total amount of material which moved between the aerial photographs of June 1965 and October 1966 is clearly larger than the figure of 140,000 cubic yards, but much of it moved into positions previously occupied by tipped material or material from earlier movements, and its volume cannot be estimated with any accuracy.

The aerial photography prior to 1963 was from a high altitude and was not suitable for making accurate estimates of surface levels. Thus only a very approximate estimate of the quantity of rubbish already tipped by September 1963 is possible. The value obtained is 180,000 cubic yards, and may well be an underestimate. The total quantity of rubbish tipped at Tip 7 is thus of the order of 320,000 cubic yards.

The height in June 1965 from the highest point on the crest of Tip 7 (1036 ft O.D.) to nominal ground level at the toe of the tip on the line of the section of Fig. 1.4 is approximately 220 ft.

8 Discussion of mechanism of failure

Evidence as to the mechanism of failure on 21st October 1966 is provided by the composite picture built up from a number of sources. These are as follows:

- (a) Evidence to the Tribunal by witnesses.
- (b) Aerial and other photographs taken soon after the event and in the preceding years.
- (c) An examination of the slip surface revealed by the October 1966 slip in the upper part of the tip and exposed by excavation in the lower part of the tip during February 1967.
- (d) The results of soil tests on the foundation materials, the tip material in its random state and on samples of the slip surface.
- (e) The hydro-geology of the site.
- (f) Stability analyses carried out on the tip profile together with an examination of the movement into the excavation carried out in February 1967.
- (g) Model tests carried out both at Imperial College and University College of Swansea.

An examination of this evidence indicates that the movements on 21st October 1966 commenced as the re-activation, consequent on rise of water pressure at the base of the tip, of the sliding movements on a pre-existing shear surface largely created by movements in earlier years. This rise in water pressure followed heavy but not unusually high rainfall.

The large magnitude of these initial shear displacements caused a major part of the sliding mass of colliery waste to degenerate into a flow slide. This secondary phase of the failure owed its occurrence to the presence of a substantial volume of loose, saturated material at the base of the tip above which lay a large volume of loose, wet material containing only a small percentage of air in its voids. The saturation of the base of the tip was caused primarily by water issuing from the ground in the absence of free drainage of the base of the tip. The flow slide was the primary cause of damage to the Junior School.

The removal of tip material and some natural ground in the initial stages of the slide released a quantity of ground water¹ which, although large compared with normal spring flows was, when first observed, considerably less, for example, than the estimated initial flow of the burst 31-in. water main in the disused canal.² This release of ground-water brought down more colliery rubbish in the form of 'mud-run' and extended the area of damage. This mud-run together with water from

¹ Evidence by J.J.D. Bowen and P.M. Grant. About 20 cu.ft./sec. at mid-day on 21st October 1966.

² Evidence by C.J. Jones, Divisional Engineer of the Taf Fechan Water Board. About 70 cu.ft./sec. immediately after the burst, falling to 30 cu.ft./sec. after 10 minutes.

the burst water mains in the disused canal hampered the initial rescue operations.

The evidence for movement on a pre-existing failure surface is based on the following :

- (i) The displacements of identifiable reference objects on the surface of the south-eastern toe (or claw) of Tip 7 in the period November 1964 to June 1965 have been determined from maps prepared by Huntings Surveys Ltd, as indicated in Section 7. These movements were in general of the order of 20 ft.
- (ii) The excavations made in February 1967 to the south-east of the 'spring' (see Fig. 1.1) revealed a polished and striated slip surface. A sample of this surface has already been illustrated in Fig. 1.10. Other illustrations are given on the transparencies, Figs. 1.13–1.17 (reproduced here in black and white).

A large flat-faced boulder of hard sandy siltstone embedded firmly in the matrix beneath the slip surface is shown in Fig. 1.13. The surfaces of the boulder showed well-developed striations and, as indicated by comparison of Figs. 1.11 and 1.12, these are in the direction indicated by the data from Huntings Surveys Ltd for the 1964–65 movements. The striations in the adjacent clay (Fig. 1.14) were directed in plan about 15° more in the downslope direction (see Figs. 1.11–1.12). Figs. 1.15 and 1.16 show other areas of the slip surface, which lay within a well marked black band of tip rubbish having a matrix of clay and silt-sized particles. The thickness of this band varied from about 1 in. to 12 in. The slip surface was located generally about $\frac{1}{2}$ in. above the base of the band. In places the black band could be uncovered by brushing off the overlying, more granular tip material. The major part of the black band could then be rolled off as a whole, as shown in Figs. 1.15–1.16, to expose the slip surface immediately below it. Fig. 1.17 shows a lump of the fine matrix material taken from just above the slip surface.

In the southern part of the area examined the striations dipped in a south-easterly direction. The material below the slip surface here appeared to be Tip 7 material at higher levels, material forming part of the flow from Tip 4 as the ground surface was approached and finally the sandy Head, and in places possibly the Boulder Clay, forming the natural ground. The tip material below the surface was in general more compact than the material sliding over it.

