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LANDSLIDE DAMAGE TO THE BOAR RIVER WATER SUPPLY PIPELINE, BROMLEY HILL, JAMAICA : CASE STUDY OF A LANDSLIDE CAUSED BY HURRICANE GILBERT (1988)

DÉGÂTS CAUSÉS PAR UN GLISSEMENT DE TERRAIN À UNE CONDUITE D'APPROVISIONNEMENT EN EAU, BROMLEY HILL, JAMAÏQUE

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Abstract

This case study highlights the importance of geotechnical investigations in the site selection, design and maintenance of life-line structures in multiple hazard prone areas.

The Boar River Pipeline, carrying part of Kingston's water supply, was damaged by a debris flow originating on the eastern slope of Bromley Hill, following the passage of hurricane Gilbert over Jamaica on September 12, 1988. Regional and site-specific geotechnical investigations indicate that landslides are ubiquitous in the region, especially on east-facing slopes, and that the slide which damaged the pipeline is a relatively shallow failure. The slide may stabilize itself in the due course of time provided there are no extreme weather events. Artificial measures of slope stabilization are recommended as a short-term solution. However, since the entire slope is involved in sliding and favourable conditions for future failures exist in the area, the better approach would be to avoid the failed slope altogether and relocate the pipeline.

Résumé

L'exemple traité dans cet article met en évidence l'importance des études géotechniques pour le choix des sites destinés à recevoir des structures durables, ainsi que pour leur conception même et leur entretien.

La conduite de la Boar River qui achemine une partie de l'approvisionnement en eau de Kingston, a été endommagée par une coulée de débris qui s'est déclenchée sur la pente orientale de la Bromley Hill, suite au passage du cyclone Gilbert sur la Jamaïque le 12 septembre 1988. Des études géotechniques à l'échelle de la région et du site montrent que les glissements de terrain sont très répandus dans la région, en particulier sur les pentes orientées vers l'Est, et que le glissement qui a endommagé la conduite est relativement superficiel. Le glissement pourrait se stabiliser de lui-même avec le temps pourvu qu'il ne se produise pas d'événements météorologiques extrêmes. Des mesures de stabilisation de pente sont recommandées comme solution à court terme. Cependant, comme la pente tout entière est affectée de glissements et que des conditions favorables au déclenchement de nouvelles ruptures existent dans tout le secteur, la meilleure solution serait d'éviter l'ensemble de la pente et de réimplanter la conduite dans un autre site.

1. Introduction

A section of the Boar River Water Pipeline, an important contributor to the water supply of the city of Kingston, was damaged by a landslide in the wake of infamous hurricane Gilbert which devastated the island of Jamaica on September 12, 1988. This, 609.6 mm diameter, pipeline was laid in 1965 to convey surface water from a number of rivers rising on the western slopes of Mount Telegraph, situated at a height of 1 275 m in the northern part of the parish of St. Andrew, to the Constant Spring Water Treatment Plant, Kingston, operated by the National Water Commission of Jamaica (N.W.C.).

The complete alignment of the pipeline is not available to us, however, it cuts across the highly rugged central mountain ranges of the island and is located within a major fault zone (Fig. 1). It has a capacity of some 41 million L/day. Minimum flows are as low as 4.5 million L/day but the pipeline is at all times an important source for domestic water which was disrupted when an exposed section of the pipeline was damaged in the Bromley Hill area (Fig. 2). In view of the said importance of the pipeline, we were asked by the U.S.A.I.D./N.W.C. Hurricane Reconstruction Project to carry out geotechnical investigations in the Bromley Hill area to determine the nature and causes of the damage and suggest protective measures. These investigations were undertaken during May 1989-August 1990 and included drilling of 4 boreholes in the vicinity of

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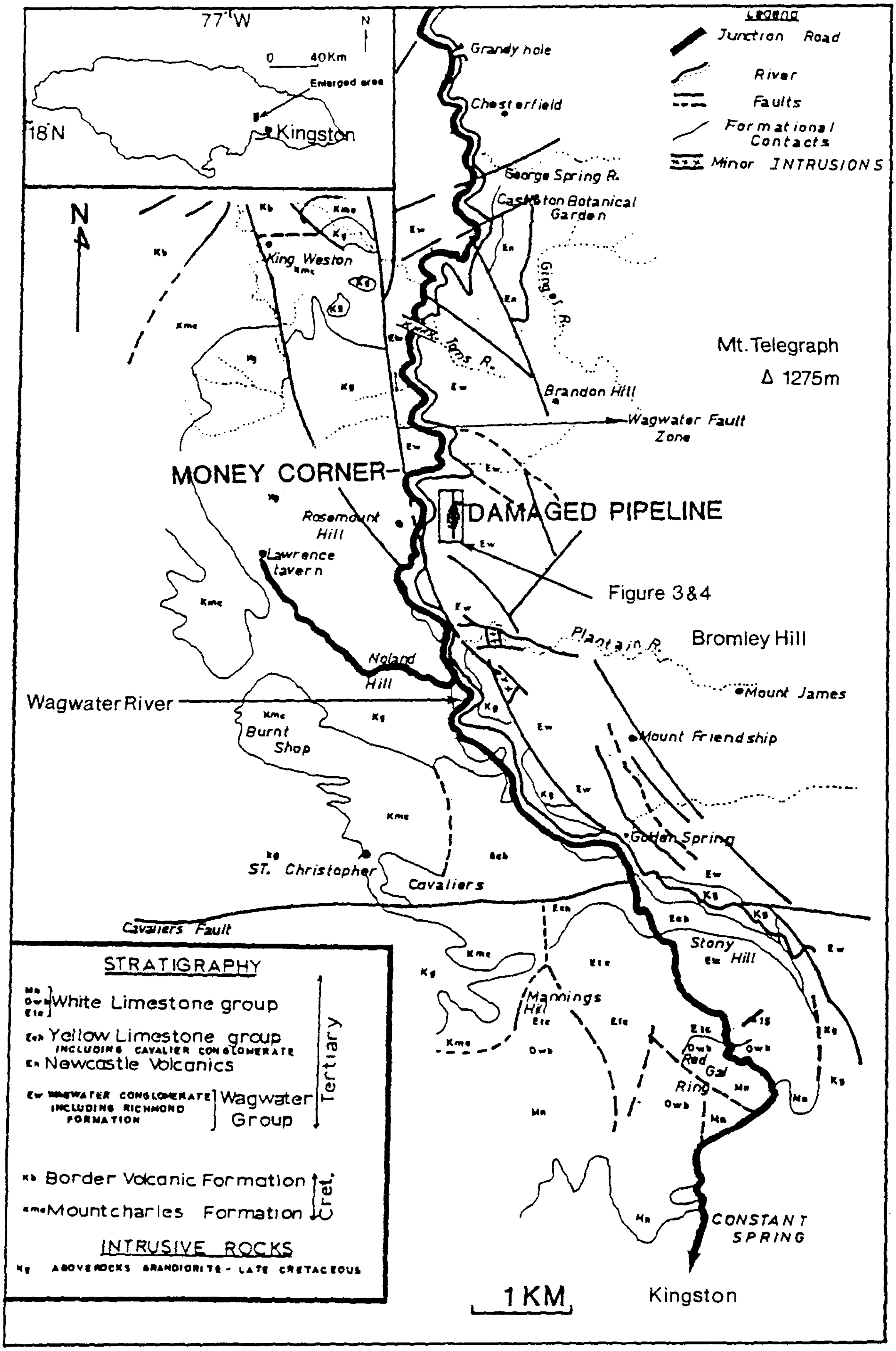


Fig. 1 : Simplified geological-structural mam of the western part of Wagwater Fault zone in Jamaica showing the location of the damaged pipeline at Bromley Hill. The location for Fig. 3 and 4 is marked. Geology and structure has been modified from Geological Survey Division, Geological Sheets Nos. 22 (1972), 25 (1974) and 24 (1978).

