

22. Investigation of a landslip at St Leonards.

C.J. Knights
W.L. Matthews

A slow-moving, elongate landslip has occurred in Tertiary sediments on the slopes above the St Leonards township and about 1.5 km north-east of the North Esk River [EQ173107]. The heel of the slip is just below two reservoirs that supply water to the St Leonards Municipality and the East Tamar. This report describes the aims and results of a programme of investigation which was undertaken during the winter of 1973.

GENERAL GEOLOGY

The geology of the Launceston area has been mapped by Longman *et al.*, (1964) and during a survey of unstable land in the Tamar region more detailed mapping was undertaken by the writers and S. Elmer. The distribution of the various rock types is shown on Figure 53.

The ridge above the slip is capped with basalt which is probably a remnant of a lava flow filling a valley which had a gradient towards Launceston from the north-east. Underlying the basalt is a quartz-sand and gravel deposit which is probably a pre-basalt stream bed or terrace material around the valley. This material is exposed in a quarry on the north end of the ridge, and is also seen on the south end of the ridge, but its presence is not obvious around much of the slope above the slip except for float downslope. Clay, sand and silty clay of the Tertiary Launceston Beds underlie the sand and gravel. These beds were deposited on an uneven surface of older rocks, the main exposures of which in the surrounding area, are of Jurassic dolerite although a small area of Permian sediments was mapped by Longman between St Leonards township and the North Esk River. Bauxite and laterite often occur around the contacts of the dolerite and the Tertiary sediments.

Flood plains up to one kilometre wide around the North Esk River are underlain by alluvium. At least two levels of terrace gravels occur above the flood plain, the lower one being almost certainly Quaternary in age whereas the upper may be Tertiary or Quaternary. When the drainage of the pre-basalt valley was disrupted by the extrusion of the basalt which filled the valley, gravel beds could be expected to be deposited near the margins of the filled valley. Rounded dolerite gravel to the north of the slip may also be a result of this stream diversion.

GENERAL STABILITY

Signs of old landslips abound in the area around the reservoirs. The approximate positions of the heels of these slips are shown on Figures 53 and 54. The presence of zones of internal drainage suggest that some of the movements were rotational, but their age is unknown. In the case of two slips, one north of the slip investigated, the other south of the entrance gate to the reservoir area the positions of their toes are clearly shown. These slips are relatively recent and may have occurred about twenty years ago. During the last four years, three new slips north of the one threatening the reservoirs, have commenced movement. The slips are of the earthflow type but except for the one most distant from the reservoirs, little movement has occurred.

The situation of basalt capping a hill underlain by Tertiary sediments is often associated with unstable conditions. Springs from near the base of the basalt add to the effects of rainwater and can cause slips at the edge of the basalt and slip movement often includes the rotation of large blocks of basalt. As at St Leonards, basalt talus on the slopes below the basalt is

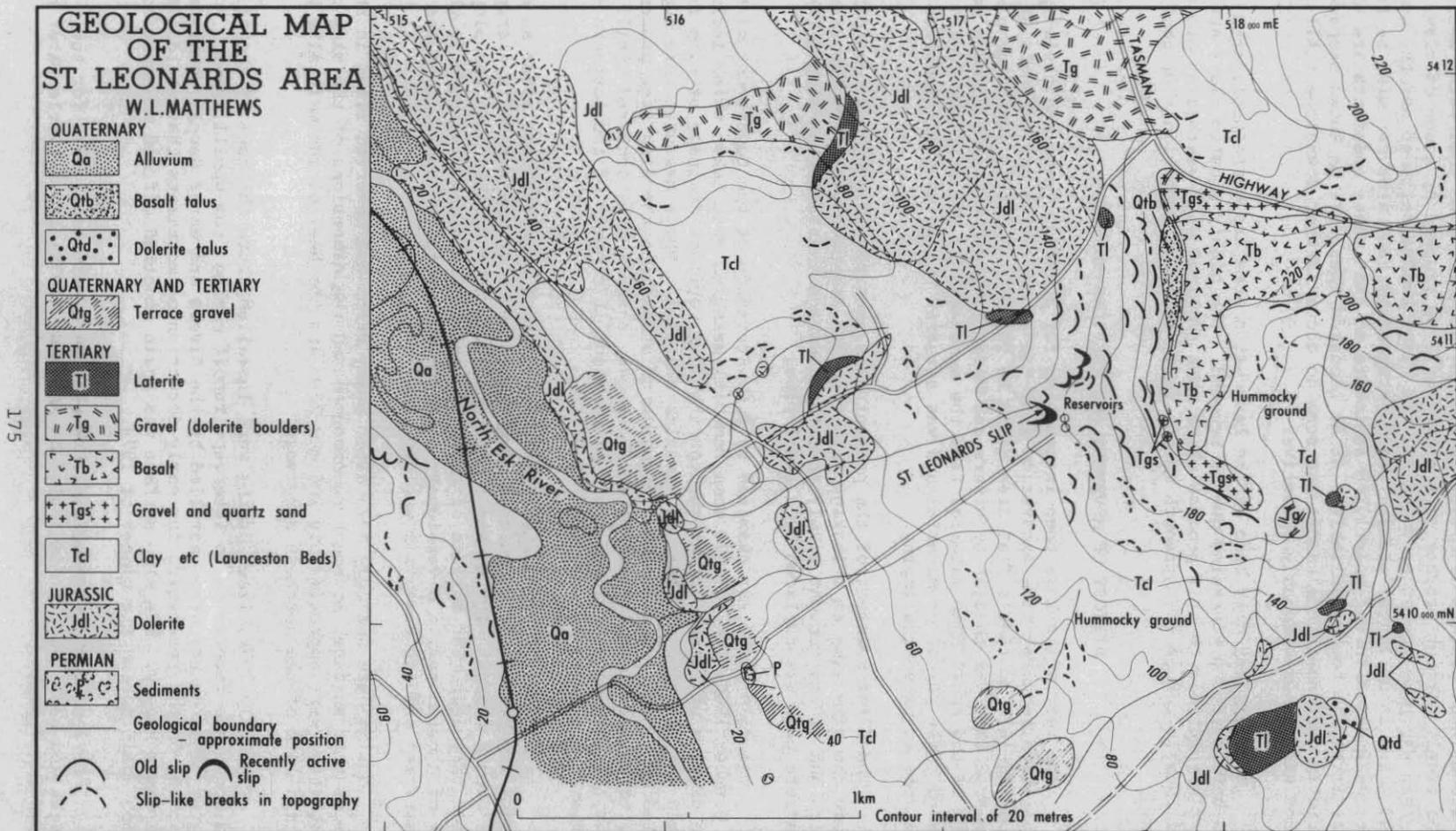
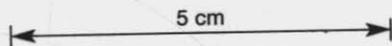


Figure 53.



GEOLOGICAL MAP OF SLIP AREA ST LEONARDS

GEOLOGIST: W.L. MATTHEWS

5 cm

QUATERNARY

Qtb Basalt talus

TERTIARY

Tb Basalt

Tgs Sand and gravel

Tcl Clays etc
(Launceston Beds)

Tl Laterite
(with some bauxite)

Active slip heel

Old slip heel

Slip-like breaks in topography

A B Section line

2 Seismic spread and number

BH 29 ● Borehole

P2 ● Resistivity probe

Contour interval of 20m

0 100 200 300 400m

SECTION THROUGH LANDSLIP AREA USING DRILLING RESULTS

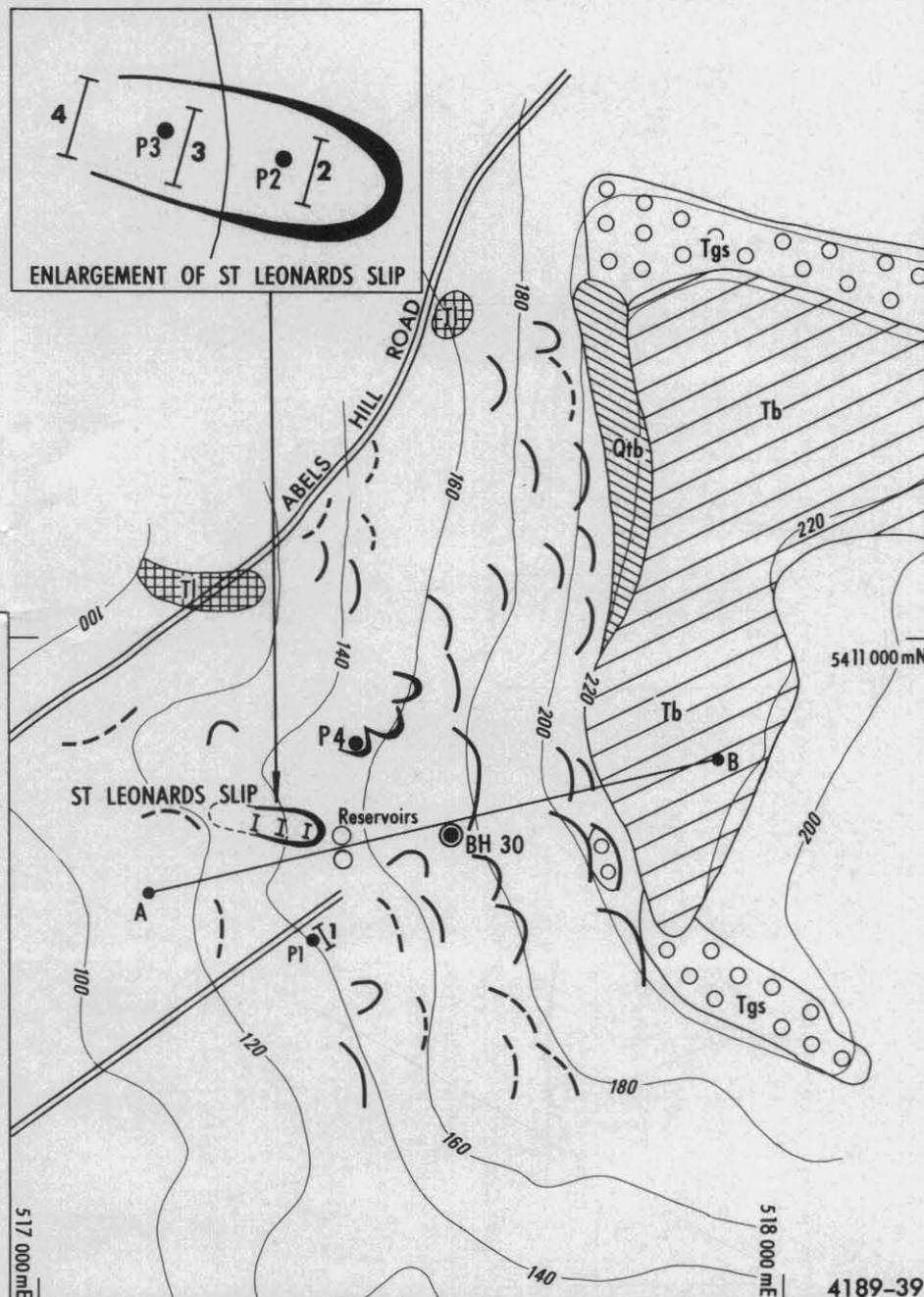
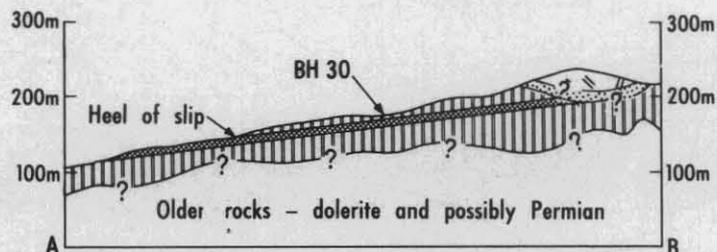
(Surface cover of basalt talus not shown)

Tertiary basalt

Blue-grey clay

Tertiary gravel

Sandy silty clay



160 ELEVATION (m)

ST LEONARDS LANDSLIP — SIMPLIFIED DRILL LOGS

GEOLOGIST C.J.KNIGHTS

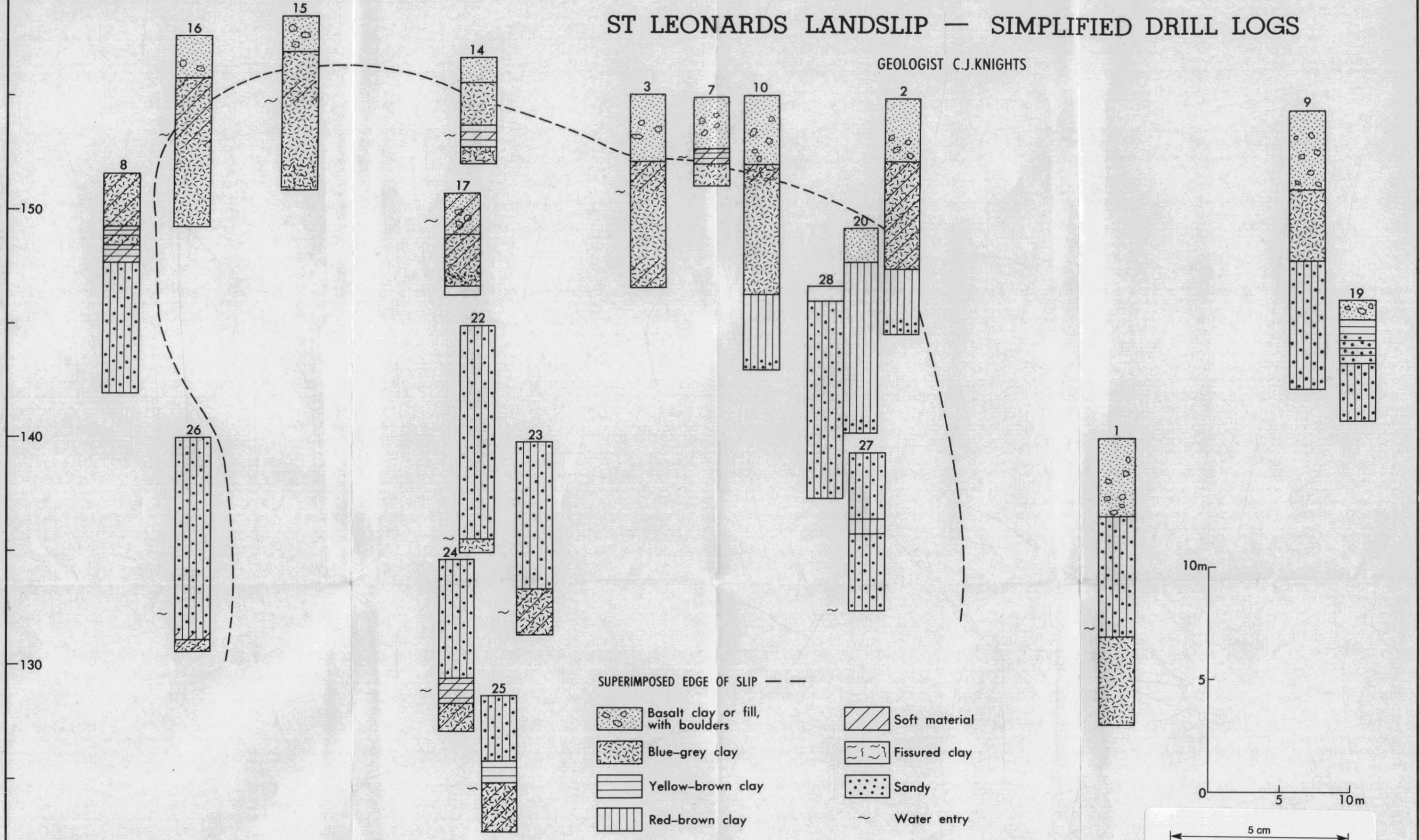


FIGURE 55

TR20-174-218

in a continual process of disintegration by weathering so that water which runs freely through patches of boulders will be trapped by zones of clay. In this way pore pressures build up, the clays become softened and the weathered talus is no longer stable. Water trapped by the talus can also be forced into weaknesses in the underlying sediments so that these sediments are also more likely to become unstable. At St Leonards there are no known seepages directly underneath the basalt but some do occur further downslope. All the other effects are probably operative.

The Tertiary clay beds of the Launceston area are overconsolidated and have suffered weakening due to rebound. The highly plastic clays are most susceptible to this process which when combined with weathering processes can locally reduce the strength to the fully softened (cohesion = 0) condition.