- (iii) When the excavation was made, the resulting reduction in toe support led to a further renewal of movement on this pre-existing slip surface. The formation of this surface clearly predated the excavation. Measurements showed the rate of these movements to be of the order of 1 in. per day. No other surfaces were detected and the trace of the crack produced in the face of the remaining part of Tip 7 by this movement was in conformity with the back of the slip surface revealed by the slide of October 1966.
- (iv) The residual angle of internal friction ϕ_r' measured on an undisturbed sample taken across this slip surface, was found to be only $18\frac{1}{2}^\circ$ in a fully drained test. Scrapings from the striated surface gave a residual ϕ_r' value of $17\frac{1}{2}^\circ$. This is to be compared with values of ϕ' at small strains in fully drained tests of 38° to 40° for the random tip rubbish and 31° to 32° for the tailings.

It is thus easier for a movement to continue on a failure surface once an appreciable deformation has occurred than for a new surface to be created. This mechanism has clearly operated in this case.

1966 slip not far below the crest of the tip and were examined in early November 1966. These areas were backed by a very compact matrix of fine material in which particles of shale and pieces of wood were embedded. The shale particles and wood were aligned approximately parallel to the surface pointing down the slope. No striations were apparent in the clay matrix but the surface had been exposed to heavy rain before our first inspection. Downslope striations were observed on some of the shale particles embedded in the slip surfaces.

The surfaces were standing at slopes of 40° to 50° and remained stable for about one month in spite of the loose character of the bulk of the tip rubbish. It may therefore be inferred that they were not newly formed by the October 1966 slide.

- (vi) Analyses of the stability of the remaining part of the tip which moved towards the excavation made in February 1967 gave an average value of angle of internal friction required for stability of only 26° , on the assumption that pore-water pressures on the failure surface were negligible. This assumption is justified by the observations referred to in Section 6. Details of these analyses are given in Appendix 4.
- (vii) The stability analyses of the central section of the tip based on the 1965 profile (Fig. 1.18) shows that a deep slip surface passing behind the crest of the tip would require an average value of the angle of internal friction of 29° to 30° to give a factor of safety of 1.0, assuming pore-water pressures to be zero. This is much below the value of 38° to 40° for the random tip rubbish.

The pore-water pressure required over a limited area (Fig. 1.18) to cause failure on a fresh slip surface of this shape would be approximately 60% of the total weight of the material above the toe. A pore pressure of this magnitude seems improbable from the hydro-geological study, and would, in any case, cause a failure of the toe of the tip (Fig. 1.18) before a deep-seated failure resulted.

- (viii) Evidence given to the Tribunal by the tipping gang suggests that the rear of the slip surface in the crest of the tip had remained in a more or less constant position since 1963, and that intermittent settlements occurred in front of this line.
- (ix) The model tests both at Imperial College and University College of Swansea (Appendix 5) show that a mechanism of failure corresponding to that observed, i.e. the sinking of the crest of the tip associated with an outward movement of the toe, could only be reproduced if a pre-existing discontinuity was introduced into the model at the base of the tip and water pressure applied beneath this discontinuity.

On the basis of this evidence we conclude that *the initial phase* of the disastrous slip on 21st October 1966 consisted primarily of a re-activation of movement on the pre-existing shear surface.

The evidence for *the second phase* of the slip having taken the form of a flow-slide is as follows:

- (1) The toe of the tip broke away and travelled down the mountain-side at a considerable speed (probably between 10 and 20 miles per hour) followed by a large quantity of material having an apparently fluid consistency.
- (2) An examination of the photographs (Figs. 1.19 to 1.24) suggests that flow-slide material, i.e. material which has become 'fluid' due to the transfer of load on to the water already contained in its pore space, formed the initial phase of the flow of material which formed two branches on either side of the bare strip of land above the Senior School. The southern branch of this fork appears to have been primarily responsible for the destruction of the Junior School (Fig. 1.21).