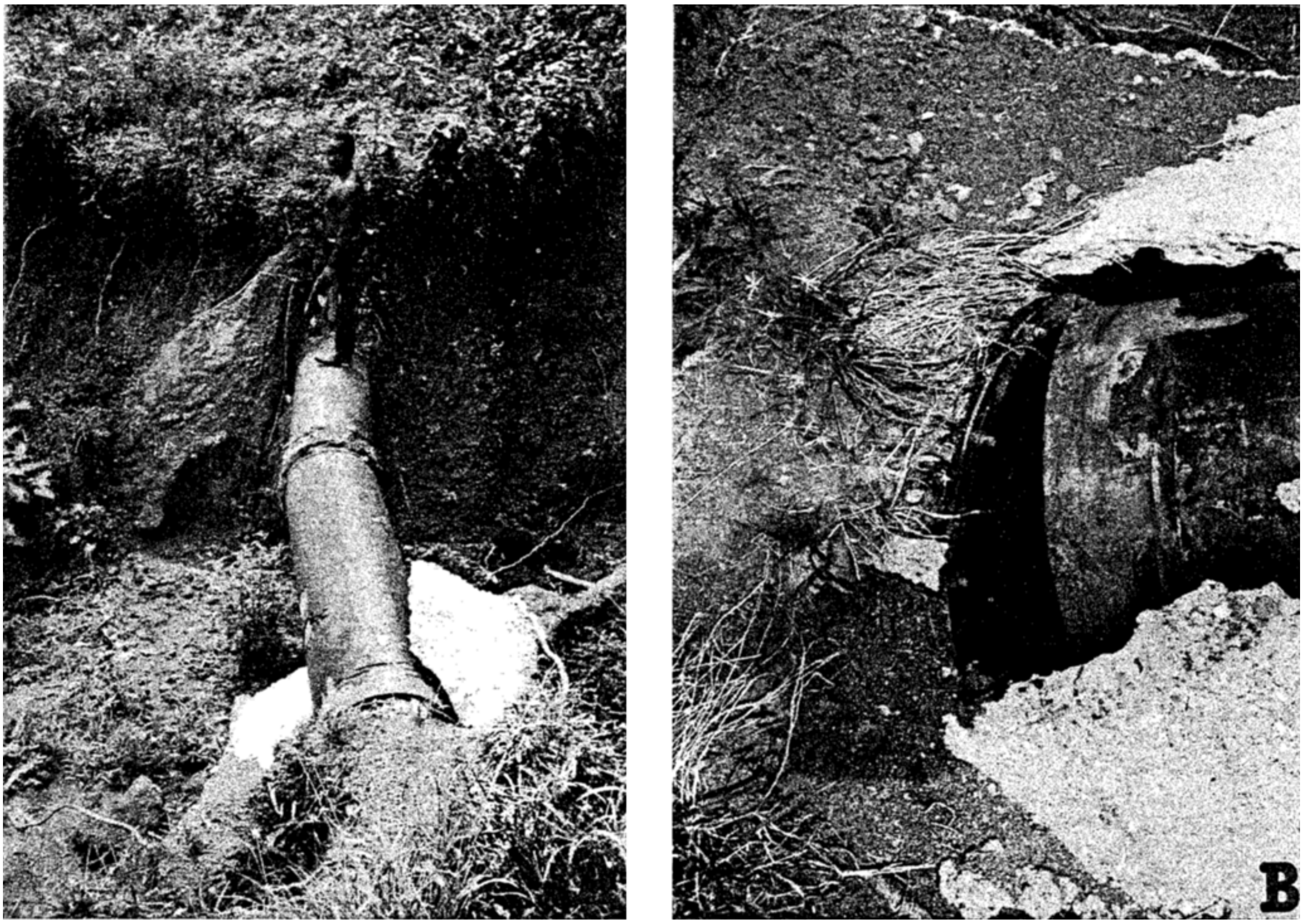


Fig. 2 : A. Northern section of the damaged pipeline at Bromley Hill.
B. A detailed view of the damage in the foreground of the photograph in A. The diameter of the pipe is 24 inches (609.6 mm).

the damage. Our study addressed the following important issues that must be taken into consideration in the design and maintenance of life-line structures in multiple hazard prone areas :

A. Ascertain to what extent geologic-tectonic-geotechnical conditions in the area were related to damage to the structure,
B. Whether these be of such a nature that recurrent problems with maintenance and repair would likely to continue into the future, and
C. Make recommendations concerning the possibility of carrying out remedial measures which would prevent future structural damage, or if it were not possible, the need for re-aligning the structure.

We present here the results of this study and show that the structure was damaged due to a debris flow (*sensu* Ellen *et al.*, 1988) triggered by heavy rainfall associated with the hurricane. The responsibility of writting this paper lies with the senior author (R.A.).

2. Hurricane Gilbert

The passage of Hurricane Gilbert over Jamaica on September 12, 1988 resulted in a widespread landslide activity which severely disrupted the life-line structures on the island (ODP and WMO, 1988). Manning *et al.* (1988) mapped a total of 478 landslides along 108 km of road sections in the Lawrence Tavern - Above Rocks area located to the west of Bromley Hill (Fig. 1). Among these landslides, debris flows were most abundant, however, rock falls, translational slides and complex rotational slides were also reported. These slope failures were initiated by excessive precipitation during the period September 10-12, 1988

Gilbert had its origin in a tropical wave which, due to a high - pressure system over the Caribbean grew into one of the most powerful and devasting storms ever recorded (category 5 on Saffir-Simpson Scale) with an extremely low barometric pressures of 885 mbar in its eye. The center of the hurricane reached the easternmost point of the island, Morant Point, at about 11 : 00 a.m. on September 12, accompanied by gusts at 51.1 m/s. the maximum rainfall intensity was of the order of 86.1 mm and the maximum 24 hour rainfall was recorded at 450.7 mm (ODP and WMO, 1988). Eastern and central sections of the island received extensive rainfall during September 10-15 and it appears that > 500 mm rainfall was localised along an almost E-W axis that coincides with the central orographic trend of the island. Northern St. Andrew area where Bromley

Hill is located (Fig. 1) received the largest amount of five-day rainfall, with the two rainfall stations in the parish at Langley recording 793.99 mm of rainfall and Hermitage 661.9 mm (ODP and WMO, 1988).