HISTORY OF MOVEMENT AND PREVIOUS REPORTS

The reservoirs have been in position for about 20 years and their installation required some excavation into the slope, which has an angle of about 12-15°, so that a flat area could be formed. About 13 years ago a slip occurred that was thought by Rivers and Water Supply Commission workmen to be only in the spoil dump material from the excavation. The slip involved a considerable volume of material and was situated on the southern shoulder of the area at present slipping.

The first movement of the present slip occurred in 1968 and took place about the same time as a leakage in a concrete drainage pipe from the reservoirs and it was thought likely that this leakage initiated the slip. The concrete pipe was replaced by a steel pipe.

The slip was first examined by P.C. Stevenson of the Department of Mines in October 1968, and in 1970 some remedial measures were taken which included the digging of french drains through the slip, surface drainage of slip fractures and planting of trees on the slip material. These measures were suggested by P.C. Stevenson. The intrusion of stock into the slip area prevented the trees from becoming established. Later, a small slip occurred uphill from the main discharge and drain pipes about 15 m north of the northern reservoir.

In February 1972, a short heavy downpour of rain (~20 mm) after an extended dry period caused further movement in the slip and seriously disrupted the french drains. The movement extended about 40 m further down the slope. Later that year, the surface of the slip was remoulded and flattened by the use of a bulldozer, a diversionary pipeline was installed uphill from the reservoirs and one reservoir was emptied.

During June and July 1973 after heavy rains and observed rises in the piezometric surface, movement recommenced and the dimensions of the slip at that stage were approximately 160 m x 75 m and the heel of the main slip was within 14 m of the northern reservoir.

In early 1974, lined drains were installed above the heel of the slip and above the reservoirs to intercept runoff coming from uphill areas. Monitoring instruments were installed by the Rivers and Water Supply Commission near and on the reservoirs for early detection of movements that would affect the water supply. The slip surface was again smoothed off and movement took place again during the winter of 1974.

Previous reports concerning the slip were written in 1972 for the Rivers and Water Supply Commission by Matthews (1974) and a little later by Stevenson (1972).

AIMS OF THE DETAILED INVESTIGATION

The aims of the detailed investigation were:

- (1) To obtain a general idea of the stratigraphy of the slip area and classify the material by visual description and Atterberg limits.
- (2) The location of subsurface water-bearing horizons and the determination of their extent, depth and origin; the monitoring of water pressure and estimation of the transmissivity of the material.
- (3) The determination of values of cohesion (c') and angle of internal friction (ϕ') from strength tests, and the location of soft zones.
- (4) To undertake a topographic survey of the slip area to aid in stratigraphic correlation of bore holes, correlation of groundwater, piezometric surfaces, location of slip and fissures and the monitoring of changes in the shape of the land surface.
- (5) The subsurface monitoring of slip movement to obtain information on the depth of unstable material.
- (6) The observation of the slip and surrounding areas especially in wet periods noting drainage patterns, opening of cracks and surface movement.
- (7) The determination of the clay mineralogy and its relation to other soil properties.
- (8) To investigate the groundwater chemistry and also the possible effects of the groundwater on the exchangeable ions in the clays with which it comes into contact.
- (9) To recommend remedial measures for the protection of the reservoirs and obtain information which may be applied to other unstable areas.
- (10) To determine whether geophysical methods are of value in land-slip investigation.

RESULTS OF DRILLING

Twenty-seven auger holes about 100 mm in diameter, totalling about 200 m were drilled on and around the slip to establish the geological sequence and also for the installation of various measuring devices. Detailed bore logs are given in Appendix 1 and a simplified version of twenty holes is shown on Figure 55. During the drilling undisturbed and disturbed samples were collected at various levels for the tests described later.

Four main strata have been recognised.

<i>Description</i>	<i>Thickness (m)</i>
Basalt talus.	0-3.25
Upper blue-grey clay.	0-6.5
Red-brown fragmental clay, often very sandy and silty.	10
Lower blue-grey clay.	

Basalt talus

Basalt talus and quartz pebbles from the gravel underlying the basalt form a cover of up to about 3 m thick overlying the Launceston Beds. In isolated areas, the cover is very thin or absent. Landslips have probably been mainly responsible for the distribution of these deposits on the slopes. The talus deposits consist of brown basalt soil, brown plastic clay and basalt boulders.

Blue-grey clay

The upper and lower blue-grey clay units are similar in lithology and range from stiff plastic clay to silty clay with a slightly fragmental nature. The upper unit is more often heavily stained with iron oxides than the lower clay beds. In zones where these clay beds are soft, there are often silty yellow bands and irregular patches. These clay beds are commonly fissured and have numerous shiny slip surfaces which are probably related to compaction rather than to landslip movement. The fissures may be several centimetres long or small fish-scale like structures. Towards the surface these fissures are able to open and allow percolation of water (e.g. Holes 3, 7, 15). Fissures are also significant in that they provide zones of low cohesion.

Both the upper and lower blue-grey clays almost invariably have 65-75% of clay size material while the silt size content ranges from 17-27%. The sand size content ranges more widely from 1-14% (fig.56-61). One sample of blue-grey clay at 2.9 m in Hole 7 is anomalous and is more like the sandy silty clay horizon (fig.56-60).

Red-brown sandy clay

Between the upper and lower blue-grey clay beds is a sandy silty clay bed which is probably about 9 m thick and dips downslope at an angle of 7-8° (fig.62). It may vary in thickness laterally. It was postulated from the dip of this bed that if it was persistent over a considerable distance, it should come close to the surface under the flat area uphill from the reservoirs. A hole (30) was subsequently drilled (fig.54) in this area and the top of the bed was struck at about 8 m from the surface. It could thus come into contact with the gravel underlying the basalt. The projection of this bed is shown in the section on Figure 54. The disturbed samples of this horizon are very fragmentary and undisturbed samples are friable. The sand size particles consist of weathered feldspar and quartz. Some magnetite is present and kaolin and a trace of montmorillonite have been recognised under the microscope (G.B. Everard, pers. comm.).

The sizing of the material indicates a range in clay size content from 36-56%, silt size from 19-34%, and sand size from 18-45% (fig.56-60).

At various levels throughout the upper blue-grey clay and sandy silty clay there are variable amounts of iron oxide staining, limonite and hematite concretions, and in Holes 8 and 17 further drilling was prevented by hard limonite horizons. Concretions of travertine and thin layers of crystalline calcite also occur in these two upper strata and travertine is occasionally present in the lower blue-grey clay. Oolites of limonite about one millimetre in diameter occur in the lower blue-grey clay in several of the holes.

ATTERBERG LIMITS

Upper and lower blue-grey clay

A plot of Atterberg limits versus per cent clay is shown in Figure 63. The blue-grey clays plot in a restricted area for both plasticity index and liquid limit. This is particularly striking when compared with other Tamar clay (see also Appendix 3).

Red-brown sandy clay

This material shows scatter on a plot of Atterberg limits versus per cent clay but generally has less than 50% clay and a low plasticity index.

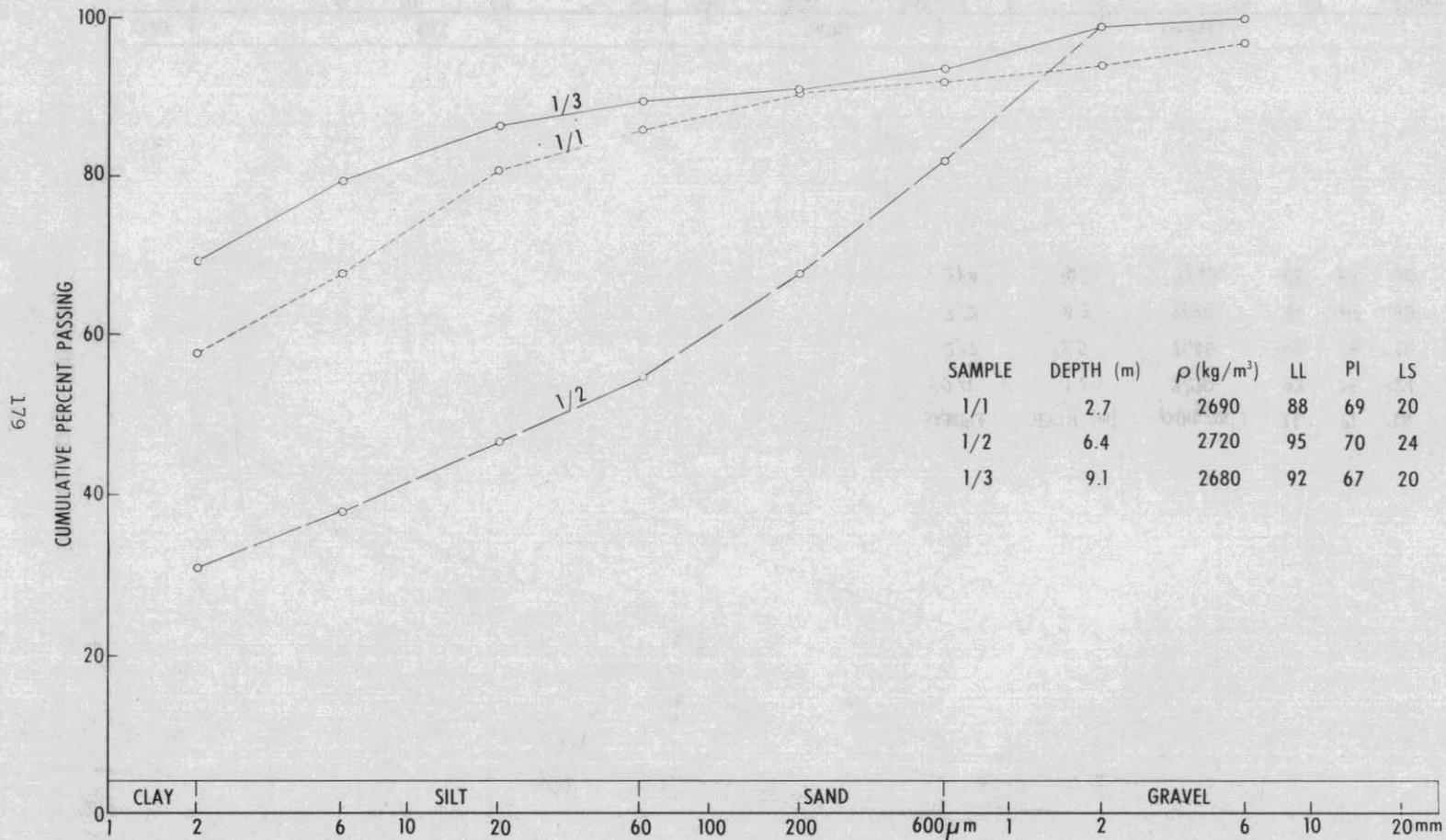
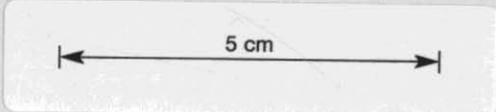


Figure 56. Particle size distribution of samples from Bore Hole 1, St Leonards.



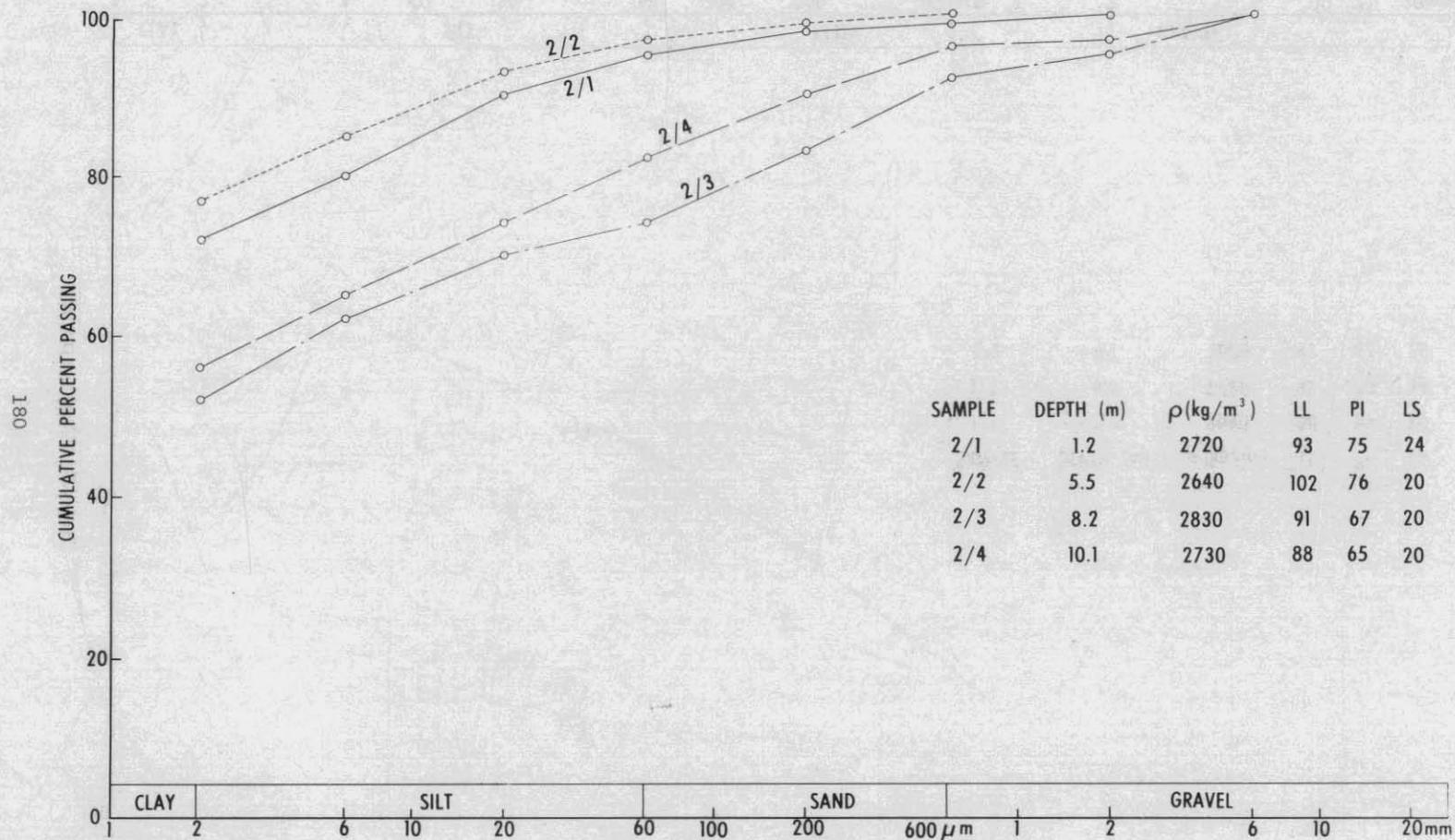


Figure 57. Particle size distribution of samples from Bore Hole 2, St Leonards.