1.19 Photograph showing general view of flowslide and mud run. 21st October 1966, approx. 1 p.m.



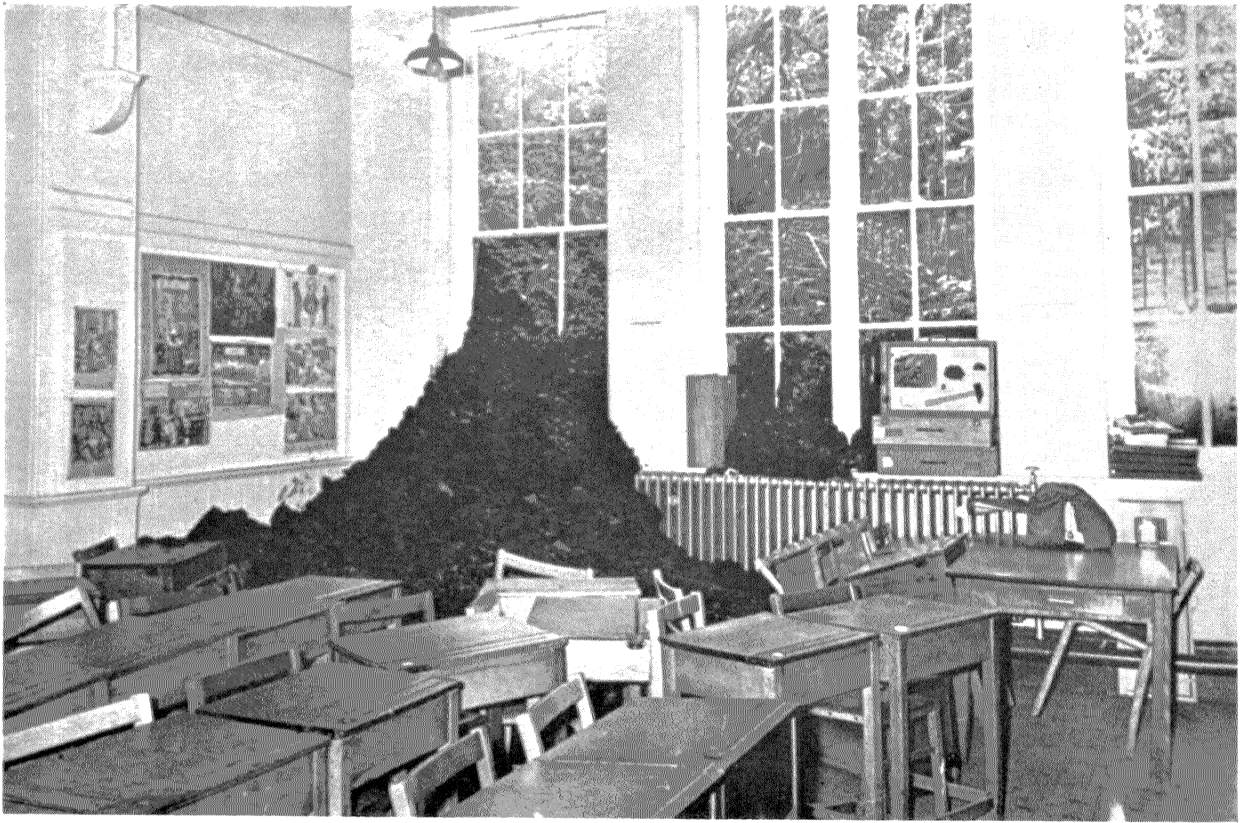
1.20 Photograph looking east showing course of mud run. 24th October 1966, approx. 2 p.m.



1.22 Photograph taken at approximately 11.15 a.m. on 21st October 1966 showing relatively 'dry' nature of rubbish with no indication of free water on the road surface.



1.21 Photograph giving a localised view in area of Junior School and showing alignment of flowslide towards this school.
21st October 1966, approx. 1 p.m.



1.23 Photograph showing a mound of rubbish in the corner of a classroom in the Senior School with no indication of free water.



1.24 Photograph showing rubbish at rear of Junior School at approximately 3.30 p.m. on 21st October. Person in light-weight shoes is able to walk across this material without difficulty.



1.25* Colour transparency showing bowl in natural ground left by the slip. The pegs mark original ground surface.

- (3) The photographs showing the state of some of the material at the toe of the flow-slide indicate that it travelled without any great excess of water (Figs. 1.22 and 1.23). Fig. 1.24 indicates that within a few hours some areas of material were relatively dry and could be walked on without difficulty.
- (4) Figs. 1.19, 1.20 and 1.21 suggest that the 'mud-run' associated with the outflow of water which followed the flow-slide was confined to the central area of the slide.
- (5) Flow-slide phenomena result from the transfer of the load initially carried by the solid skeleton of the material on to the water in the pore space. In the case of a slide on a slope such as that at Aberfan, i.e. approximately $12\frac{1}{2}^\circ$, the percentage of load which needs to be carried by the pore-water for a slide to take place is much less than on a flatter surface. For a value of the angle of internal friction of 38° this percentage would have to be 72%. For a value of the angle of internal friction of 32° (e.g. as in the tailings or in the finer material) the percentage would have to be 64% and for a value of the angle of internal friction of 18° the percentage need only be 32%. Loose, saturated material could thus flow without difficulty and loose material containing a percentage of air in the pore space could also flow under these conditions.

A full discussion of a major flow-slide has been given by Professor Arthur Casagrande in the 1965 Terzaghi Lecture entitled, 'The Role of the "calculated risk" in Earthwork and Foundation Engineering'. In an appendix to the lecture, Casagrande quotes the work of Hazen (1920) who discussed the possible relationship of this phenomenon to the crushing of the granular structure of soft rocks.

The third phase of the slip took the form of 'mud-run' resulting from the addition of water to the tip debris, in general, after it was already in motion. This 'mud-run' is illustrated in Figs. 1.19–1.21.