3. Regional Geological and Geotechnical framework

The damage site is located within the Wagwater Fault Zone (Fig. 1), which is an area of major tectonic disturbance in eastern Jamaica (Lewis and Draper, 1990). This setting has important implications for the pipeline alignment. The fault zone, over 750 m wide, has juxtaposed a sequence of interbedded conglomerates, sandstones, and shales (Wagwater Formation) against a coarse-grained, granodiorite pluton known as the Above Rocks Granodiorite. The sedimentary rocks of the Wagwater Formation are thrust over the granodiorite, a relationship which can be seen on the Junction Road (Fig. 1), where a major landslide, popularly known as Money Corner Landslide, marks the contact. Fracturing and hydrothermal alteration of the rocks of the Wagwater Formation, in and near the Fault Zone, are pervasive, and our observations suggest that sections of the pipeline route are within this zone, including the section where damage has occurred. The region is marked by a high relief and steep slopes. The major physiographic features in the area are controlled by the underlying geology and tectonic structures. High level river terraces suggest recent, probably continuing, uplift of the region. The valley slopes have been cleared for agricultural use, and this together with some degree of urbanization, has made many of the slopes unstable. Bedding discontinuities within the Wagwater Formation are subparallel to the trend of the ridges. Therefore, when slope vegetation is cleared, or interfered with, the incidence of slope instability is dramatically increased. The material underlying the slopes is deeply weathered for the most part, due to its inherent chemical composition. The depth of the weathered zone ranges up to as much as 9 m, sometimes more. Extreme climatic events, such as the passage of hurricane Gilbert have had a marked impact on the area. Landslides (debris flows and debris avalanches) were triggered along a majority of slopes by Gilbert. The debris flow which damaged the Boar River pipeline resulted from high precipitation associated with the hurricane, in an area where soil moisture was already at the saturation level.

Most of the water courses in this region follow fault-controlled valleys, and the valley slopes themselves are marked by active mass wasting. The damaged section of pipeline, on the eastern slope of Bromley Hill, lies in a zone where the ridge and valley system is underlain completely by sedimentary rocks of the Wagwater Formation, which are extensively dissected by NNW-SSE trending fractures, subparallel to the main Wagwater Fault (Fig. 3). The sedimentary units consist of dark red and purple conglomerate, sandstone and shale, with occasional limestone beds. The sequence is massive to thinly layered, and is characterised by silt to boulder size clasts of andesitic tuffs, granodiorite, hornfels, limestone and mafic rocks, set in a fine matrix of similar material. Cement is ferruginous to calcitic in composition. Several different kinds of discontinuities have been noted. In order of abundance, these are :

Bedding – a pervasive feature, developed on a millimetre to metre scale, and is inclined towards the NE and E, at angles ranging between 55° to 5°.

Joints – these are mm to cm spaced brittle fractures, also pervasive, occurring in at least three sets, inclined at a high angle to the bedding, in some cases even subparallel to it.

Veins – calcite-filled extension joints are common in regions close to the major faults.

Faults – besides the major NNW-SSE trending faults mentioned already, there are many faults which occur at high angles and subparallel to the bedding.

The Wagwater Fault Zone has a complex history of movements, with the earliest ones dating back to as early as Palaeocene (about 60 million years B.P.). It is a seismically active fault zone, and during the last five years a number of shallow seismic events have been reported from within the area (Personal Communication, Seismic Research Unit, Mona). The preceeding discussion of the regional geology provides perspectives pertinent to problems which may be encountered in the area when planning for any future engineering works related to readjustment of the damaged pipeline.

4. Geotechnical background at the damaged site

The damaged section of the pipeline is located on the eastern slope of Bromley Hill (Fig. 4), which is made up of a thinly bedded sequence of alternating mudstones and coarse, gravelly sandstones belonging to the geological unit known as the Wagwater Formation. Mount Dakin River, which flows along a northwest to southeast trending valley controlled by faulting and possibly bedding, marks the eastern boundary of the area (Fig. 3 and 4).

Physiography : The mapped area is outlined on Figures 3 and 4. The ridge crest of Bromley Hill is at a height of 325 m and the slope profile, which is uneven, ends at 228 m in the Mount Dakin River. The ridge has a general north-south orientation, and two major landslides have been identified along the eastern slope, which is drained by the main, north-flowing, Mount Dakin River. The narrow Mount Dakin River valley is fault controlled, and a large landslide has been mapped along its eastern tributary (Fig. 3). The regional drainage pattern is dendritic, with a high drainage density. The perennial, fast flowing Mount Dakin River is about 3 m wide and the river bed is strewn with boulder to silt sized material. The channel profile is v-shaped with steep valley walls. During peak discharge the water level of the river rises as high as 2 m above low flow levels and there are abundant signs of rapid bank erosion and slope undercutting. Dense vegetation, consisting of guinea grass, scrub, trees and fruit trees, is