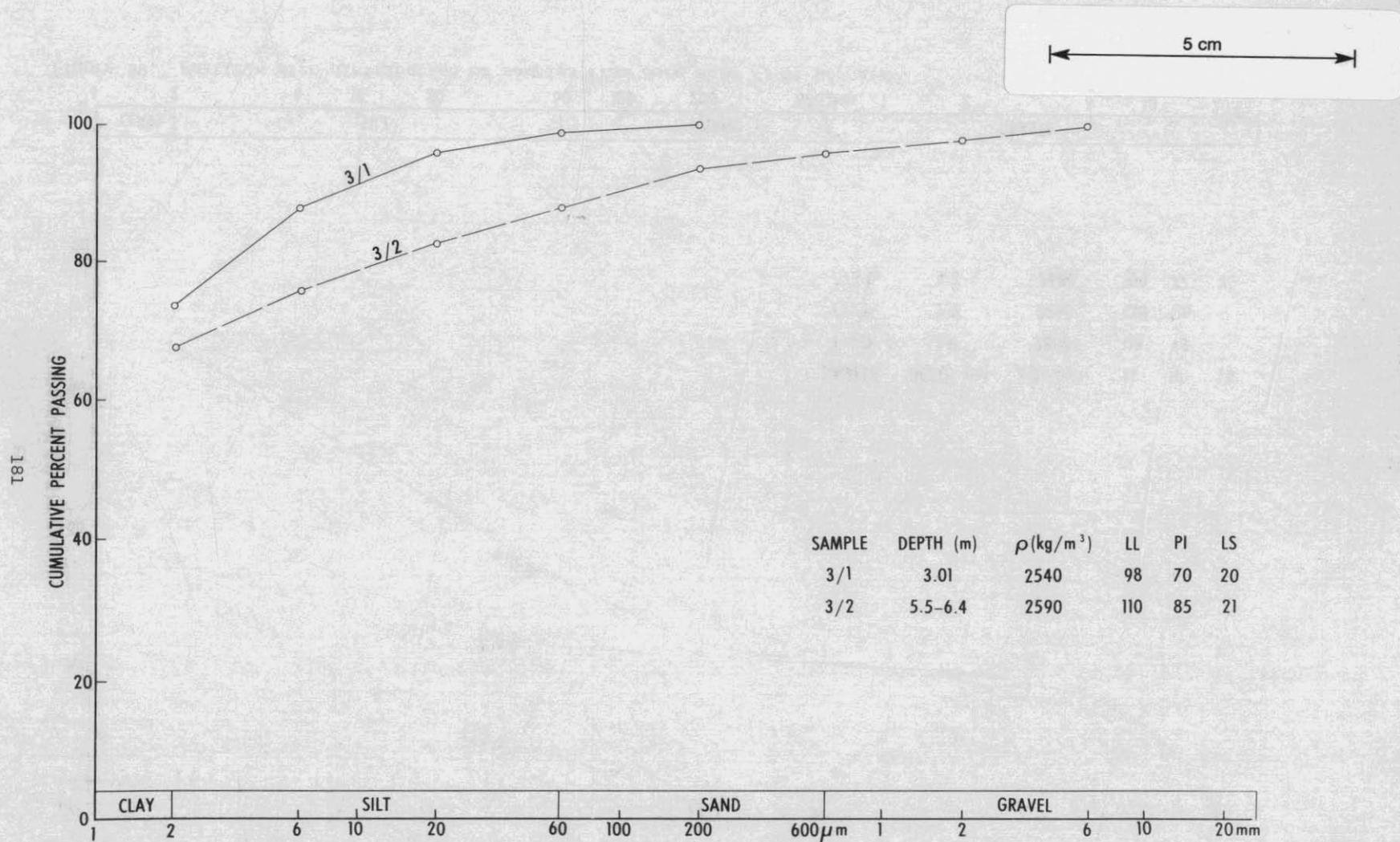


Figure 58. Particle size distribution of samples from Bore Hole 3, St Leonards.

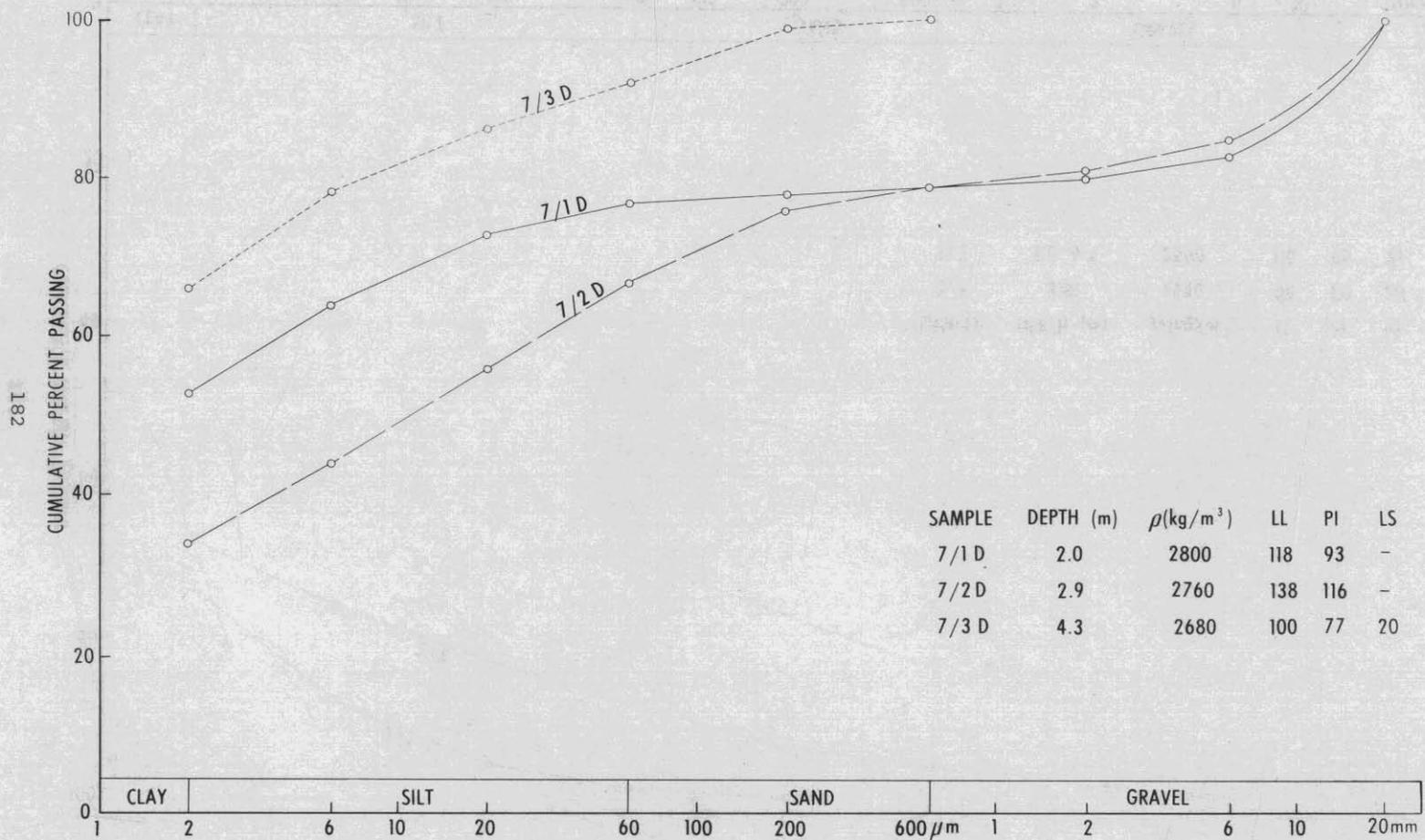


Figure 59. Particle size distribution of samples from Bore Hole 7, St Leonards.

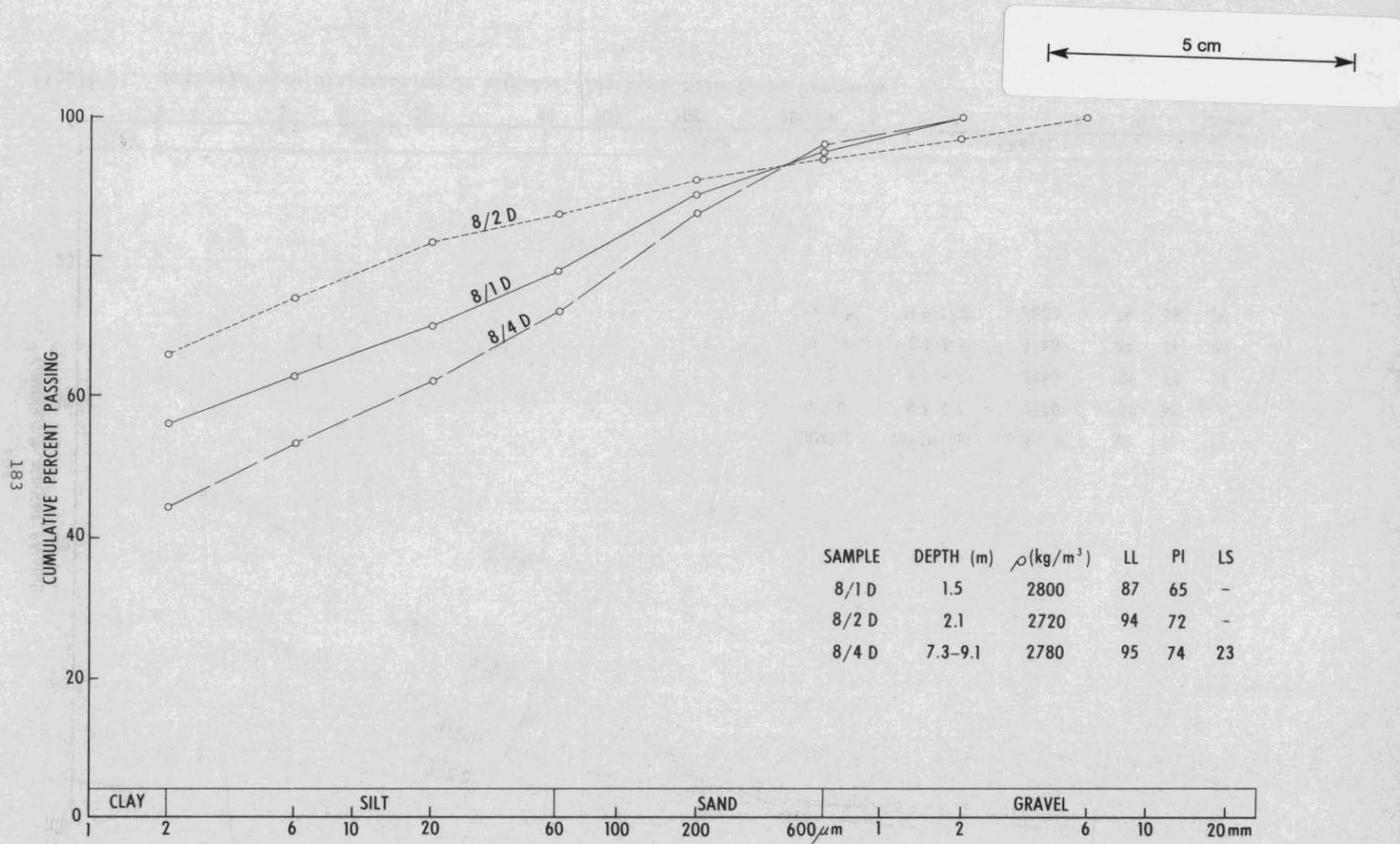


Figure 60. Particle size distribution of samples from Bore Hole 8, St Leonards.

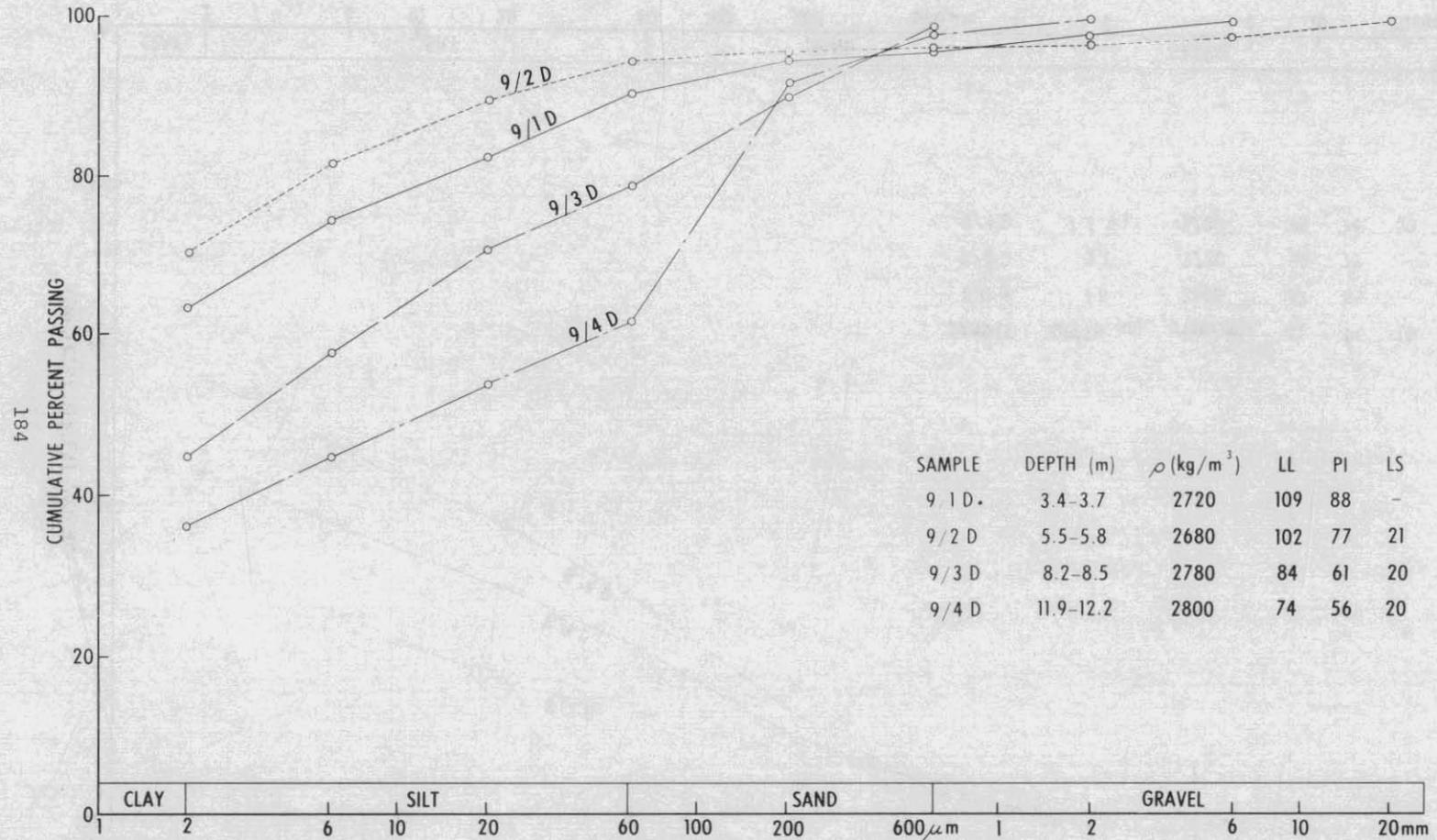
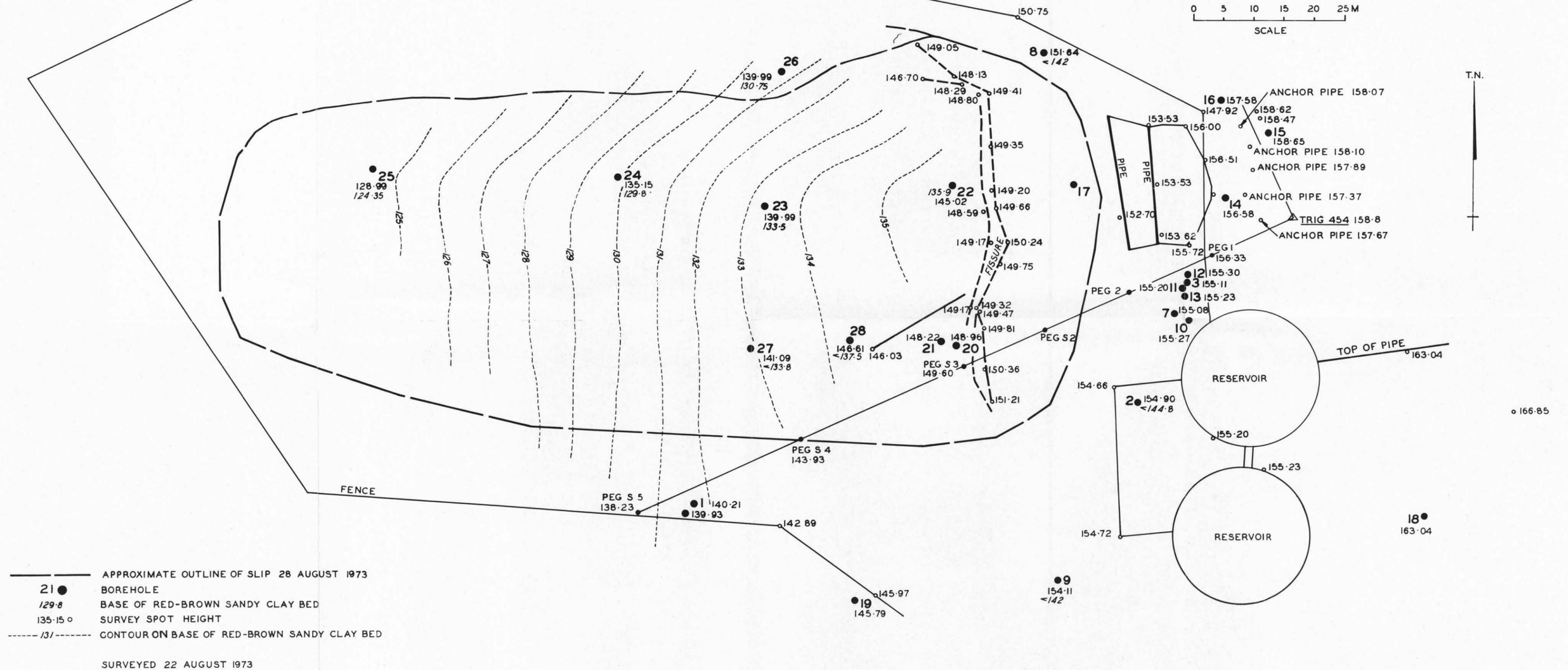


Figure 61. Particle size distribution of samples from Bore Hole 9, St Leonards.