As has been mentioned earlier, the water content of a small 'mud-run' occurring during a period of heavy rain at the beginning of December 1966 averaged about 14%. The colliery rubbish is thus very clearly susceptible to flow with the addition of water. The estimated initial flow of the 'spring' revealed at the toe of the tip after the flow of material had largely ceased was 20 cu ft/sec.¹ Although greatly in excess of the normal flow of the 'spring' of about 0.1 cu ft/sec, this value is appreciably less than the initial flow estimated for the burst 31-in. water main in the disused canal.²

From an examination of Figs. 1.19, 1.20 and 1.21 and on the basis of observations of the December 1966 'mud-run', the deep channel eroded in the upper part of the material appears to have been eroded by the 'mud-run' itself rather than by the flow of water from the 'spring'. (The form of the lower part of the 'mud-run' is consistent with this view.)

No objective criteria exist for determining the relative amounts of damage caused by the flow-slide, the subsequent 'mud-run' and the water from the burst water mains in the disused canal. An examination of the photographs, however, strongly suggests that the flow-slide was the primary cause of the damage to the Junior School and to the houses between the Junior School and the Senior School. The area of damage was clearly extended by the 'mud-run' and, to a limited extent, by additional water from the burst water mains.

The development of an issue of water or spring from the area in which the 'spring' was finally seen to emerge is linked with the history of previous movements in this area of the base of the tip. The amount of definite evidence is very limited, but, as has been mentioned in Section 7, it is apparent that water was issuing from this area by May 1963 and was resulting in back-sapping on a large scale. By November 1964 the cross-sections (Figs. 1.4 and 1.5) indicate that some of the drift overlying the water-bearing layer of Sandstone Rubble had already been removed. The fact that the lag between the slip of 21st October

¹ ² See footnotes on p. 50.

1966 and the preceding period of heavy rainfall corresponds approximately to the lag between the flow of the present 'spring' and a preceding period of rain suggests that the base of the slip was directly influenced by water from the underlying Pennant sandstones.

The development of the 'spring' in its final position on 21st October 1966, almost certainly resulted from the removal of a further part of the drift mantle after the initial movement of the slip had begun. Whether this occurred during the initial stage of the slip or during the subsequent stage of rapid collapse is difficult to establish. If the former were the case, additional water from this source would have assisted in the saturation of the lower part of the tip, which is one of the prerequisites of a flow-slide. On the other hand, the shape of the surface of the actual ground exposed immediately adjacent to the 'spring' by the excavation made in February 1967 (Fig. 1.25) is more consistent with a slip surface having in section a smaller radius, such as the toe circle shown on Fig. 1.18.¹ This would, however, have resulted in the release of additional water in the tip material only after the first stage of the slip had been completed.

In considering the quantity of saturated material involved in the slide it is to be borne in mind that the quantity of tailings and slipped material from the area of back-sapping and from the 1963 slip and flow-slide, estimated at some 30,000 cubic yards, already lay on the mountainside immediately below the toe of the tip, and much of this material would have been in a condition approaching full saturation.

The formation of the slip surface which already existed in October 1966 is the result of the previous history of sliding of Tip 7. The large movements on this surface have been accentuated by the tipping of material at the crest and removal of material at the toe by back-sapping.

The history of Tip 7 summarised in Section 7 indicates that major movements were occurring in the period 1964–65 and that a slip having the same rear scarp position as the 1966 slip had occurred in October or November 1963. The aerial photographs suggest that even before this slip, which was of considerable magnitude, the lower part of the tip to the south-east and south had already bulged due to shear failure within the tip or the material forming its foundation.

The stability analyses presented in Appendix 4 suggest that with the average values of angle of internal friction found in the drift foundation, the factor of safety would be low but that actual failure would be unlikely unless small values of pore-water pressure were present in the foundation. It must, however, be noted that the date at which failure probably first occurred differs little from the date at which tailings were first dumped on Tip 7. If an apron of tailings had formed at the toe of Tip 7 on which additional rubbish was tipped their lower angle of internal friction and low permeability would have rendered them a less satisfactory foundation than all but the poorest of the drift material. The introduction of tailings into Tip 7, therefore, cannot be ruled out as a factor associated with an initial failure of the tip before that of 1963.

It should also be noted that the angle of internal friction of the finer material associated with the slip surface was found to depend on the pressure at which it was tested and, when sheared in a direction not corresponding to a pre-formed slip surface, varied from 35° to 20° as the pressure was increased (see Appendix 3). This suggests that zones of degraded material formed by minor slipping at the toe may assume greater significance as the height of the tip is increased and may partly account for the fact that both Tip 7 and Tip 5 developed distinct bulges on their south-eastern sides at much the same height (an undeformed slope of more than about 160 ft in height appears to be rare).

The development of the slip surface has thus most probably been the result of a succession of failures of which the 1963 failure in moving along a continuous deep slip surface approximated most closely to the 1966 slip.

¹ This shape could also have been formed by erosion of the drift as material slid down to form the 'mud-run'.

It is of interest to note that Tip 2, whose base may be particularly well drained and largely free of excess pore pressure, is in fact standing to a height of 200 ft without any significant sign of deformation on the slope. This may indicate that the margin between the initiation of instability and apparent complete stability may depend very critically on the effectiveness of the drainage at the base of the tip. It should also be noted that the slope of the face of this tip is approximately 30°. The stability analyses given in Appendix 4 show the important effect of flattening the slope on the value of the factor of safety.