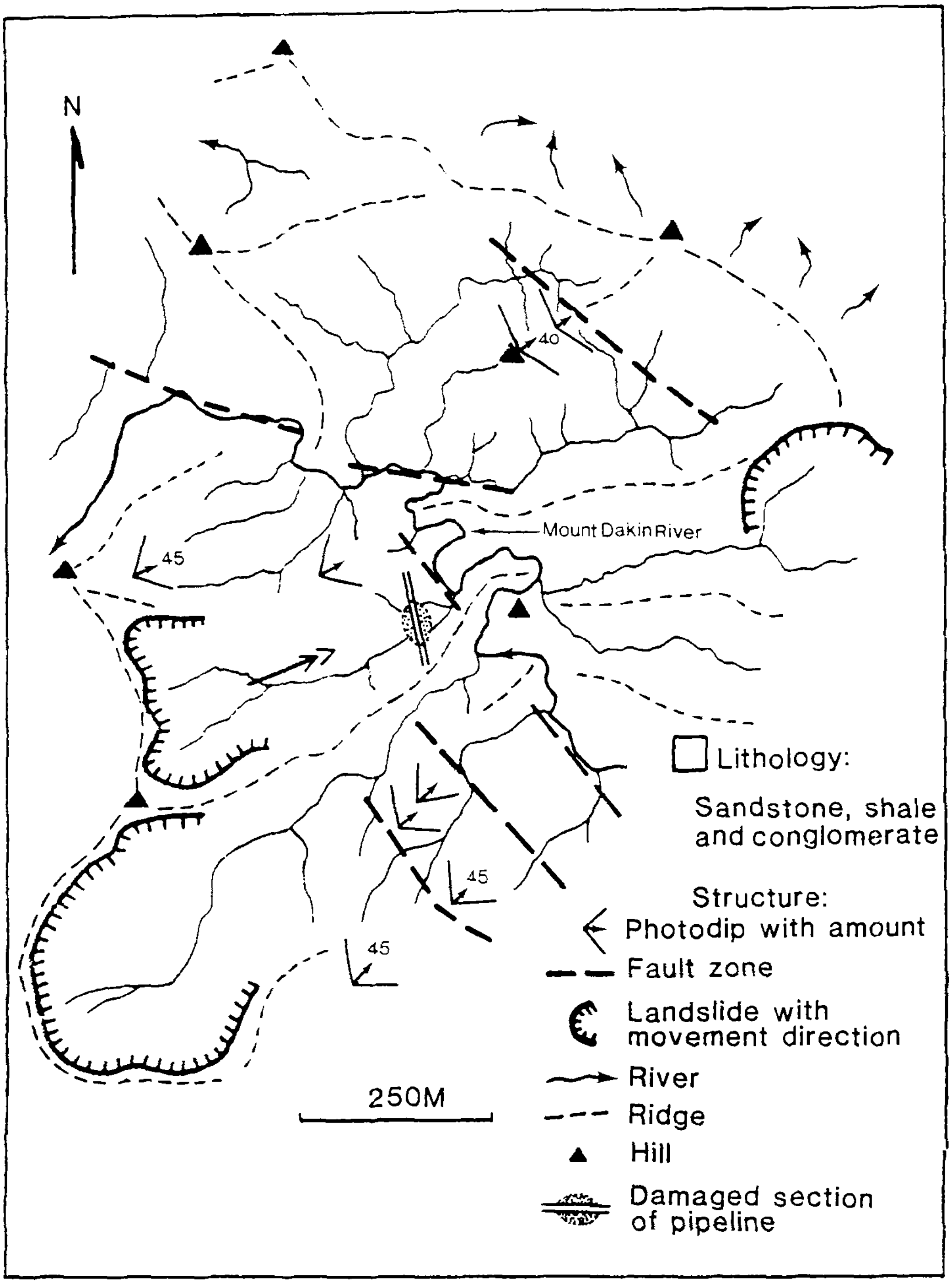


Fig. 3 : Uncontrolled photogeological map of the area around the damaged section of the pipeline, Bromley Hill. See Fig. 1 for location.

common along the valley slopes. The slopes with landslides are generally sparsely vegetated. The damaged section of the pipeline (Fig. 2) is located on an active landslide (debris flow) on the eastern slope of Bromley Hill. The pipeline is aligned north-south and is located midway along the slope at 246 m. The main scarp of the slide is at 264 m and many minor scarps have been mapped along the length of the slide. The toe of the slide is located at the confluence of two east-flowing streams, which delineate the northern and southern flanks of the slide. Water seepage zones are characteristic of the toe region, and are shown, together with other morphological features, on the geotechnical map and cross-section (Fig. 4 and 5).

Lithology and Soils : Bedrock exposures are rare and much of the area is underlain by residual soils (engineering soil terminology). Where bedrock has been mapped, it consists of alternating beds, ranging in thickness from 2 cm to about 1 m, of red-purple conglomerate, sandstone, breccia, and shale, which may often be greyish-brown. Sandstone beds are frequently massive and are up to 1.5-3 m thick. The sedimentary sequence throughout the area dips uniformly to the

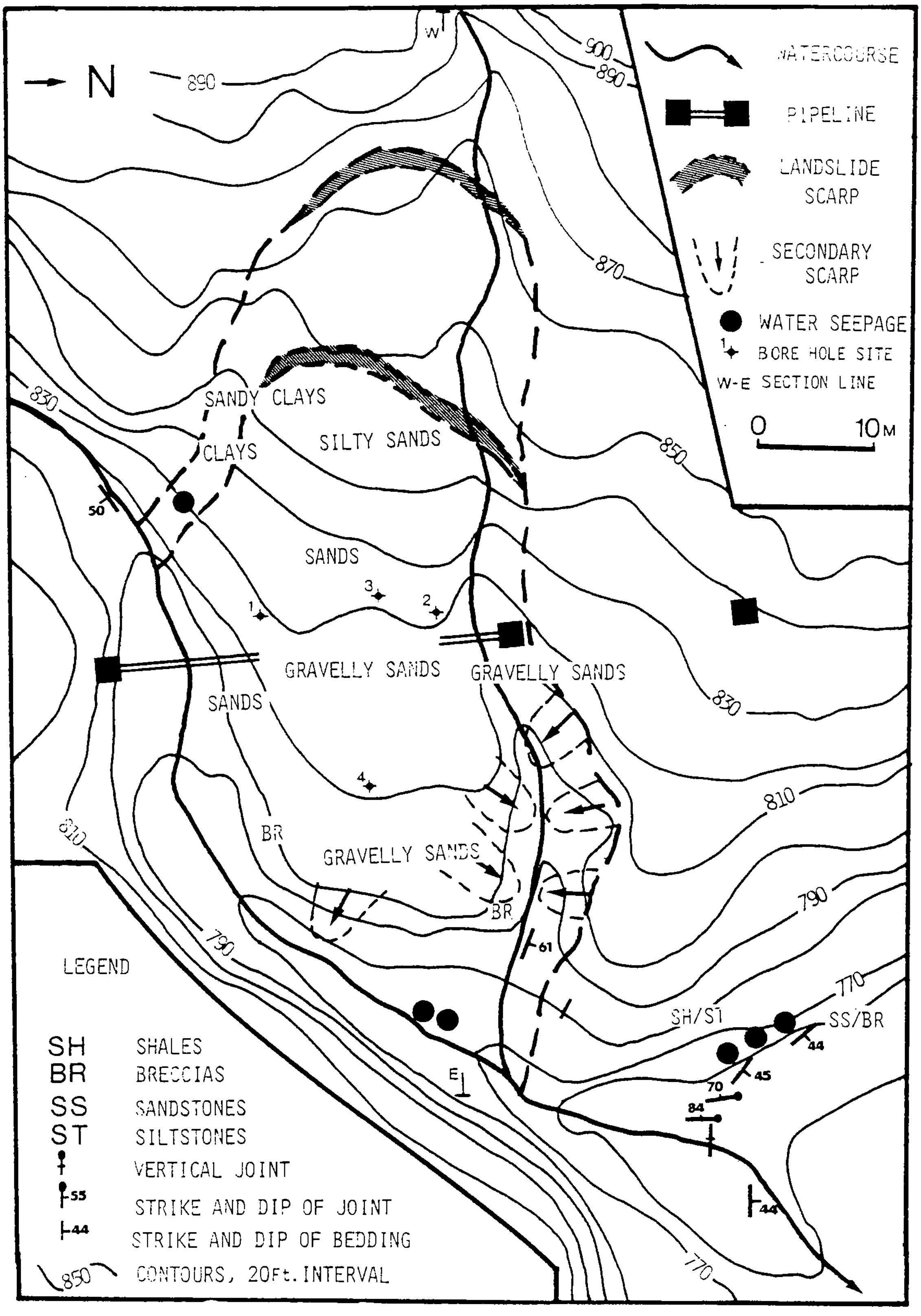


Fig. 4 : Geological map of the debris flow at Bromley Hill. See Fig. 1 for location.

northeast (050°) at angles ranging from 35° to 55°. The regional strike is more or less parallel to the trend of slopes through the region (Fig. 3). Although deep weathering is characteristic for all the rocks, the massive sandstone and conglomerates are relatively more resistant. Medium to coarse grained sandstones dominate the sequence, and consist of clasts of plagioclase, rock fragments, quartz, with mud matrix and ferruginous, and/or calcitic cement. Two types of soil are common (Fig. 4) :