SURVEY OF ST LEONARDS SLIP 1973

WITH CONTOURS ON BASE OF RED BROWN SANDY CLAY BED

Geologist W.L. Matthews Surveyor G. Benn



——— APPROXIMATE OUTLINE OF SLIP 28 AUGUST 1973
 21 ● BOREHOLE
 129.8 BASE OF RED-BROWN SANDY CLAY BED
 135.15 ○ SURVEY SPOT HEIGHT
 - - - - - 131 - - - - - CONTOUR ON BASE OF RED-BROWN SANDY CLAY BED

SURVEYED 22 AUGUST 1973

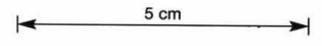
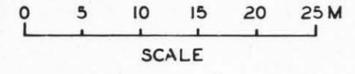
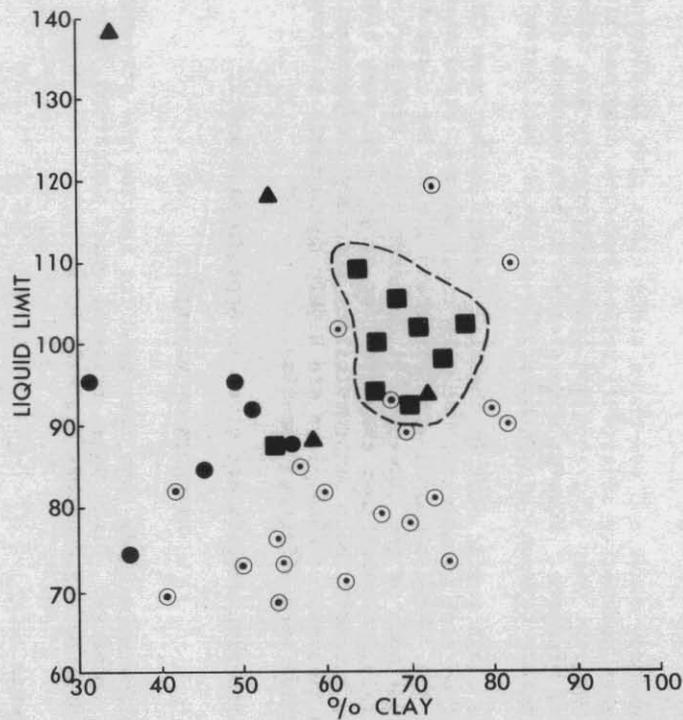
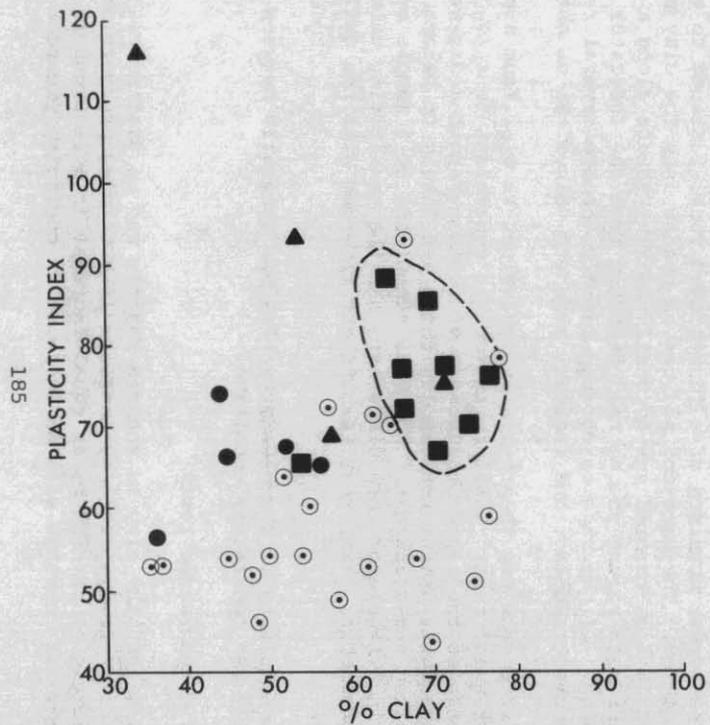


FIGURE 62



- ST LEONARDS
- ▲ Basalt clay
 - Red brown sandy clay
 - Blue-grey clay
 - ⊙ Other Tamar Valley clays

Figure 63. Plot of Atterberg limits against per cent clay.

←————— 5 cm —————→

and liquid limit. Remoulded residual strength tests show these clays to have a ϕ'_R of 23° compared with the blue-grey clay samples tested which have a ϕ'_R of 15-16°.

Basalt-derived clay

Atterberg limits show normal to high plasticity.

Results of soil classification

The blue-grey clays and red-brown sandy clays plot in distinctive areas on the graphs of plasticity index (PI) versus per cent clay and liquid limit (LL) versus per cent clay (fig. 63) and these differences are reflected in their residual strength. However when plotted on a Casagrande diagram (fig. 64) the difference between the two materials is not so well marked.

All the clays tested plot in the soil classification zone CH, i.e. inorganic clays of high plasticity, but only the blue-grey clays have liquid limits above 95%. When compared with Atterberg limits for clays from other areas (fig. 64) some of the blue-grey St Leonards clays have noticeably high LL and PI. This indicates that they are 'fat clays' with very high plasticity, high dry strength, high compressibility and very low permeability (except through fissures). Such clays are highly susceptible to progressive failure and have zero effective cohesion.

Classification results are given in Appendices 1 and 2.

STRENGTH OF MATERIALS

The following methods have been used for testing the strength of materials at St Leonards: field vane, triaxial quick undrained, triaxial consolidated undrained and shearbox drained tests.

Field vane tests

The instrument consists of a four-bladed vane, fastened to the bottom of a vertical rod. The vane and rod can be pushed into the clay and a torque applied through a calibrated spring until the clay shears along a cylindrical surface. Strength values can be read directly from the indicator on the calibrated spring. If the vane is rotated rapidly through several revolutions the soil becomes remoulded and residual strength values can be obtained.

Vane strengths are theoretically equivalent to c_{cu} , from a consolidated undrained triaxial test. Sensitivity (St) is equivalent to s_p/s_r . The field vane test enables the rapid measurement of field strength and sensitivity, which is especially useful for samples which are likely to become remoulded during sampling and transport. However, remoulding of a sample by vane, and remoulding in a laboratory are different, and the sensitivity values are not strictly comparable. Vane test results are recorded with the drill logs (Appendix 1).

The sensitivity of the blue-grey clay was generally between 2 and 4 i.e. the clay was moderately sensitive.

Triaxial quick undrained tests

In this test the clay is sheared rapidly and no drainage is allowed. Because there is no drainage any increase in confining pressure on a fully saturated sample is matched by an equal increase in pore pressure, so that strength does not increase with an increase in confining pressure and is

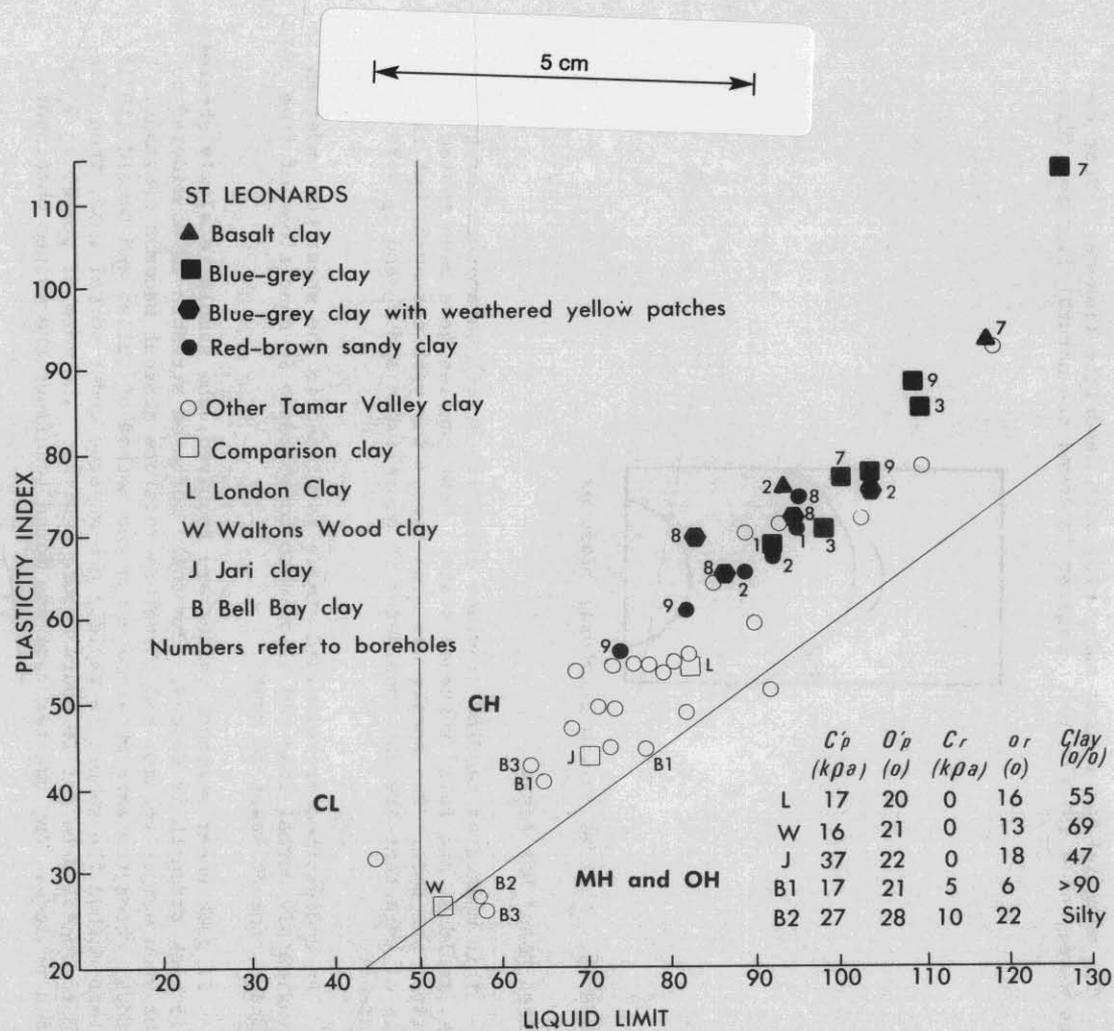


Figure 64. Atterberg limits, St Leonards and other clays.

partly controlled by the moisture content of the sample. Strength values obtained from these tests are suitable for the analysis of conditions of rapid loading, *i.e.* $\phi = 0$ conditions, but are not really suitable for analysing long term landslip conditions. Results are recorded in Appendix 1.

Consolidated, undrained triaxial test with pore pressure measurement

This test gives effective stress and strength values (c' and ϕ') which can be used to evaluate drained conditions. Only one series of these tests has been done for the St Leonards clays.

The material was a grey silty clay with dendritic fissures. Test results were: $c' = 15$; $\phi' = 18^\circ$. Failure followed the natural fissures (fig. 65).

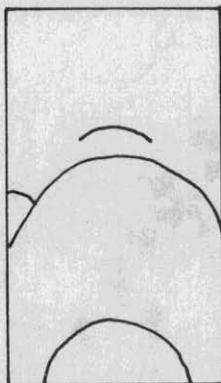


Figure 65. Failure followed natural fissures.

Drained shear box tests

This method of testing provides effective stress parameters for the peak, residual and fully softened state. Four samples have been tested for residual strength. One sample was also tested for peak strength, but the results of this test are not considered to be reliable and c'_p and ϕ'_p were not obtained.

An undisturbed or remoulded sample is placed in the shear box under an approximately normal load and allowed to consolidate in conditions of free drainage, for at least 16 hours.

If peak shear strength values are required, the sample is slowly sheared until peak strength is passed. The fully softened strength is considered to occur when sample volume, and therefore moisture content becomes constant. Residual strengths were obtained using the method of Cullen and Donald (1971). In this method the sample is rapidly pre-sheared under normal load, then allowed to consolidate for 16 hours before testing. The rate of travel is 9.75 $\mu\text{m}/\text{min}$ or less. Any greater rate was found to affect the values obtained.

Test results

Sample 1. Hole 16, depth 2.7 m. Grey, plastic, silty fissured clay. Sample condition: natural.

The results of this test series are shown in Figure 66a: $c' = 0$ and $\phi' = 27^\circ$ at normal loads of less than 60 kPa; at greater loads, $c' = 17$ and $\phi' = 14^\circ$.

Sample 2. Hole 16, depth 4.6 m. Grey, plastic, silty fissured clay with rounded ironstone gravel. Sample condition: natural.

The results of this test series are shown in Figure 66,b. The values are scattered, but a line can be drawn from which $c' = 9$ kPa, $\phi' = 12^\circ$. The one anomalously high value is attributed to the effect of ironstone becoming jammed between the box halves.

Sample 3. Hole 16, depth 8.2 m. Grey and yellow plastic, silty fissured clay. Sample condition: air dried and remoulded.

The results of this test are shown in Figure 66,c: $c' = 0$, $\phi' = 15^\circ$. Stress paths and volume change are shown in Figure 67.

Sample 4. Hole 27, depth 3 m. Red, brown sandy clay. Sample condition: air dried and remoulded.

The results of this test are shown in Figure 66: $c' = 8$ kPa, $\phi' = 22.5^\circ$. Alternatively, the results can be interpreted as: $c' = 0$, $\phi' = 26^\circ$ at normal loads of less than 97 kPa. Stress paths and volume change are shown in Figure 67.

Discussion. Three tests on the blue-grey clays to determine fully softened strength all gave ϕ' values of between 13° and 15° . A triaxial test on a sample of blue-grey clay gave peak strength values of $c' = 15$ kPa and $\phi' = 18^\circ$. Although these two test methods are not strictly comparable, there appears to be a frictional loss of $3-5^\circ$ from peak strength to fully softened strength.

Samples 1 and 4 both show residual c' values. Generally a failed clay is taken to be in the $c' = 0$ condition, but some workers have made reference to significant values for residual c' (Bishop *et al.*, 1971; Cullen and Donald, 1971). Alternatively it can be taken that $c' = 0$ and that some soils have a higher angle of internal friction at low normal pressures. Residual c' values are probably due to incomplete saturation and hence localised suction pressures on the failure plane. On a natural slip plane bubbles of air may cause localised suction and some cohesion which maintains a marginal stability, until the air bubbles become dissipated.

The clays of the St Leonards hillside are highly plastic and often fissured: both conditions that favour progressive slope failure. Also, there are topographic humps and hollows which suggest that much of this hillside has already failed. For these reasons the fully softened strength values are considered to be the most suitable for analysis.

SLOPE ANALYSIS

Slope analysis was used to see if it is possible for the slip to be moving on the lower aquifer at the base of the sandy clay in softened blue-grey clay, and not just near the surface. Analysis followed the method of Bishop (1955). This method employs an effective stress failure criterion and allows for normal horizontal forces but ignores the shear forces, between slices. These shear forces can be ignored with a loss in accuracy of <1%.

The formula which Bishop derived for each slice, is taken on the basis that the slip plane is a circular arc. An arc may be fitted along the anticipated slip plane of St Leonards, but only by putting much of it through the stronger red clays. Hence the calculated safety factor will be higher than it should be.