9 Conclusions

1 Tip 7 at Aberfan had been unstable and intermittently sliding for a number of years prior to the final failure which caused the disaster of 21st October 1966. These slips were deep-seated and are not to be confused with runs of tailings.

This conclusion is based on the following evidence :

- (a) The displacements of identifiable objects on the surface of the south-east toe of Tip 7 (or claw) between November 1964 and June 1965 have been determined from plans made by Huntings Surveys Ltd from aerial photographs. The majority of these displacements were of the order of 20 ft in plan over a seven-month period.

The displacements are taken to be the result of deep-seated shear movements since an extensive excavation in this area has revealed a polished and striated slip surface such as would be produced by a very large shear displacement. The directions of the striations are in the same general directions as the movements obtained from the aerial photography.

It was noteworthy that a large flat-faced boulder of hard sandy siltstone embedded firmly in the matrix beneath the slip surface had developed striations parallel in plan, to within observational error, to the 1964–65 displacement of the nearest reference object. The striations on the surface of the adjacent matrix of fine grain material, which would tend to represent the final rather than the long-term movement, were orientated more towards the valley bottom by an angle of about 15°. The depth of fill at this point was of the order 25–30 ft during the 1964–65 period referred to. Its slope was relatively flat compared with the face of the tip behind it, so that surface creep was likely to be small.

- (b) The occurrence of a slip accompanied by a flow-slide of tip rubbish for a distance of over 700 ft down the mountainside in the latter part of 1963, probably late October or early November, is supported by evidence from the tipping gang. The occurrence of such a slip between September 1963 and November 1964 is confirmed by a comparison of the relevant aerial photographs.

Though the flow of material down the mountainside resulting from this slip may have been small¹ as compared with the final flow in October 1966, the statements that the cut-back at the crest was about 30 ft and that the slip surface formed on this occasion has persisted as the dividing line between the stable and unstable parts of the tip are compatible with the strength characteristics of this material as revealed in the later stages of the investigation. These statements are also compatible with the crest position of the tip indicated by the maps made from the aerial photographs of 1963, 1964, 1965 and 1966.

- (c) An examination of the September 1963 aerial photographs, together with the map and sections based on them, indicates that

¹This is a relative term. P.M. Grant (p. 2211 of the Transcript) stated that the Tymawr slip involved about 1000 tons. The 1963 slip was on a larger scale, the total volume of material passing the nominal toe of the tip between September 1963 and November 1964 being approximately 30,000 cubic yards or 40,000 tons.

back-sapping (or the removal of material from the toe by an issue of water or a spring leading to intermittent slips of progressively increasing size) was already well advanced at this date, and that the material having a relatively flatter surface to the south of the area of back-sapping can only have reached that position by slipping.

- (d) Evidence from the sections prepared from the 1963, 1964, 1965 and 1966 maps and witnesses' accounts of the slip shows that just before the tip slipped in October 1966, the crest position approximated to that of September 1963.

2 For much of the time that sliding has been occurring, the movement has been taking place mainly along the same slip surface. This conclusion is based on the following evidence:

- (a) When the excavation was made in February 1967 to the south of the present 'spring' position, a single well-striated slip surface was discovered. At all points examined the slip surface was associated with a distinct layer of fine tip material generally from 1 in. to 12 in. in thickness. The striations cut in the hard sandy siltstone boulder embedded in the lower surface indicated that large displacements had occurred. The directions of these were in conformity with the 1964–65 movements of the overlying tip determined from the aerial surveys. The tip material below this surface was in general more compact than the material sliding over it. In the southern part of the area examined the material below the slip surface appeared to be Tip 7 material at the higher levels, Tip 4 slip material as the ground surface was approached and finally the drift forming the natural ground.
- (b) When the excavation was opened the relative movement across this slip surface was found to be of the order of 1 in. per day. No other surfaces were detected. The trace of the crack produced on the face of the remaining part of Tip 7 by this movement is in conformity with the back of the slip surface revealed by the slide of October 1966.
- (c) The residual angle of internal friction, ϕ_r' measured on an undisturbed sample taken across this slip surface, was found to be only $18\frac{1}{2}^\circ$ in a fully drained test. Scrapings from the striated surface gave a residual ϕ_r' value of $17\frac{1}{2}^\circ$. This is to be compared with values of ϕ' at small strains in fully drained tests of 36° to 40° for the random rubbish and 31° to 32° for the tailings. It is thus much easier for movement to continue on a failure surface once a large deformation has occurred than for a new surface to be created.
- (d) Two large areas of slip surface were exposed by the October 1966 slip not far below the crest of the tip and were examined in early November 1966. These areas were backed by a very compact matrix of fine material in which particles of shale and pieces of wood were embedded. The shale particles and wood were aligned approximately parallel to the surface, pointing down the slope. No striations were apparent in the clayey matrix but the surface had been exposed to heavy rain before our first inspection. Downslope striations were observed on some of the shale particles embedded in the slip surfaces. The surfaces were standing at slopes of 40° to 50° , and remained stable for about one month in spite of the loose character of the bulk of the tip rubbish. It may therefore be inferred that they were not newly formed by the slip of October 1966. Thus, both the surfaces examined in November 1966 and in February 1967 are considered to be part of a common slip-surface and to pre-date the October 1966 slip. These are in conformity with tipping gang's references to a line of weakness persisting since the 1963 slip.

material which gives it a low residual angle of internal friction are matters which call for very detailed consideration.