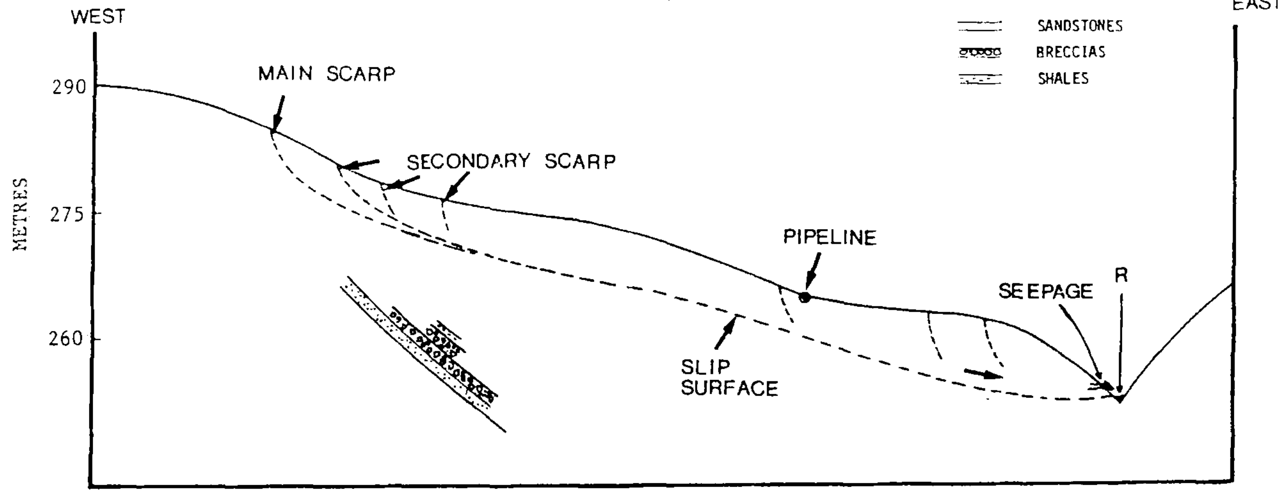


Fig. 5 Geological Cross-Section (W-E) across the damaged section of the pipeline.

a) Coarse grained soils (predominant) – are sandy to gravelly, less commonly silty and moderately weathered. Grains are generally angular, partly stratified to non-stratified. These soils are moist.
b) Fine grained soils – are silty clays, plastic and highly weathered, and stiff; they are inorganic and fissured. They are saturated, and ponding of water in clays is common. Vegetation cover does not allow the preparation of an accurate superficial deposit map for the whole area, but the extent of soils and bedrock within the immediate area of the pipeline is shown in the geological map (Fig. 4).

Structure/Discontinuities

Bedding, joints, faults, and minor calcite filled extension joints are prominent in the area. Measurements of typical orientations are presented as stereographic projections in Figure 6.

Bedding. – Defined by lithological variations, with alternating thicknesses. It is a pervasive feature. Beds are consistenly oriented throughout the area, as noted above.

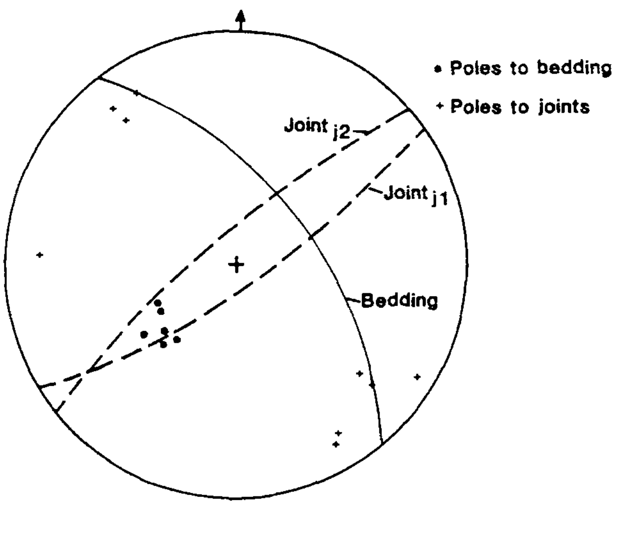


Fig. 6 : Equal area stereoplot of bedding and joints at localities around the damaged pipeline.

Joints. – Five joint directions have been identified, j1-j5, with spacing generally varying between 25 mm and 30 cm. Of these, only j1 and j2 are important and well developed, and have been included in the stereogram.

j1 and j2. – strike northeast-southwest and dip respectively, at about 80° to the northwest and southeast.

j3. – very minor development, trends at 300°, vertical dip and at low angles to the bedding.

j4. – also very minor, trends north-south, almost vertically, and at high angles to the bedding.

j5. – minor, has the same trend as j3, but dips at 40° to the southwest.

Faults. – Two major faults have been mapped in the area (Fig. 3). Mount Dakin River flows along a WNW-ESE trending fault. The other NW-SE trending fault is visible on the aerial photographs along the eastern slope of Bromley Hill.

5. Landslide at the site

Figure 5 is a cross-section through the eastern slope of Bromley Hill at the location of the damaged pipeline. The damage is a consequence of a landslide which developed near the crest of the ridge, upslope of the pipeline. Following Varnes (1978) this landslide would be classified as a complex slide, involving debris flow and avalanching, however, we prefer to describe this slide as a debris flow (*Sensu* Ellen *et al.*, 1988). The main type of displaced material is debris, derived from a thick cover of residual soils, overlying the highly weathered bedrock. The damaged sections of the pipeline suffered considerable displacement because of debris flows and avalanching related to the slide. The toe region is located within the confluence of the two east flowing streams, which define the northern and southern flanks of the slide (Fig. 4). Water seepage was observed in the toe region of the slide and along possible failure planes (Fig. 4 and 5). That the slide is active can be seen from several secondary slides which have developed on the flanks of, and within the main body of the failure.

OFFICE BOREHOLE LOG

BORE HOLE 1 SHEET ____ OF ____

PROJECT BOAR RIVER PIPELINE

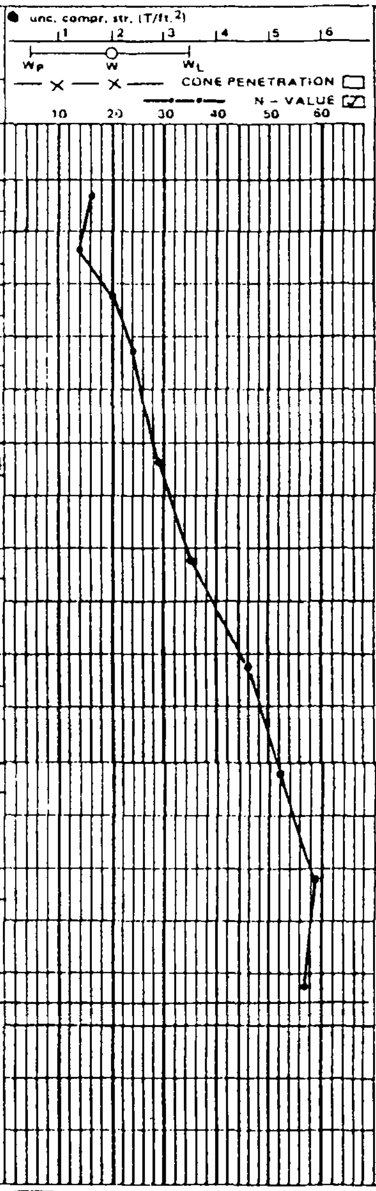
LOCATION DAMAGE SITE, BROMLEY HILL

DATE JULY/AUGUST 1990 SURFACE ELEVATION 820ft (249.94m)