5 cm

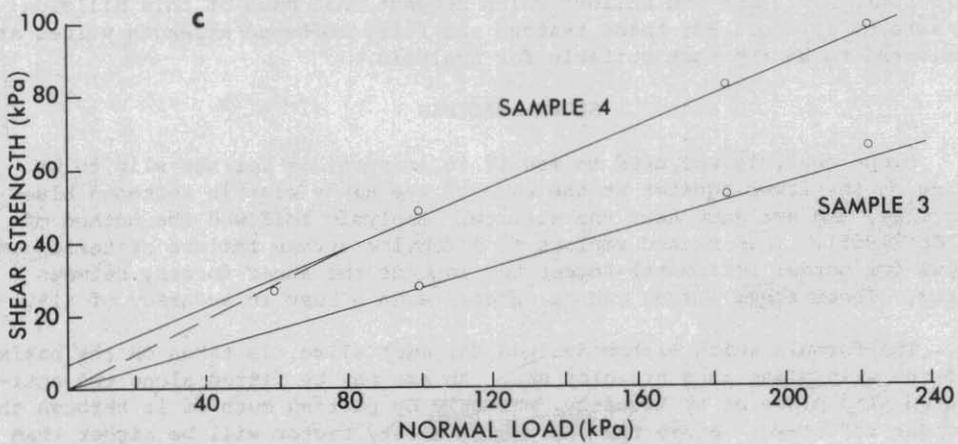
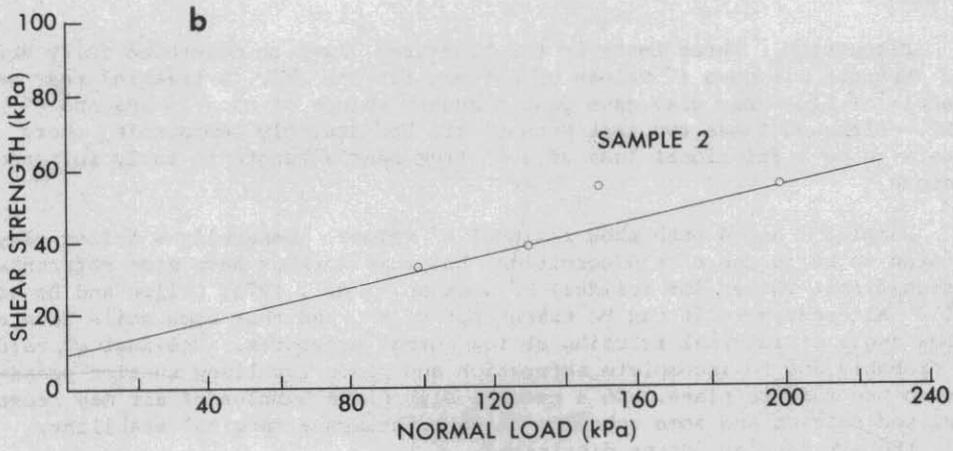
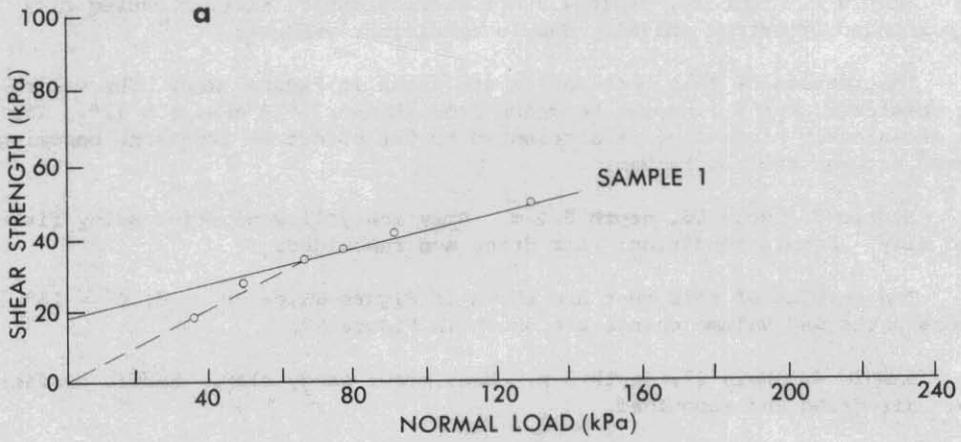


Figure 66. Results of shear box tests.

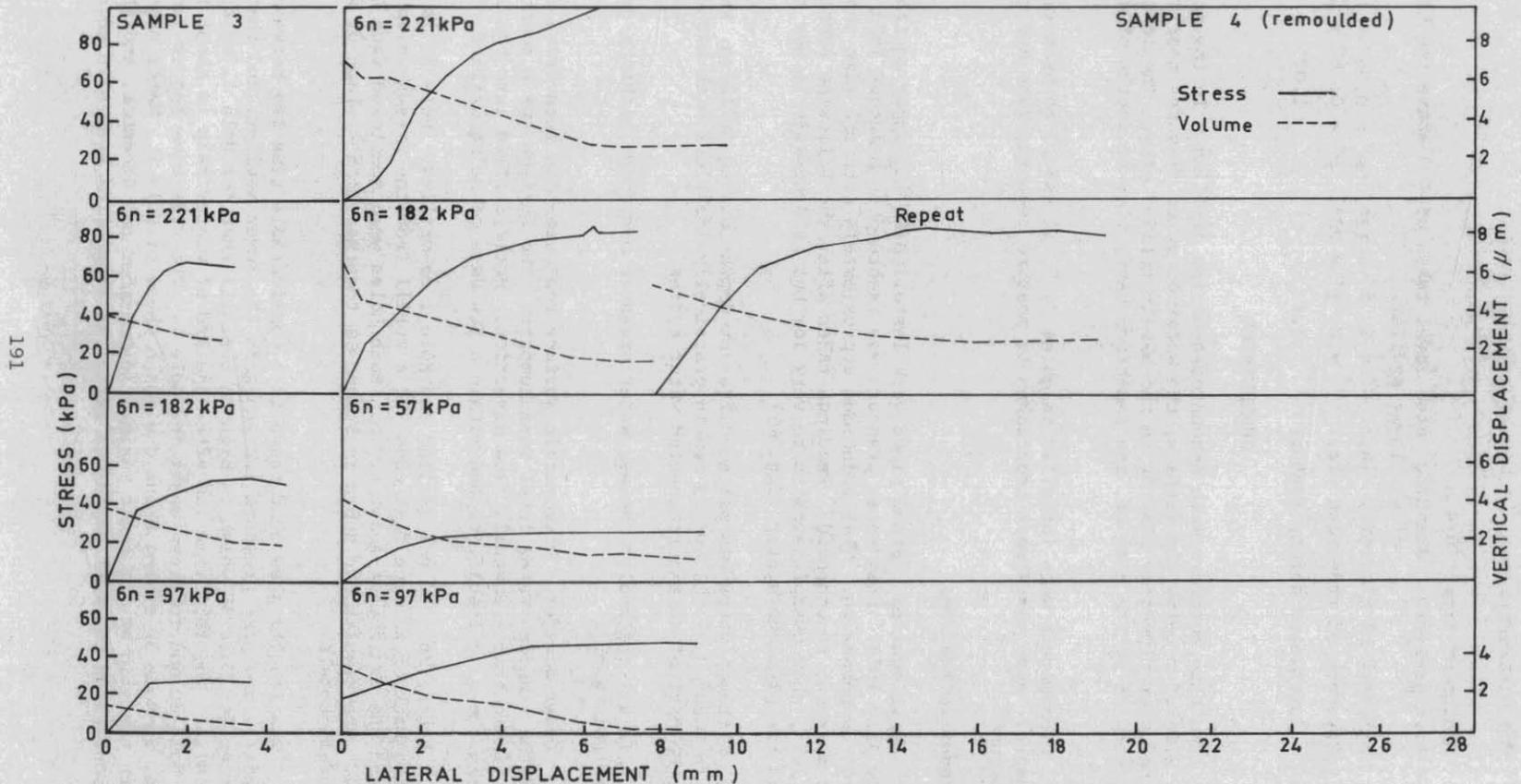
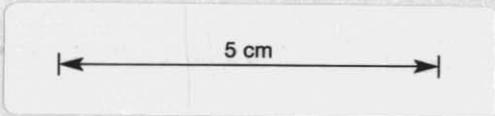
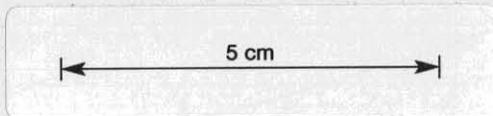
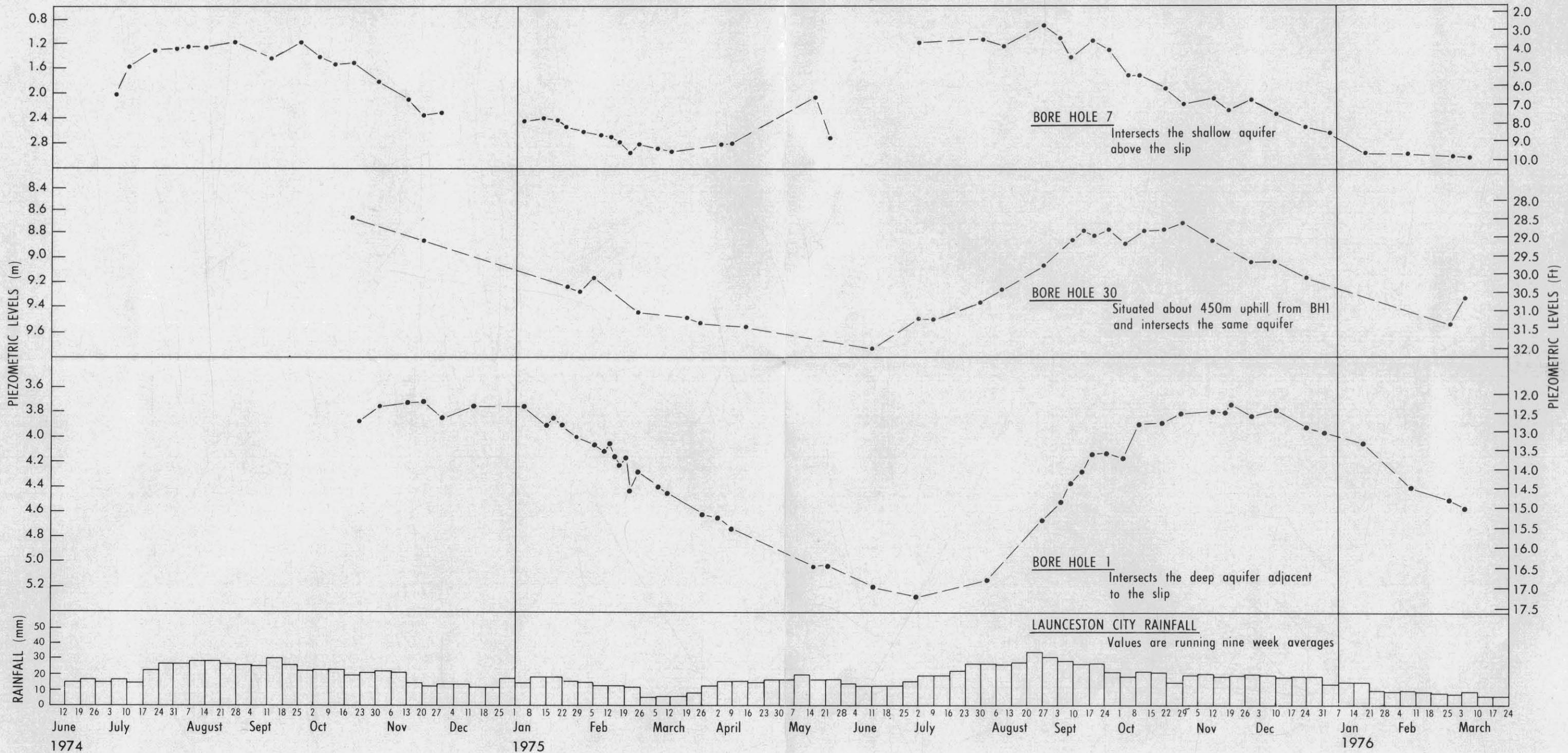


Figure 67. Stress paths and volume change, drained shear box tests on Samples 3 and 4, St Leonards.

ST LEONARDS LANDSLIP

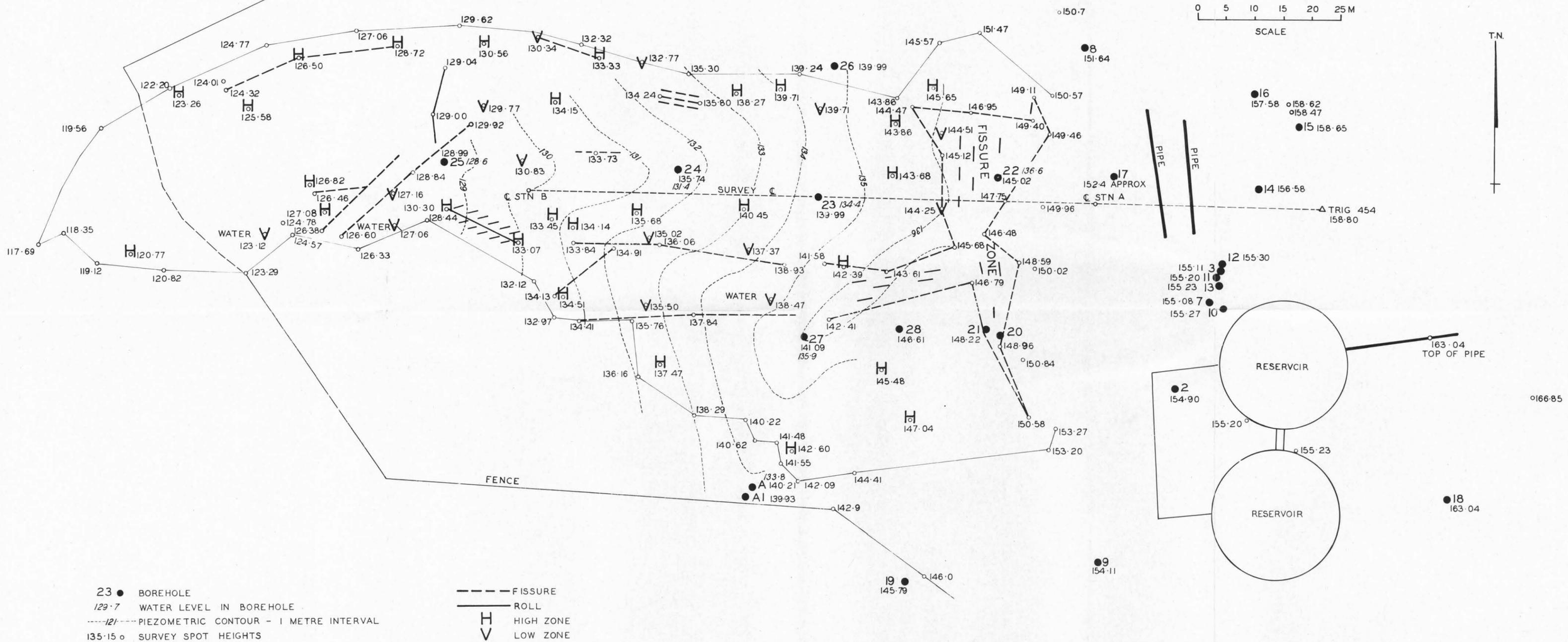
PIEZOMETRIC LEVELS COMPARED WITH RAINFALL JUNE 1974 - MARCH 1976



SURVEY OF ST LEONARDS SLIP 1974

WITH CONTOURS ON PIEZOMETRIC SURFACE OF DEEP AQUIFER

Geologist W.L. Matthews Surveyor G. Benn



23 ● BOREHOLE
 129.7 WATER LEVEL IN BOREHOLE
 - - - - - 121 - - - - - PIEZOMETRIC CONTOUR - 1 METRE INTERVAL
 135.15 ○ SURVEY SPOT HEIGHTS

- - - - - FISSURE
 ——— ROLL
 H HIGH ZONE
 V LOW ZONE

SURVEYED 22 OCTOBER 1974

5 cm

FIGURE 69

The parameters used in the calculation were:

Radius of arc: 78.4 m

Pore pressure: Standing water level taken as 4 m above the base of the lower aquifer.