During the period February 1962 to December 1963, the output of tailings from Merthyr Vale Colliery is reported as having been included in the rubbish tipped. Also by September 1963 there is evidence from aerial photographs that active back-sapping was occurring and that the toe of the tip had therefore advanced over a substantial issue of water or spring. Both factors would have contributed to the first significant slip in the tip.

The extent to which the clay-sized material in the immediate vicinity of the slip surface is derived from the degradation of shales in the tip rubbish by the large relative movement of the surfaces, by the smearing of existing fines and tailings, or by other causes is currently being examined. Present evidence indicates that degradation of the shale and segregation of the fines provide the most likely explanation. The continual addition of material to the crest of a tip which is settling due to movement on a shear surface is a most effective way of ensuring large displacements along this surface. Removal of material from the toe by back-sapping has a similar effect.

4 The pre-existence of a slip surface along which a reduced angle of friction is operative means that fresh movements would be initiated by a much smaller rise in pore pressure, or by a much smaller steepening of the toe by back-sapping, than would be the case in an intact and stable tip.

This is consistent with the evidence that intermittent settlements of the crest occurred during the three years prior to the final failure.

This also is consistent with the indication from model tests, that to cause, in an otherwise stable tip, a failure having a sequence of events similar to that observed at Aberfan would require much higher water pressures than appear compatible with the hydro-geology of the site.

5 Water has contributed to the disastrous slip of October 1966 in four principal ways:

- (1) Water issuing beneath the tip has caused back-sapping and led to recurrent movements over the years since 1963.
- (2) Water under pressure acting in the tip material and in the limited area of the foundation where the slip surface was adjacent to the natural ground reduced the effective stresses in the fill and initiated a shear displacement. In view of the presence of pre-existing slip surface, this pressure need not have been very large.
- (3) Water filling (or nearly filling) the voids of the loose fill comprising the tip and covering the area of mountainside below it made it susceptible to a catastrophic flow-slide since a shear displacement or shock wave¹ could result in the transfer of most of the load on to the relatively incompressible water in the voids, thus reducing the frictional strength to a very low value.
- (4) Water released by the slip and consequent flow-slide caused a 'mud-run' of tip rubbish.

Rain water percolating directly downward through the tip increases its degree of saturation, but does not lead to an excess pore pressure unless it is impeded by a less pervious layer. The rate of percolation is in any case slow in material of this grading. Piezometers (pore pressure gauges) installed in the tip material after the disaster showed no significant pore pressures in the remaining part of Tip 7, nor did they in general show any significant response to rainfall.

6 The shape of the area of back-sapping mapped from the September 1963 aerial photographs strongly suggests that the chief source of water causing it was not the issue of water shown on the 1957

¹ Correspondence with the U.K.A.E.A. suggests that seismic disturbance can be ruled out in the present case.

Ordnance Survey, but was, at that date, mainly from a location closer to the position of the spring revealed by the October slip.

The section of Fig. 1.5 suggests that by 1964 the action of back-sapping and the associated slipping had already removed the upper part of the drift mantle which forms the natural ground surface in this area. The release of underground water from this area would in consequence have been facilitated.

7 The information now available to us indicates the following sequence of events on 21st October 1966 :

- (a) Overnight the rise in water pressure in the ground immediately beneath the tip and in the lower part of the tip re-activated sliding movements on the pre-existing slip surface. A slow outward movement on the toe took place accompanied by a 10 ft settlement of the crest. This settlement was observed by the tipping gang to have taken place by about 7.30 a.m.
- (b) This settlement increased to about 20 ft by about 8.30 a.m. The accompanying shear strains in the lower and most saturated part of the tip were by this time approaching the critical condition for a flow-slide.
- (c) The flow-slide commenced in the central steep section of the toe of the tip at about 9.10 a.m. After the initial slow movement, the flow-slide accelerated down the mountainside to the village, taking with it saturated material lying downslope from the tip. Following on, and possibly carried by, this semi-fluid material, the bulk of the slightly less wet tip material slipped down, removing in the process both tip material and drift to release the water impounded in the fissured sandstone.
- (d) The estimated initial flow of water from the vicinity of the spring thus formed (based on the evidence given before the Tribunal) was of the order of 20 cu ft/sec and is compatible with the size of the open joints of fissures identified by raking boreholes in this area. This led to a 'mud-run' which carried down more material, which extended the central part of the flow-slide further into the village and finally scoured a deep channel in the flow-slide material (i.e. the deep channel was scoured by the 'mud-run' rather than by water). On the basis of evidence from Bowen and Grant it must be assumed that part of this flow initially came from a source behind the present spring position, which ceased to operate as the water level fell. Bad weather has delayed attempts to expose this particular area.