TYPE OF BORING: HOLLOW STEM AUGER ☐ ROTARY DRILLING ☐ CONE PENETRATION ☐ WASH BORING ☐ TEST PIT ☐ CONTINUOUS ☑

DIA. OF BORING 3inches ϕ

Sample No.	Sample Type	Sample Condition	% Recovery	SPT 1st 6"	SPT 2nd 6"	SPT 3rd 6"	Description of Strata
1	ss	D	72	5	7	9	STIFF DARK BROWN CLAYEY SILT
2	ss	D	78	8	8	6	
3	ss	D	89	7	9	11	VERY STIFF DARK BROWN CLAYEY SILT WITH PIECES OF SHALE
4	ss	D	72	11	12	12	VERY STIFF DARK BROWN CLAYEY SILT AND DECOMPOSED SHALE
5	ss	D	94	13	15	14	
6	ss	D	67	15	17	18	
7	ss	D	94	19	22	24	
8	ss	D	78	24	26	26	DENSE DARK BROWN DECOMPOSED SHALE
9	ss	D	89	27	29	30	
10	ss	D	83	28	31	26	
							END OF BOREHOLE



SOIL SYMBOLS: SHATTERED BEDROCK, FILL, PEAT OR ORGANICS, CLAY, SILT, SAND, GRAVEL, BOULDER, SEA SHELLS, SOUND BEDROCK

SAMPLE CONDITION: D – DISTURBED; L – LOST; F – FAIR; G – GOOD (UNDISTURBED)

SAMPLE TYPE: SS – SPLIT SPOON; TW – THIN WALL SHELBY; BS – BAG SAMPLE; WS – WASH SAMPLE; RC – ROCK CORE

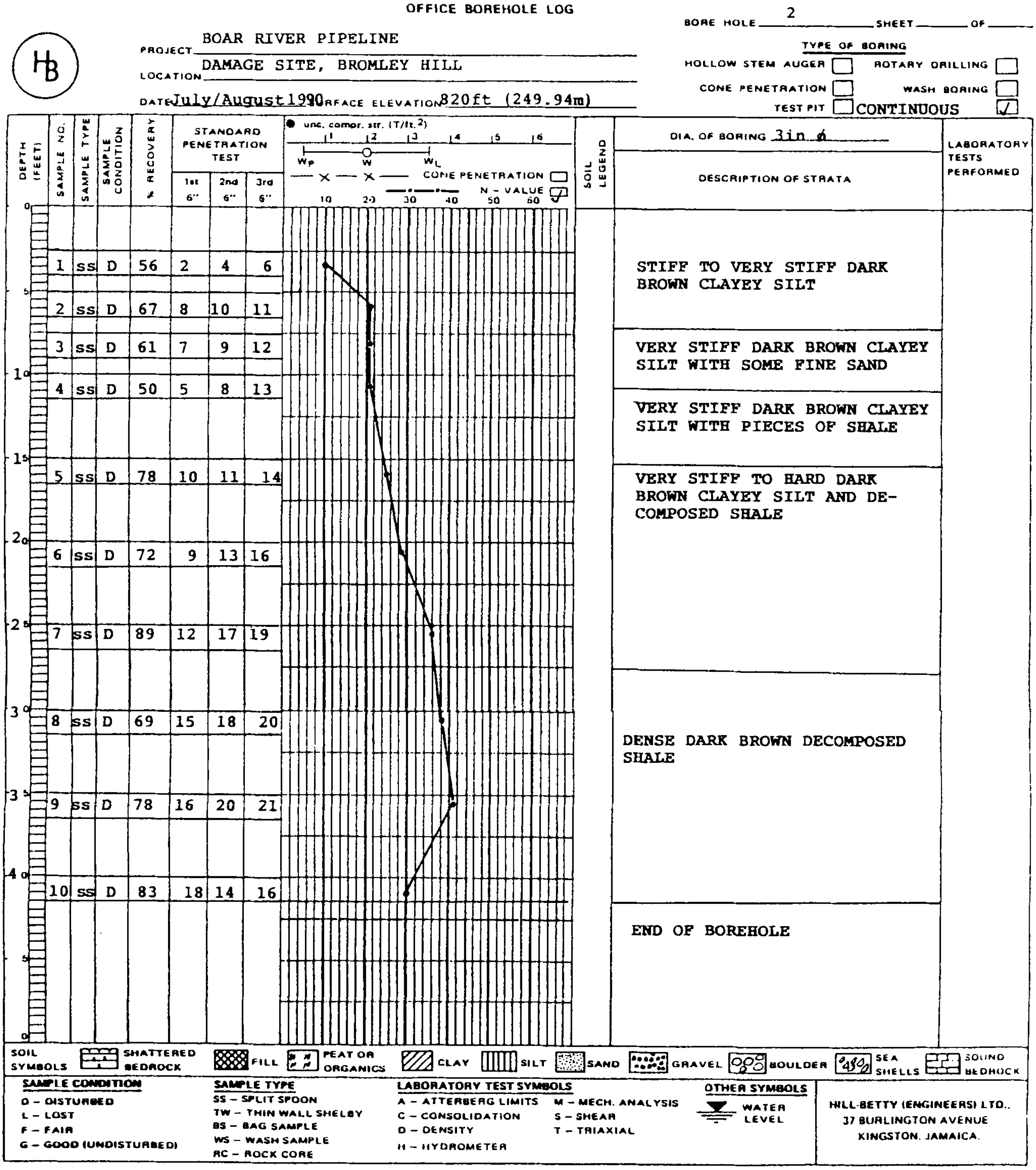
LABORATORY TEST SYMBOLS: A – ATTERBERG LIMITS; C – CONSOLIDATION; D – DENSITY; H – HYDROMETER; M – MECH. ANALYSIS; S – SHEAR; T – TRIAXIAL

OTHER SYMBOLS: WATER LEVEL

HILL-BETTY (ENGINEERS) LTD., 37 BURLINGTON AVENUE, KINGSTON, JAMAICA.

Fig. 7 : Borehole log standard penetration test data and N-value graph for Borehole No. 1. The location for all the boreholes, which were drilled and logged by Hill-Betty (Engineers) Ltd; Kingston, is given in Fig. 4.