Strength of blue-grey clay: $c' = 9$, $\phi' = 12^\circ$; $c' = 0$, $\phi' = 12^\circ$

Strength of red-brown clay: $c' = 8$, $\phi' = 22^\circ$; $c' = 0$, $\phi' = 22^\circ$

Calculated safety factor: 1.4 1.00

GROUNDWATER

Two thin aquifers were encountered during drilling. In the upper aquifer, 2.5-3.5 m below the surface, the water occupied fissures near the top of the upper blue-grey clay or in the basalt-derived clay. The lower aquifer was near, or at the base of, the red-brown sandy clay at depths of about 8-9 m.

Piezometers were installed in Holes 3, 7, 11 and 13 to measure pore pressure. Pump tests were undertaken to measure recharge rate and radius of influence.

Piezometric readings

Upper aquifer. Stand pipes were installed in the upper aquifer during early July 1973. Peak water pressure was recorded on 8 August 1973 with 1.75-2 m of overpressure. This coincides approximately with the time that shallow slip movement recommenced. Readings taken after the following summer, in May 1974, show overpressure to be very low but by June-July it was as high as in the previous winter (fig. 68).

Although water was met at different depths during drilling, water levels in Holes 3, 7, 11 and 13 remain practically identical with each other and must be part of an interconnected water system.

In all the shallow holes, water pressure responded within a day to heavy rainfall.

Lower aquifer. Piezometric surface contours have been drawn (fig. 69) from the standing water level measurements. The surface has a downhill slope, thus indicating a downhill flow direction. Holes drilled into the lower aquifer in the slip itself, closed within a few days of being drilled.

Later, Hole 30 was drilled and Hole 1 re-drilled. Hole 30 is situated at the back of a large flat area 450 m uphill from the present slip and intersected the aquifer at about 8.8 m. Both holes were monitored from December 1974. The results are shown in Figure 68 together with a graph of weekly rainfall totals.

The results show that there is a considerable time lag between high rainfall, and pore pressure increases in the lower aquifer, and that this is shorter for Hole 30 which is high on the hill than for Hole 1, adjacent to the slip. The fall time lag after the end of winter rain is about four weeks for Hole 30 and fourteen weeks for Hole 1. The rise time lag is less: the level in Hole 30 rising about one month ahead of Hole 1. Water pressures beneath the slip are at their maximum in November and December, and this must be considered the most dangerous period in respect of deep slip movement.

Recharge

Holes 13 and 14, in the upper aquifer were siphoned out in order that the recharge rate and radius of influence could be measured. Recoveries are shown in Figures 70 and 71. In both holes water was siphoned out to well below the level of the aquifer. Recovery was then linear until the water reached this level; above it recovery was logarithmic. If the hole diameter is taken as being that of the plastic tube (i.e. 63.5 mm) then Hole 13 made 4520 l/day and Hole 14 made 4750 l/day.

Radius of influence

Hole 13 was siphoned to 3.2 m below ground level. Within one hour the water level in Hole 11 one metre away, had dropped 130 mm and in Hole 7, three metres away, by 25 mm.

SUBSURFACE MONITORING

Two methods of subsurface monitoring have been used (fig. 72).

Standpipe with string

Some of the augered holes on the slip had plastic tubing installed in them. A weight tied to a piece of string was lowered to the bottom of the hole. After the slip movement, the pipe becomes crushed where it is affected by the slip and when the string is pulled from the surface the weight becomes wedged in the crushed part of the pipe. The depth of the slip surface can thus be determined.

This method has two disadvantages. Once the string has been pulled, after slip movement has occurred, it cannot be used again so that subsequent movement cannot be detected. If the slip moves too much before the string is pulled, the string may not move at all.

The main advantages of this method are its cheapness and simplicity. It is most appropriately used in a slow moving slip.

Tube monitored by strain gauges

A 32 mm diameter plastic tube was used for this purpose. At intervals of approximately 750 mm a pair of paper strain gauges was attached with Araldite to opposite sides of the tube. Wires from each pair of gauges were threaded up inside the pipe to a terminal at the top. The strain gauges are constructed so that their electrical resistance varies in response to strain and these variations can be monitored. The main disadvantages of this system is the fairly high cost and as with the other method, if a large movement takes place, the tube and wires may be sheared off. It has the advantage though that movement can be monitored during a long period over a range of depths.

Results

Closure depths from the first method are as follows:

Hole	Closure depth (m)
22	3.2
23	3.1
24	4.3
25	3.8
28	1.6

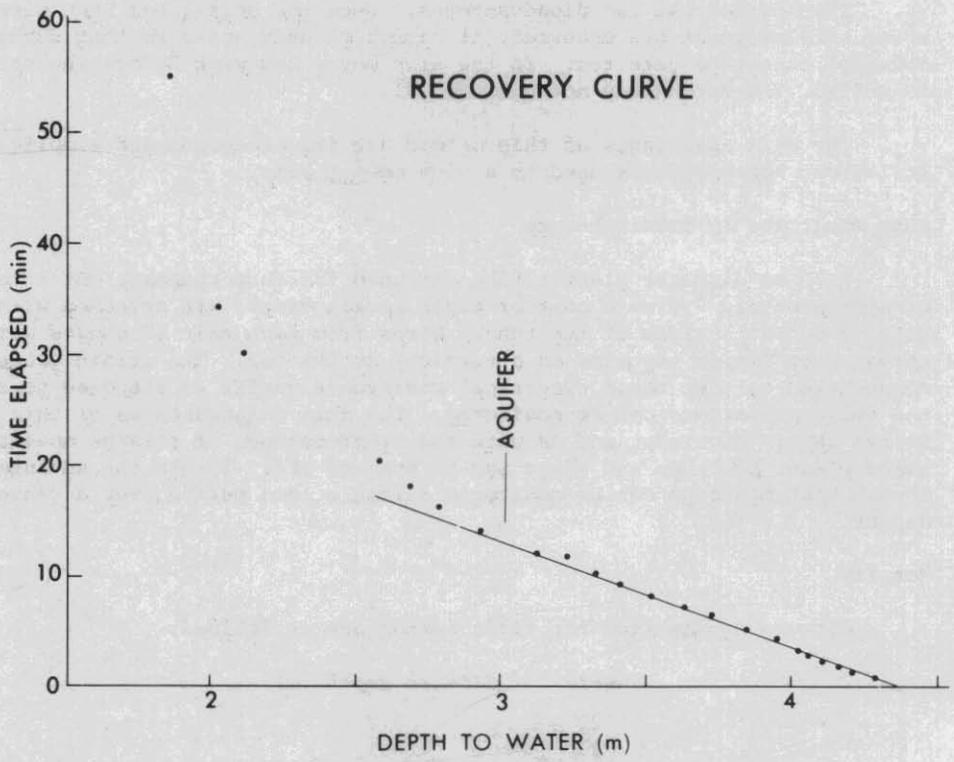
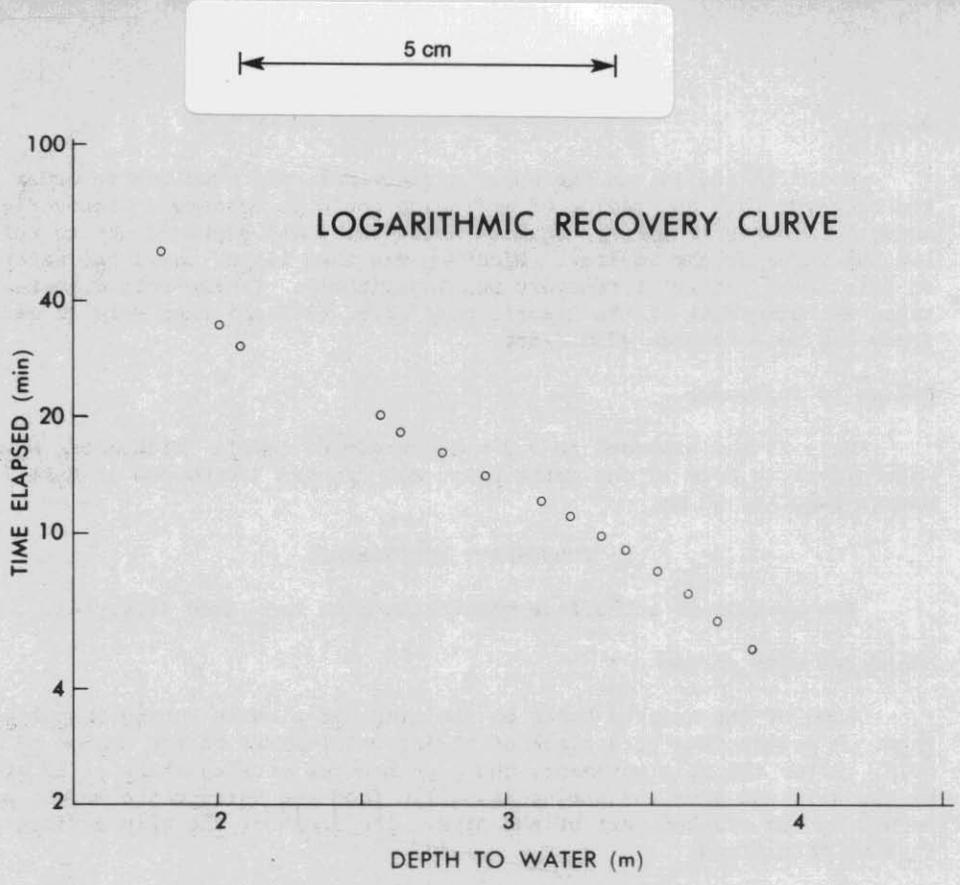


Figure 70. Recovery curves, Bore Hole 13.

5 cm

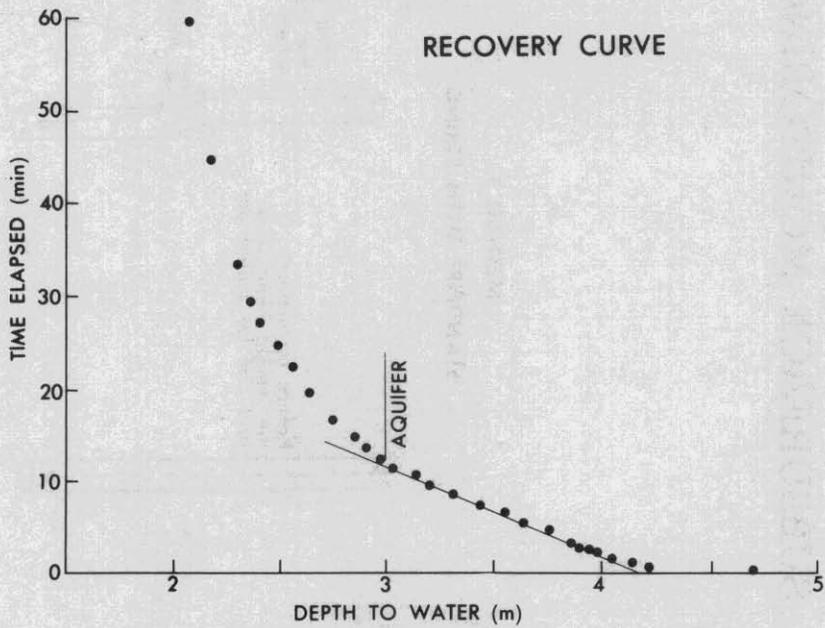
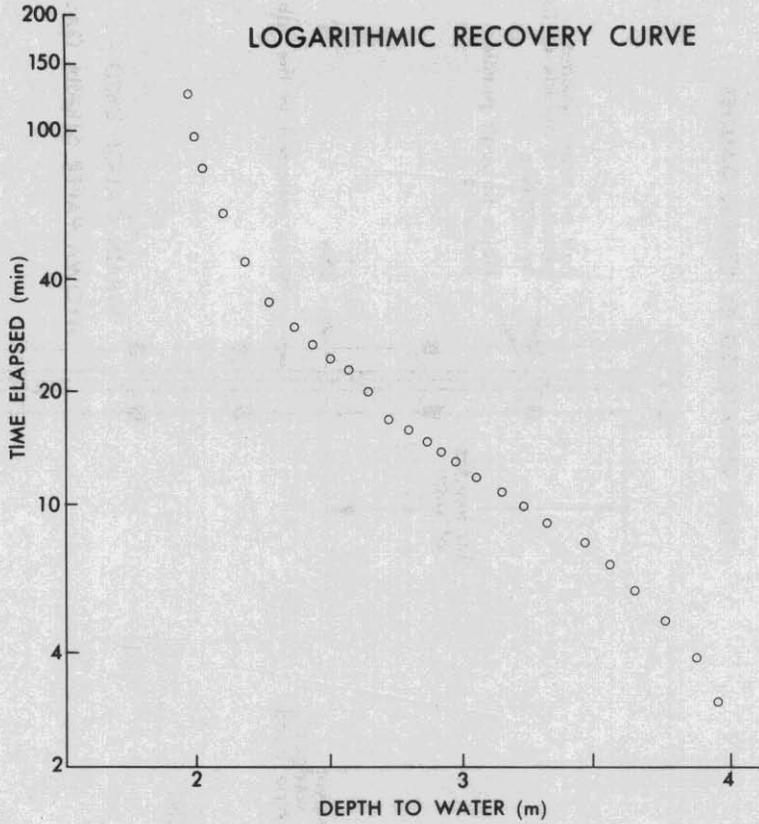
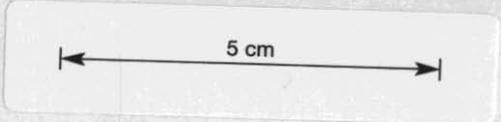


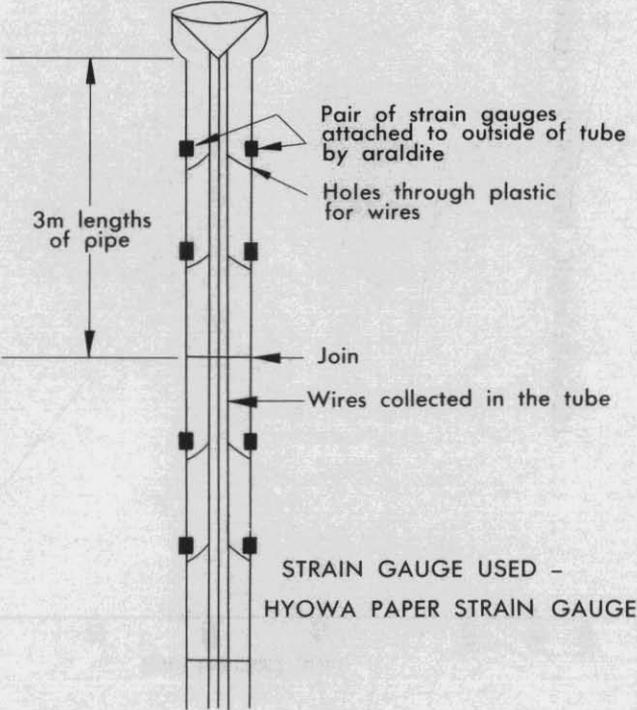
Figure 71. Recovery curves, Bore Hole 14.



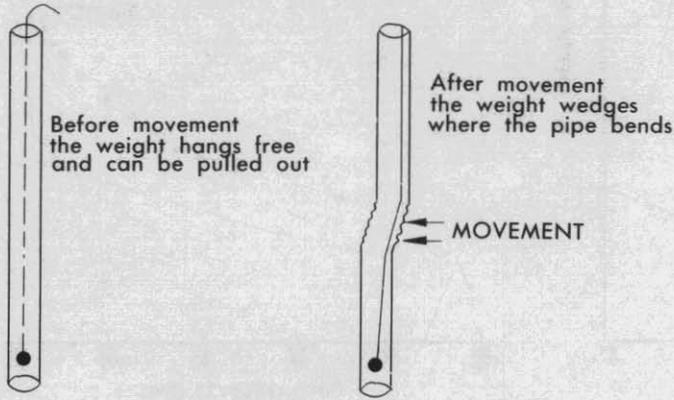
SUBSURFACE MONITORING

METHOD 2

TUBE MONITORED BY STRAIN GAUGES



METHOD 1 STANDPIPE WITH STRING



196

Figure 72.