8 It is difficult to establish objective criteria for assessing how much of the damage was due to the initial flow-slide, how much was due to the subsequent 'mud-run' and how much to the additional water released by the fracture of the two water mains in the canal behind the railway embankment.

An examination of the various photographs and the statements of witnesses about the consistency of the material and of the depth to which it accumulated after passing over the embankment, suggest that the flow slide was the primary cause of the destruction, in particular of the Junior School.

This view is supported by a detailed examination of the evidence from the Abercynon flow-slide in 1939, which was not accompanied by a significant outflow of water but was as potentially destructive as that at Aberfan in 1966.

9 For a tip whose face is defined by a constant slope angle, geometrically similar slip surfaces will embrace a volume of soil per unit breadth of slip which depends on the square of the height. Since the breadth of a slip is likely to be roughly pro rata with its height, the volume displaced will depend approximately on the cube of the height.

by the height of its centre of gravity, which is also in direct proportion to its height. Thus for a given density the potential energy will depend on the fourth power of the height from the crest to the toe, quite apart from the slope below it.

Thus if the height of a tip is doubled, the mass moving in a slip may be multiplied by a factor of about 8, and the potential energy available may be multiplied 16 times. Height is therefore an important factor in the destructive ability of a tip.

10 In tips of soft rocks such as shale, the greater stresses in high tips may lead to crushing at inter-particle contacts and make the lower saturated layer more susceptible to flow-slide phenomena. It is noteworthy that the slips at Abercynon in 1939, Aberfan Tip 4 in 1944 and Aberfan Tip 7 in 1966 occurred when the crest-to-toe vertical height was of the order of 200 ft.

11 Tips constructed at a slope angle or angle of repose which approximates to the angle of internal friction ϕ' have, even in the absence of excess pore water pressure, a very low factor of safety against sliding on relatively deep surfaces. For example, a surface tangential to a base slope of 1 in 4 and cutting back 30 ft at the crest for a crest-to-toe vertical height of 200 ft has a factor of safety of 1.15.

The factor of safety is reduced by building on a foundation having a lower value of angle of internal friction, particularly if steeply sloping. It is also reduced by the presence of pore-water pressure in the foundation or tip rubbish.

Factors of safety of this order are much below those called for in other structures whose failure could be potentially destructive. These low factors do not include any allowance for long-term deterioration of the material. However, flow-slide phenomena appear to have been limited to active tips. This aspect of the problem requires more detailed study and it will be one of our recommendations that the question of acceptable risk should be reviewed by an appropriate Committee.

12 Flow-slides occur only in loose cohesionless materials. The density at which flow-slides will occur increases with pressure and thus with the height of the tip. According to Casagrande (1965), no precise dividing line can yet be drawn between materials which will flow and materials which will not. The trigger mechanism and the slope of the ground over which the flow-slide is to travel are controlling factors. However, flow-slides in compacted materials are highly improbable.

The full saturation of a loose granular material makes it most prone to move as a flow-slide. This emphasises the importance of drainage in tips of loose materials. However, it is also clear that loose partly saturated material can 'flow' if the gradient is sufficient. The 'flow' of powder snow in an avalanche is an example of this phenomenon.

For complete safety, therefore, attention has to be given both to compaction and to drainage.

13 The principal lesson to be learned from this disaster is that large tips of colliery rubbish (or indeed of any type of spoil) have to be treated as engineering structures. The procedures of site investigation and control customary in other fields of civil engineering should thus be applied.

Our detailed recommendations are given below.

Summary of Conclusions

A rise in pore-water pressure at the base of the tip due to an increase of pressure in the water in the fissures of the Pennant sandstone following heavy but not unusual rainfall reactivated sliding movements on a shear surface created mainly by movements in earlier years.

The large magnitude of this displacement caused a flow-slide to

commence due to the presence of a substantial volume of loose, saturated material at the base of the tip and of a large volume of loose, wet material, containing only a small percentage of air in its voids, above it. The saturation of the base of the tip was primarily caused by water issuing from the ground in the absence of free drainage at the base of the tip. The flow-slide was the main cause of damage to the Junior School.

The removal of tip material and of some natural ground by the two initial stages of the slide released a quantity of water, which, though large compared with normal spring flows, is estimated to have been only 20 cu ft/sec at mid-day on the day of the disaster. This release of ground water brought down more rubbish in the form of a 'mud-run' and extended the area of damage. This 'mud-run', together with water from the burst water mains in the disused canal, hampered the initial rescue operations.

Recommendations

1 Large or potentially dangerous tips of colliery rubbish (or of other industrial waste or spoil) should be considered as engineering structures. The procedures of preliminary site investigation and control during placing, customary in other branches of civil engineering should be applied.

2 The initial site investigation necessary for a new tipping area or for the extension of an existing tip complex should be under the direction of a civil engineer experienced in the field of soil mechanics. The civil engineer should be responsible for seeking the advice, when necessary, of a geologist familiar with the local stratigraphy.