Our field data and cross-section across the length of the landslide (Fig. 5) indicated that the slip-surface would be expected to be shallow, less than 9 m below the surface. Therefore, in order to confirm the depth to the base of the slide, 4 boreholes were drilled in the vicinity of the pipeline. Borehole #1 to #3, drilled to a depth of 12.2 m, were located across the width of the slide, above the pipeline at an elevation of about 250 m, whereas hole #4 was drilled to a depth of 7.6 m and was located below the pipeline, in the central part of the slide at about 247 m (see Figure 4 for borehole locations). Standard Penetration Test (SPT) data, N values, core samples analysis and borehole logs are given in Figures 7 to 10. this data was supplied by the



OFFICE BOREHOLE LOG

PROJECT: BOAR RIVER PIPELINE

LOCATION: DAMAGE SITE, BROMLEY HILL

DATE: July/August 1990 SURFACE ELEVATION: 820ft (249.94m)

BORE HOLE: 2 SHEET ___ OF ___

TYPE OF BORING: HOLLOW STEM AUGER ☐ ROTARY DRILLING ☐ CONE PENETRATION ☐ WASH BORING ☐ TEST PIT ☐ CONTINUOUS ☑

DIA. OF BORING: 3in ø

Sample No.	Sample Type	Sample Condition	% Recovery	SPT 1st 6"	SPT 2nd 6"	SPT 3rd 6"
1	ss	D	56	2	4	6
2	ss	D	67	8	10	11
3	ss	D	61	7	9	12
4	ss	D	50	5	8	13
5	ss	D	78	10	11	14
6	ss	D	72	9	13	16
7	ss	D	89	12	17	19
8	ss	D	69	15	18	20
9	ss	D	78	16	20	21
10	ss	D	83	18	14	16

DESCRIPTION OF STRATA:

STIFF TO VERY STIFF DARK BROWN CLAYEY SILT

VERY STIFF DARK BROWN CLAYEY SILT WITH SOME FINE SAND

VERY STIFF DARK BROWN CLAYEY SILT WITH PIECES OF SHALE

VERY STIFF TO HARD DARK BROWN CLAYEY SILT AND DECOMPOSED SHALE

DENSE DARK BROWN DECOMPOSED SHALE

END OF BOREHOLE

SOIL SYMBOLS: SHATTERED BEDROCK, FILL, PEAT OR ORGANICS, CLAY, SILT, SAND, GRAVEL, BOULDER, SEA SHELLS, SOUND BEDROCK

SAMPLE CONDITION: D – DISTURBED; L – LOST; F – FAIR; G – GOOD (UNDISTURBED)

SAMPLE TYPE: SS – SPLIT SPOON; TW – THIN WALL SHELBY; BS – BAG SAMPLE; WS – WASH SAMPLE; RC – ROCK CORE

LABORATORY TEST SYMBOLS: A – ATTERBERG LIMITS; C – CONSOLIDATION; D – DENSITY; H – HYDROMETER; M – MECH. ANALYSIS; S – SHEAR; T – TRIAXIAL

OTHER SYMBOLS: WATER LEVEL

HILL-BETTY (ENGINEERS) LTD., 37 BURLINGTON AVENUE, KINGSTON, JAMAICA.

Fig. 8 : Borehole log standard penetration test data and N-value graph for Borehole No. 2.

consulting engineers, Hill-Betty (engineers) Ltd., Kingston, Jamaica.

A significant increase in the drilling pressure was encountered at a depth of 6-7.6 m in boreholes #1 to 3 with the corresponding N-values ranging between 20-46 (Fig. 7 to 9). This suggests the presence of relatively compact strata (bedrock ?) at this depth and is supported by the presence of well indurated sandstone fragments in the core samples. The data from borehole #4 (Fig. 10) show similar material properties at a depth of 5.6 m. Based on above, it is suggested that the slip-surface for the slide is located approximately 6 m below the present level of the pipeline and is in support

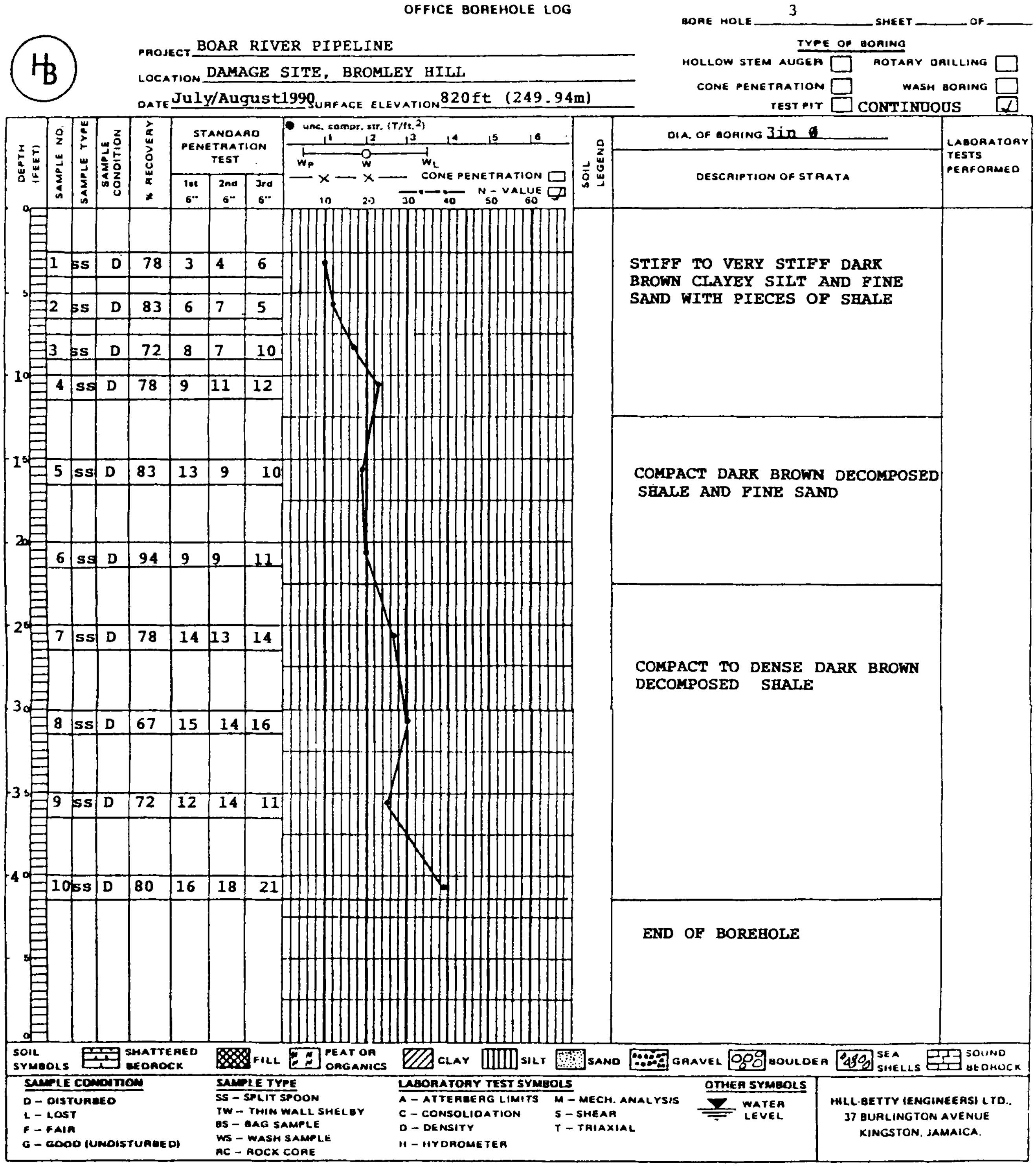


Fig. 9 : Borehole log standard penetration test data and N-value graph for Borehole No. 3.

of our pre-drilling analysis. It appears to us that the weathered zone in the area of investigation is at least 6 m thick and most of the storm triggered debris flows are confined to this zone. This information may be used in designing and construction of foundation structures in the area.