STRAIN GAUGE MONITORING

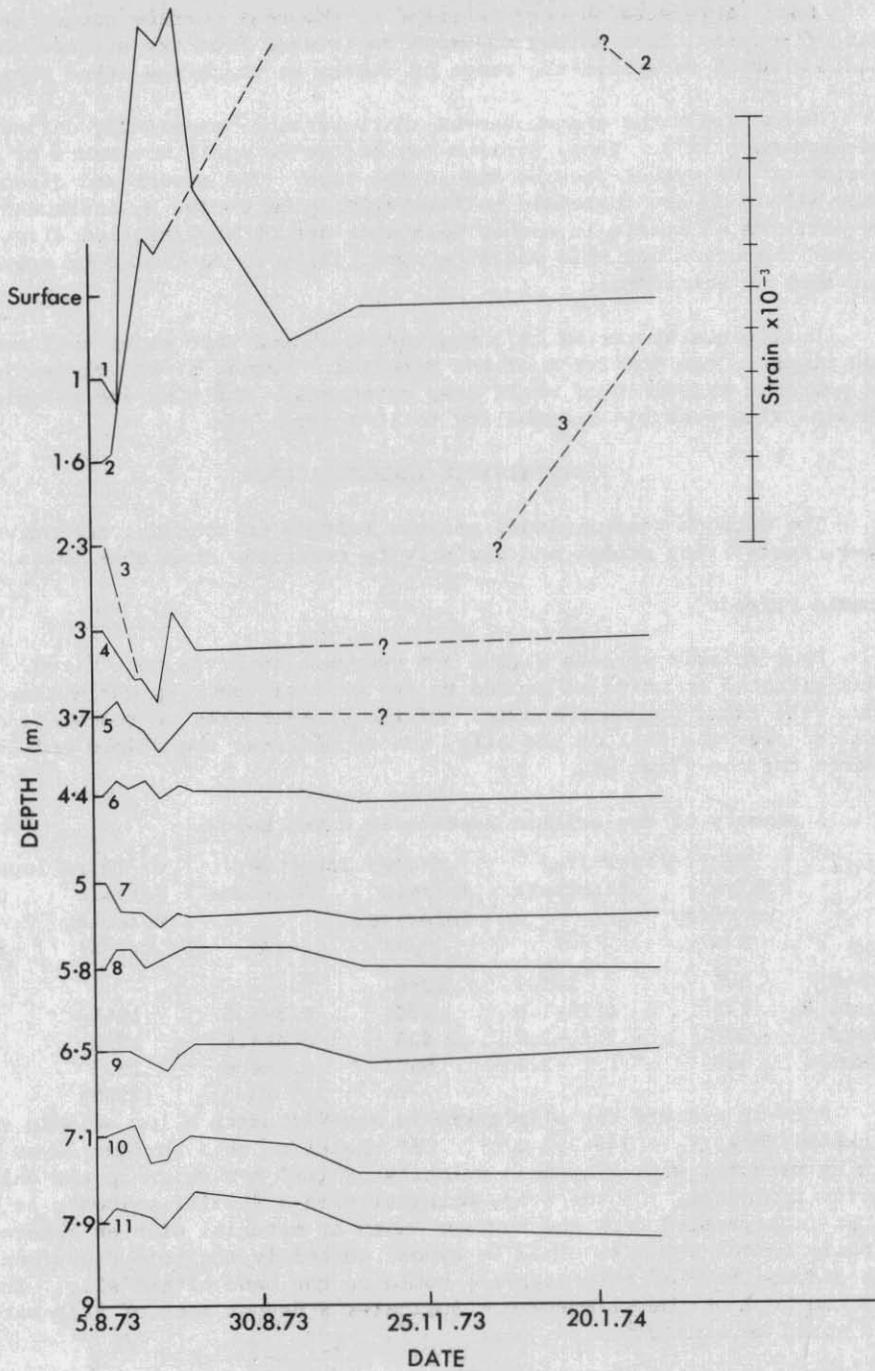


Figure 73.