3 To ensure that only suitably qualified engineers are employed for the purpose specified in paragraph 2, a panel of approved engineers should be established by the appropriate Ministry on lines similar to those of the Reservoirs (Safety Provisions) Act of 1930 (as amplified in the Report on Reservoir Safety published by the Institution of Civil Engineers in 1966). It may be noted that some lagoons for the disposal of fly ash are already constructed to the requirements of this Act.

4 The principle of regular statutory inspection by an independent qualified engineer should be extended to large or potentially dangerous rubbish tips.

5 It appears from the present investigation that catastrophic flow-slides as at Aberfan and Abercynon, and the failure of lagoons of tailings as at Tymawr and Williamthorpe, are associated with active tipping operations. The frequency of the independent inspection of active tips should be at least once per year, decreasing, as recommended by the inspecting engineer, to once in, say, 10 years for old tips.

6 The present investigation has been concerned primarily with the causes of the failure of one particular tip rather than with the examination of the possible hazards involved under other geological conditions, with rubbish or tailings of different geological origin, placed by other methods.

We therefore recommend that a Tip Safety Committee be set up by the appropriate Ministry to report, *inter alia*, on :

- (a) The standards of safety which should be called for in large tips adjacent to inhabited property, to public highways and to railways, etc; and whether or not lower standards should be accepted for tips at present more remote from developed areas.
- (b) The definition of a large or potentially dangerous tip for statutory purposes.

The Committee should also make recommendations on :

- (c) Which of the observations and investigations begun during the present Inquiry should be continued, under the sponsorship of the National Coal Board, the Science Research Council or the National Environmental Research Council. Obvious examples are long-term observations of the effect of rainfall on ground-water level, and further studies of the degradation of shale rubbish after tipping and the influence of this process on the strength and drainage of the tip.
- (d) What other lines of investigation should be followed up, involving either field observations or laboratory investigations relevant to the safety aspects of both new and old tips.
These investigations might include studies of the feasibility of applying to waste tips the techniques of controlling ground-water level by relief wells and of controlling pore pressure in the fill by drainage layers currently used in the construction of embankments.
- (e) What hazards, if any, are involved in the present methods of disposing in bulk of other similar industrial waste products.

APPENDIX 1

Summary of paper 'Landslides in South Wales' by Professor George Knox

Summary of paper on:

'Landslides in South Wales Valleys', by Professor George Knox, FGS, MIME. Read and discussed in Cardiff, 29th March 1927. Further remarks and discussion in Cardiff on 28th April 1927.

All published in *Proc. S. Wales Institute of Engrs*, **43**, 161–233, Discussion, 234–247; **43**, 257–267, Discussion, 267–290.

Scientific background

The main stimuli behind the paper appear to be the books of the geologist Heim (1882) and the geomorphologist Penck (1894), both published in German.

Although writing two years after the publication of Terzaghi's *Erdbaumechanik*, Knox appears to be quite unaware of the principle of effective stress and rejects (p. 290), a suggestion by one of his audience (Mr R. James, p. 284) in which this principle is implicit. For his applied mechanics, Knox appeals only to Rankine (1857) and 'Boussinesq' (actually Coulomb, 1776) and to early American work on the Panama Canal slides. It is perhaps significant that the most recent of the papers quoted in the bibliography to Knox's paper was published 11 years earlier, in 1916. The rest of the bibliography is of pre-1914 date.

Knox's paper was thus, at least with respect to its theoretical aspects, out of date when it was written.

Objectivity

Although the author rightly stresses the widespread occurrence of natural landslides in the Welsh mining valleys, he appears to lack objectivity in attempting to establish that 'the weight of a colliery tip has nothing whatever to do with initiating a landslide' (p. 181). This view is maintained despite inclusion in the paper of five case records of landslides involving colliery tips (Cwm, pp. 206–209; Blaina, pp. 209–211; Pentre, 1916, pp. 211–218; Pentre, pre-1916, pp. 218–219; Pochin, pp. 260–264), probably because Knox is incorrect both in his theoretical treatment of the failures (pp. 180–182) and in ascribing their physical mechanism to 'underground mud streams' (p. 221). Of such failures it is stated (p. 229) that 'if a colliery tip . . . rests on soil or rock liable to slide, it must slide with them, but it is in no way responsible for causing the slide'. In the case of the 1916 slide at Pentre the claim is made, in support of this view, that when the rock beneath the tip gave way it moved 'faster than the colliery refuse riding on it' (p. 216).

In the case of the landslide at New Tredegar (p. 194), the Brecon and Merthyr Railway Company is commended for removing large quantities of debris from the toe of a landslide, a practice which is rightly discouraged elsewhere in the paper (pp. 172, 188, 228–229).

Valuable features of paper and discussion

Despite the shortcomings indicated above, Knox's paper contains much that is of value. The full discussion and the demand for a second meeting show that a considerable awareness of and interest in landslide problems existed amongst engineers in South Wales in 1927, and that through qualitative experience some valuable conclusions had already been reached.