6. Conclusions

The heavy rains which preceded Gilbert were responsible for increasing the soil-moisture content in the weathered bedrock. The resulting downslope movement

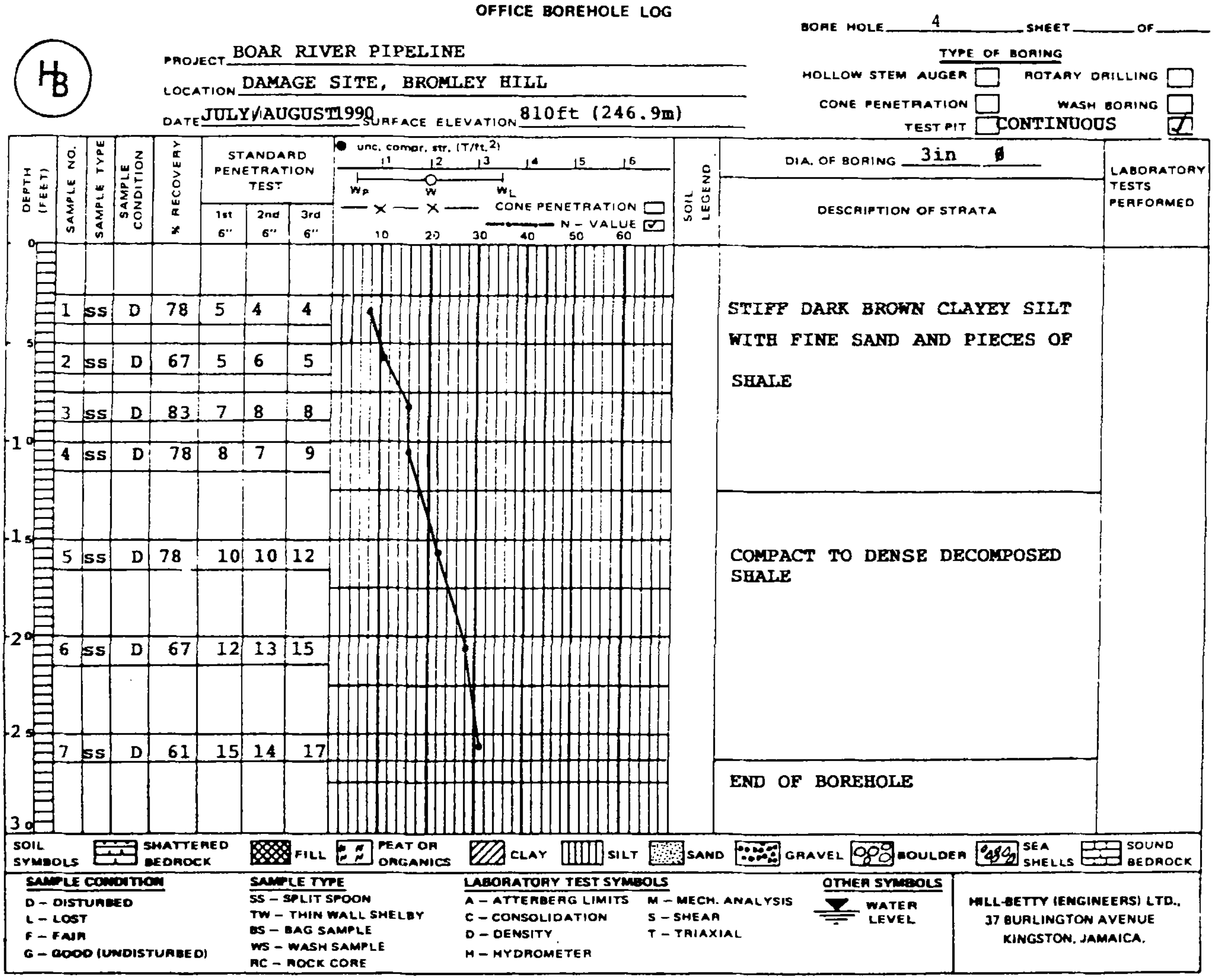


Fig. 10 : Borehole log standard penetration test data and N-value graph for Borehole No. 4.

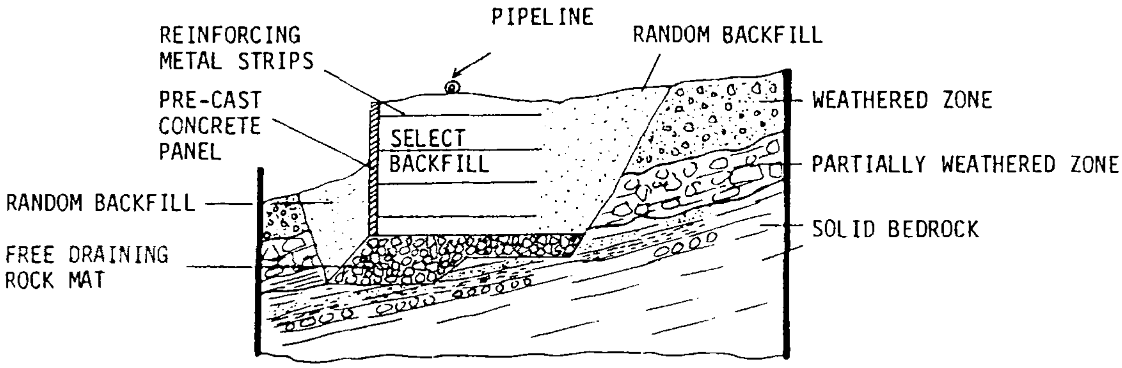


Fig.11 : A suggested shematic procedure for the remedy of the landslide using reinforced earth block and select backfill.

involved flow in clays and drilling results suggest that the slide is shallow with the slip-surface located at a depth of approximately 6 m below the surface. Slope failure at the site appears to be related to drainage conditions along the slope. Soil stratification, mimicking the stratification in the bedrock, is likely, and if present below the surface, will increase the instability of the slope as a whole. It appears that the toe is continually being eroded by streams, and, during heavy rainfall, active removal of the toe will continue to take place, removing support for the slide materials and thus leading to further, continuing downslope movements. This movement will only cease if the slope (and slide) materials can be stabilized on the slope itself, or when the unconsolidated material on the slope has all been consumed via erosion of the toe of the slide. however, without stabilization, potentially unstable debris will continue to be generated on the slope. We are of the opinion that the best long term solution to the problem would be to reroute the pipeline altogether. The shortest safe route would be around the toe of the present slide, along the far bank of the stream. Another possibility would be to bridge the slide by suspending the pipeline from stable supports on the flanks of the slide. If the pipeline has to remain in its present position, then it is suggested that a block of the slide surrounding the pipeline supports be taken out and replaced with a compact, granular fill of sharp gravel/sand as suggested in Figure 11. This should be done in conjunction with a scheme to improve the drainage of the entire slope, using contour drains and paying special attention to the crown of the slide and the places where seepage has been observed, and with a programme to plant vegetation on the slope to assist in binding slope materials and controlling runoff.

Acknowledgements

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