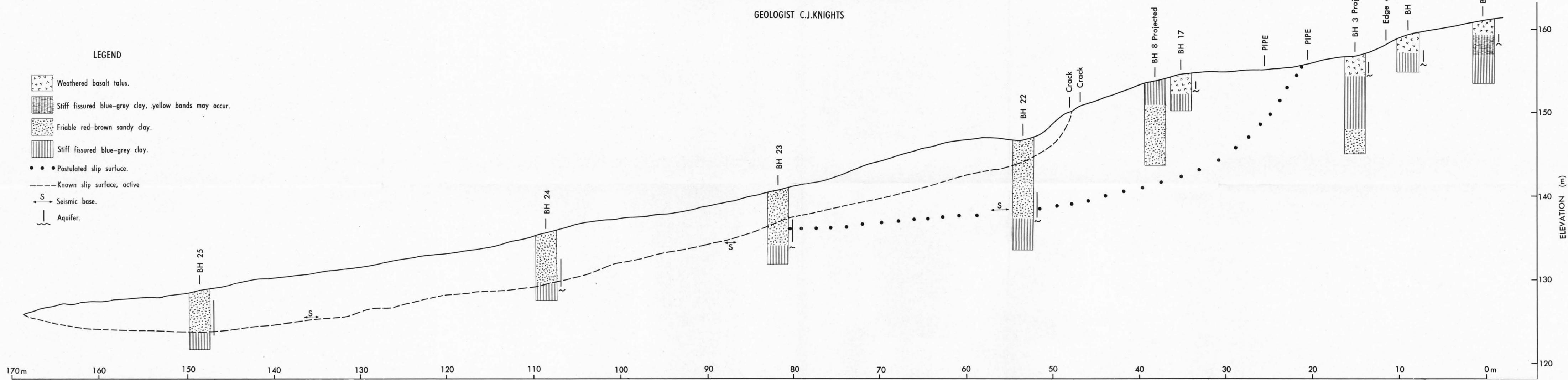
SECTION THROUGH LANDSLIP, ST LEONARDS

GEOLOGIST C.J. KNIGHTS

5 cm

LEGEND

-  Weathered basalt talus.
-  Stiff fissured blue-grey clay, yellow bands may occur.
-  Friable red-brown sandy clay.
-  Stiff fissured blue-grey clay.
-  • • • Postulated slip surface.
-  - - - Known slip surface, active
-  S Seismic base.
-  ~~~~~ Aquifer.



A strain gauge tube was installed in Hole 21 and monitored between August 1973 and February 1974. Unfortunately the value of these readings is limited to some extent because, due to the collapse of the hole, the tube reached only 9 m. The surface terminal was destroyed and readings could not be taken after February 1974. The pipe and gauges survived considerable slip movement and proved a useful monitoring method (fig. 73).

Such large strains were recorded by the near surface gauges that they went off-scale. This strong movement registered from the surface to a depth of 2.3 m which is within the range of depths at which the stand pipes closed.

Below 2.3 m the gauges showed small strains, especially during August and September 1973. These strains may be due to small movements or to compaction of the gravel packing around the tube. The amount and direction of gauge strain do not correlate sufficiently to be caused by instrument drift. The patterns of strain in gauges 4-11 show strong similarities (i.e. the same bending direction and this would be more likely to be caused by ground movement than by settlement).

During the winter of 1973 monitoring showed that major soil movement took place in the top 2-4 m of the material. Deeper strain gauges indicate the probable existence of small deep movements. Drilling and seismic investigations show possible instability to 10 m (fig. 74).

GEOPHYSICAL INVESTIGATIONS

The methods used included seismic refraction spreads, resistivity traverses, resistivity probes and resistivity traverses down bore holes.

Seismic spreads

Four seismic spreads with a 3 m geophone interval were fired. Spread 1 was situated on unfailed ground to the east of the slip while the other three were fired across the slip. Of those undertaken on the slip, one was situated near the heel of the slip, the second near the middle and the third towards the toe (fig. 54).

A summary of the seismic results is given below:

	First layer (V_0)		Second layer (V_1)		Third layer (V_2)	
	Seismic velocity (m/s)	Thickness (m)	Seismic velocity (m/s)	Thickness (m)	Seismic velocity (m/s)	Depth to V_1/V_2 interface (m)
Spread 1	305	1-1.3	1280			
Spread 2	245	0.75-1.8	400	4.3-5.5	1265	6.1-7.0
Spread 3	230	9.9-2.7	425	0.6-4.0	1220	3.2-5.0
Spread 4	350	1.1-2.1	580	2.6-4.6	1525	4.3-5.8
					(2285)	

Both on and off the slip there is material with a low seismic velocity at the surface ($V_0 = 245-350$ m/s). Off the slip, this surface layer is underlain by material with a seismic velocity of 1280 m/s which is the only refractor indicated. On the slip, material with a similar velocity is present but it is separated from the surface layer by material with an intermediate velocity of 400-580 m/s. This is almost certainly the soil disturbed by the slip and the base of this material would be the base of the slip. The spread near the heel of the slip however indicates a deeper zone of slip material than would be expected.

The spread near the toe indicated a high seismic velocity at depth when

fired with a 3 m geophone spacing suggesting the possibility of dolerite underlying the area. Later a spread with 7.6 m spacing was fired in the same area and had a maximum indicated seismic velocity of 1525 m/s. The high velocity obtained with the 3 m geophone spacing spread may have been due to a hard iron oxide band that may have underlain several geophones. Seismic profiles are shown in Figure 75. In this particular slip it has been possible to determine the approximate depth of material involved in the slip using seismic refraction spreads.

Resistivity

Resistivity traverses from stable ground across the slip to stable ground on the other side did not yield any significant results. There were areas of higher resistivity where the ground was buckled (and dried out) and lower resistivity in the low poorly drained areas, which is the expected situation.

Four probes were set out at various points on and around the slip (fig. 54). The results are shown in Figure 76. The material of the slip has a slightly lower resistivity than the disturbed material on the slip. This again is probably due to larger voids in the slip material near the surface, thus increasing resistivity.

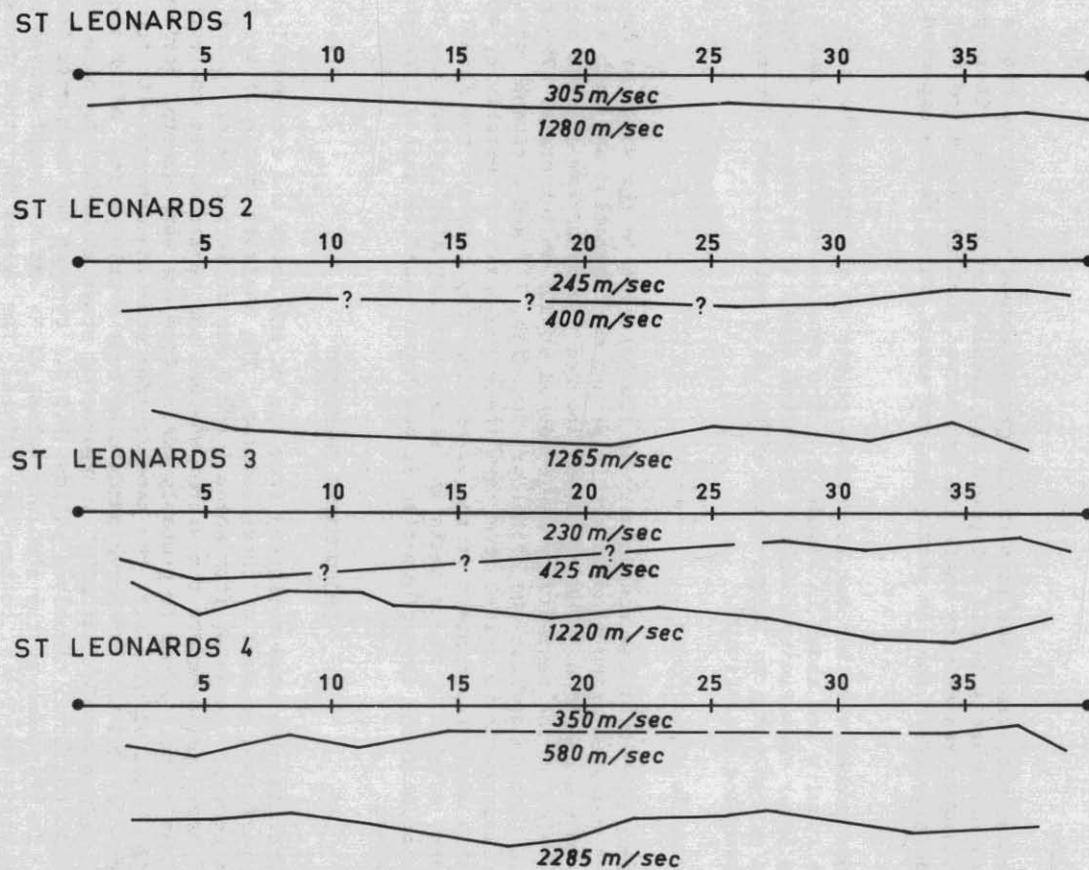
Resistivity in drill holes

Where possible, the resistivity of the material in the walls of drill holes was measured using a probe with a Wenner configuration and with a 150 mm electrode separation. The probe was lowered to the bottom of each hole and the value of the resistivity was measured at 305 mm intervals. The results are plotted against the lithologic log (fig. 77) and although nothing very conclusive can be gained from them there are peaks of resistivity around or slightly above the contact of the lower blue-grey clay and the friable red-brown sandy material. These peaks in resistivity may also reflect the depth to the slip surface, the information it was hoped would be gained from these measurements.

GROUNDWATER CHEMISTRY

Water samples were collected from six of the holes and a chemical analysis was performed on each of these samples. The analyses (table 1) are of interest because the water from Holes 1 and 3 was collected prior to any substantial heavy rains before the winter whereas the remainder was collected after these rains. Water is probably coming from the same general horizon in all the holes sampled i.e. the same aquifer near the contact with the lower blue-grey clay and the red-brown sandy clay beds overlying it. After the rains it is noticeable that HCO_3^- increases or stays at about the same value even though the total dissolved solids (T.D.S.) content has been more than halved. In the same way the absolute values of Na and K content stayed about the same while the T.D.S. content was halved. The values for other constituents show decreases.

The high HCO_3^- content is probably derived from the weathering of basalt uphill as it is common to have high carbonate and bicarbonate water near or in basalt. Some of this has been deposited lower down the slope as calcite in the form of travertine nodules and seams of crystalline calcite. The fact that Na content does not change with dilution means that the sodium adsorption ratio (S.A.R.) value increases with the dilution. This in turn means that the exchangeable sodium percentage (E.S.P.) is likely to increase in the clays with which this water comes into contact although this effect is not apparent



Geophone interval of 5 metres

Figure 75. Seismic sections, St Leonards landslide.

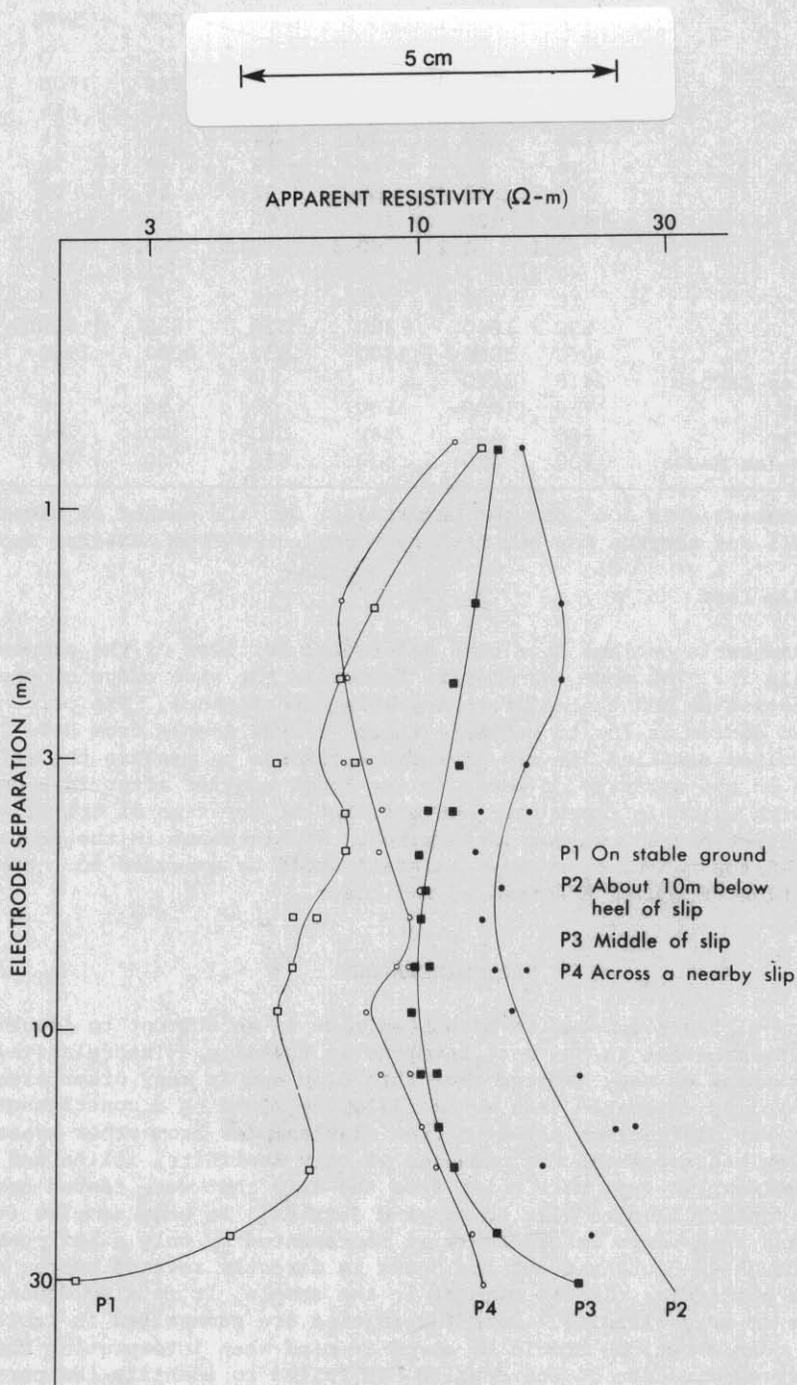


Figure 76. Resistivity probes, St Leonards landslip.

Table 1. ANALYSES OF GROUNDWATER SAMPLES FROM BORE HOLES

	Hole: 1	3	22	23	24	25	26
pH	7.5	7.0	7.0	7.4	7.9	7.4	7.1
	<i>ppm</i>						
CO ₃	0	0	0	0	0	0	0
HCO ₃	850	510	770	790	960	1000	715
Cl	1890	2650	635	490	740	655	645
SO ₄	130	155	34	24	45	46	44
SiO ₂	14	17	14	19	9	21	7
Ca	175	360	60	42	16	58	30
Mg	480	320	155	140	180	150	145
Fe	<0.1	0.2	<0.3	<0.3	<0.3	<0.3	<0.3
Al	<0.3	2	<1	<1	<1	<1	<1
K	18	8	22	20	22	7	27
Na	520	1040	380	320	530	530	430
TDS	4060	5090	1800	1530	2090	1930	1700
Hardness (as CaCO ₃)	2410	2220					
Permanent	1710	1800	160	30	80	0	85
Temporary	700	420	630	650	700	760	585
Alkalinity (as CaCO ₃)	700	420	630	650	700	760	585

from the exchangeable ion analyses undertaken, but the number of samples is rather small and samples may not have been collected from critical depths.

Exchangeable ions

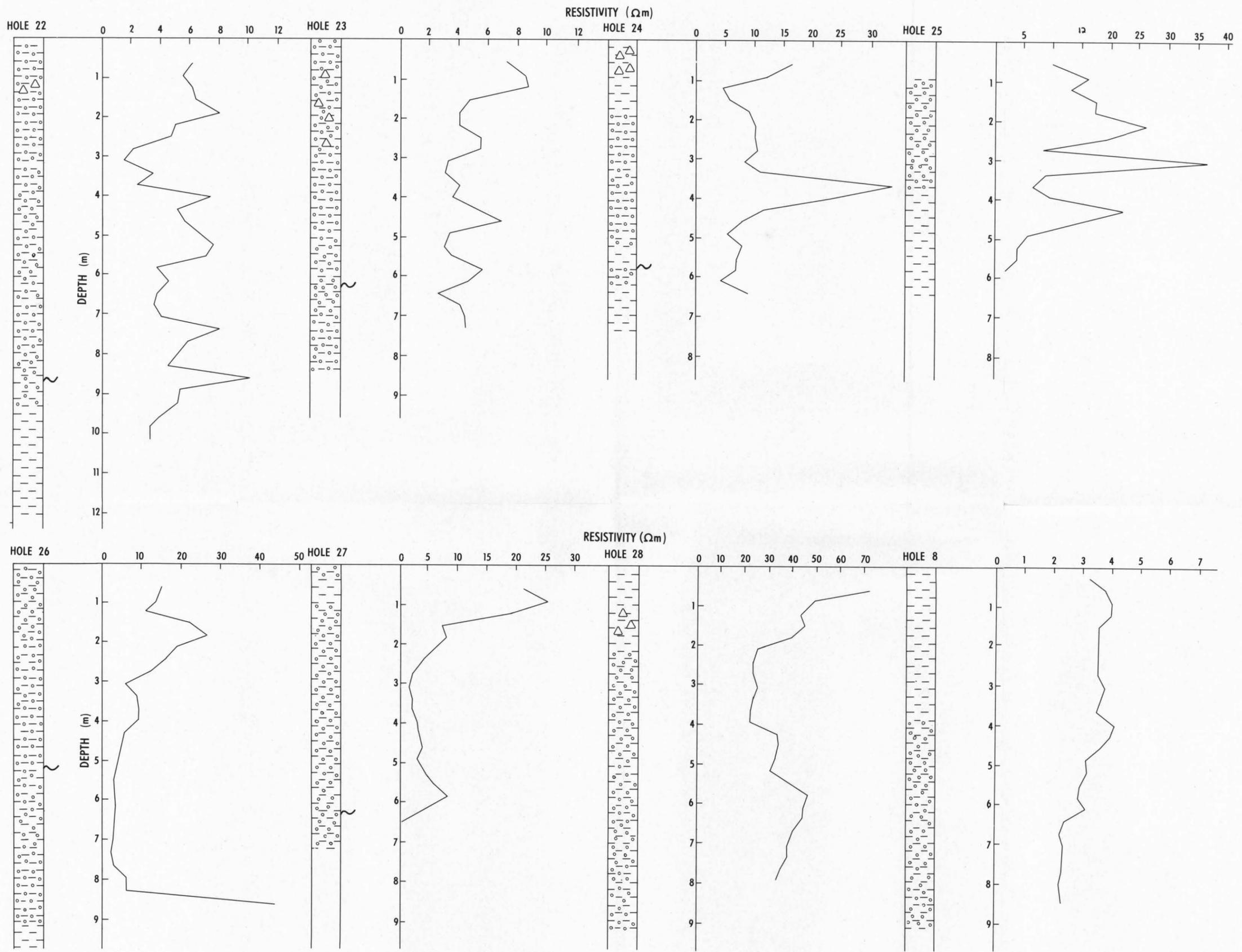
Exchangeable cations have been determined for some of the samples collected (table 2). The most significant factor is the wide range of the calcium and magnesium and their interchangeable predominance. The percentage of adsorbed sodium is low to moderate except in one sample from Hole 2. With more controlled sampling, it may have been possible to measure the effects of changes in the salinity of water in the lower aquifer after rain, on the material with which it comes into contact, but at the time of drilling this salinity variation had not been determined. The increase in the proportion of sodium in the water after heavy rainfall would be expected to increase the proportion of sodium adsorbed by the clays.

CLAY MINERALOGY

X-ray diffraction studies have been made in an attempt to identify the various clay minerals in the soil involved in the slip. The relatively high linear shrinkage of many samples from this slip and in many other areas from the Tamar Valley suggested that montmorillonite might be a constituent, but previous X-ray diffraction patterns from clay samples from other areas in the Tamar Valley had suggested the presence of only kaolinite, illite and quartz. Most of the samples from bore holes from the slip that were tested had indications of montmorillonite clay to varying degrees. In some samples it is the dominant peak while in others it is represented by only a low peak (fig. 78). Although the intensity of the peaks is directly related to the proportion of the particular mineral present in the sample, it is also dependent on the degree of crystallinity. Peak intensities are summarised in Table 3 but the above considerations should be borne in mind when interpreting them. A preliminary examination of the results has failed to identify the persistent peak at $2\theta = 18.4^\circ$.

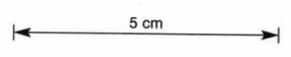
COMPARISON OF LITHOLOGICAL AND RESISTIVITY LOGS, ST LEONARDS

GEOLOGIST W.L.MATTHEWS



LEGEND

- Sandy clay
- Clay
- Basalt boulders
- Water level



5 cm

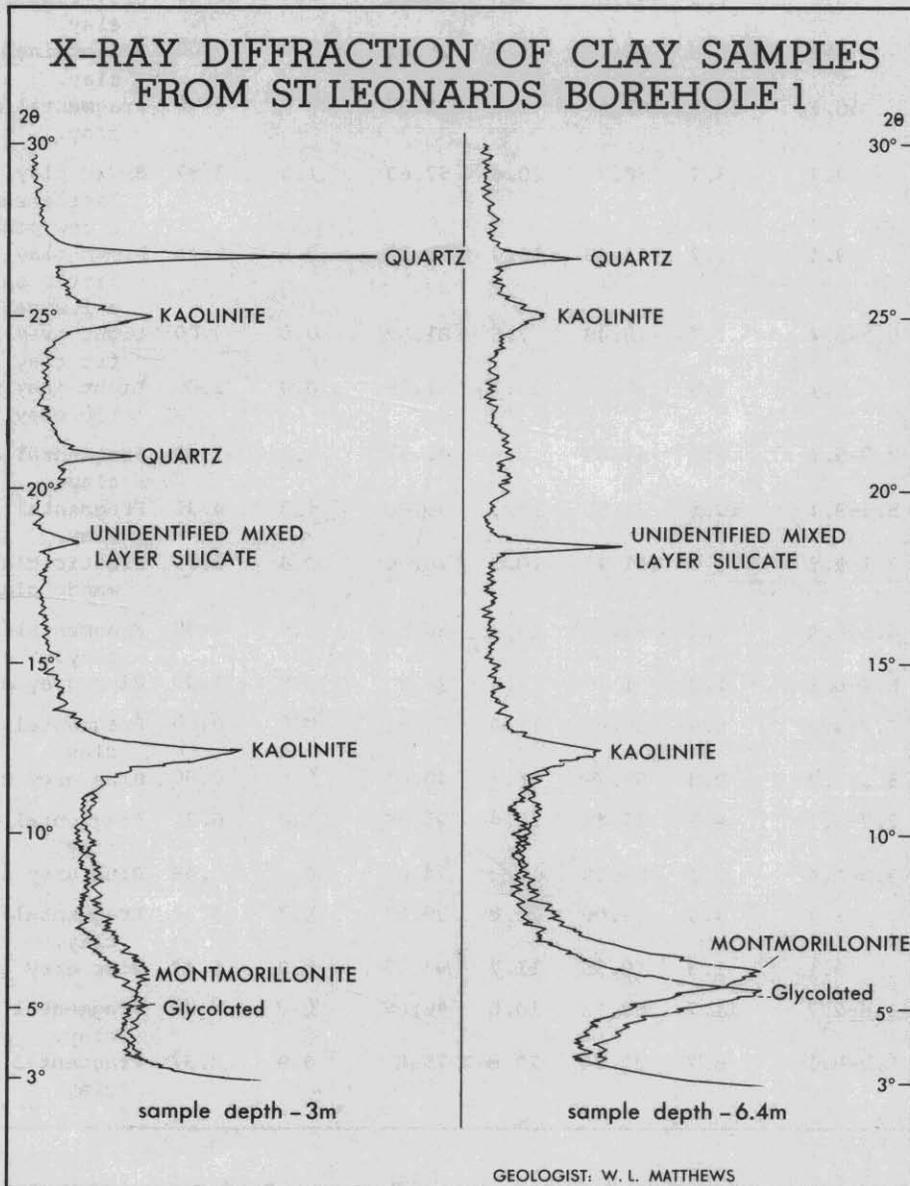


Figure 78.

Table 2. EXCHANGEABLE CATIONS IN GROUNDWATER SAMPLES

Hole No. and Sample Depth (m)	Ca		Mg		Na		Material	
	ml mol 100 g	%	ml mol 100 g	%	ml mol 100 g	%		
1	2.7	20.5	66.34	10.0	32.36	0.4	1.29	Grey brown clay.
	5.5	4.0	27.59	9.2	63.45	1.3	8.97	Fragmental sandy clay.
2	2.7	3.2	14.75	14.6	67.59	3.9	17.97	Brown plastic clay.
	5.5	7.5	43.86	9.6	56.14	0.0	0.00	Grey plastic clay.
	8.2	16.5	73.99	5.8	26.01	0.0	0.00	Red stained grey clay.
	10.1	13.5	62.5	7.1	32.87	0.0	0.00	Fragmental sandy clay.
3	2.7	13.7	38.7	20.4	57.63	1.3	3.67	Brown clay, a little sandy, a few pebbles.
	3.1	1.7	13.49	10.0	79.37	0.9	7.14	Brown clay, a little sandy, a few pebbles.
	5.5-6.4	1.7	18.48	7.5	81.52	0.0	0.00	Light grey plastic clay.
	9.1	7.0	36.65	11.7	61.26	0.4	2.09	Light grey plastic clay.
22	2.7-5.5	8.3	47.43	7.9	45.14	1.3	7.43	Fragmental sandy clay.
	5.5-9.1	10.5	34.88	18.3	60.80	1.3	4.32	Fragmental sandy clay.
	9.1-9.5	3.0	21.13	10.8	76.06	0.4	2.81	Plastic clay, sandy clay.
23	4.6-6.4	6.7	33.5	13.3	66.5	0.0	0.00	Fragmental sandy clay.
	6.4-8.2	1.9	71.7	7.5	28.3	0.0	0.00	Blue grey clay.
24	2.7-4.6	4.3	20.48	15.4	73.33	0.0	0.00	Fragmental sandy clay.
	5.5-7.3	9.8	59.39	6.7	40.61	0.0	0.00	Blue grey clay.
25	2.7-3.7	4.8	17.84	20.4	75.84	1.7	6.31	Fragmental sandy clay.
	5.5-6.4	3.0	22.39	10.0	74.63	0.4	2.98	Blue grey clay.
26	2.7	4.5	14.06	25.8	80.63	1.7	5.31	Fragmental sandy clay.
	9.1	1.3	9.35	11.7	84.17	0.9	6.47	Blue grey clay.
28	1.8-2.7	11.7	53.92	10.0	46.08	0.0	0.00	Fragmental sandy clay.
	8.2-9.1	6.7	21.34	23.8	75.8	0.9	2.87	Fragmental sandy clay.

Table 3. X-RAY DIFFRACTION PEAK INTENSITIES

Hole	Depth (m)	Montmorillonite	Kaolinite	2θ = 18.4	Quartz	Material
1	2.7	Moderate	Strong	Moderate	Strong	Basalt clay
	6.4	Strong	Moderate	Strong	Moderate	Sandy clay
9	11.9-12.2	Weak	Moderate	Moderate	Strong	Sandy clay
	8.2- 8.5	-	Strong	Moderate	Strong	Sandy clay
	5.5- 5.8	Weak	Strong	Moderate	Strong	Upper clay
	3.4- 3.7	Strong	Strong	Weak	Strong	Upper clay
22	2.7- 5.5	-	Weak	Strong	Moderate	Sandy clay
	9.1- 9.4	Weak	Strong	Moderate	Strong	Lower clay
24	2.7- 4.6	Strong	Moderate	-	Moderate	Sandy clay
	5.5- 7.3	Weak	Strong	Moderate	Strong	Lower clay
25	5.5- 6.4	Moderate	Strong	Moderate	Strong	Lower clay
27	6.4- 7.3	Strong	Moderate	Moderate	Weak	Sandy clay

REMEDIAL MEASURES

Further movement has taken place since the work described above was done (fig. 69). The slip is now wider in the heel area and the toe has extended through a fence onto neighbouring property. Various drainage measures have been tried and have not been successful in stopping the movement. A drain around the top of the slip prevents surface water from entering onto the slip. It is apparent from the drilling that groundwater is affecting the slip and rises in the piezometric surface may be reduced to some extent by installing bores at various points and pumping or siphoning the water out and away from the area.

A possible mechanical method which seems to be the only system which could be installed with relative ease is piling and the placing of barriers on the uphill side of pairs of piles to prevent flowage around them. Rather than drive the piles, with consequent risk of the vibration initiating slip movement, holes could be drilled with an auger drill and the piles placed in holes drilled to a depth of about 10 m (into the lower blue-grey clay). At least 15 to 25 such pairs of piles would probably be needed to have any effect on stabilising the slide, even temporarily. Such a system would be relatively cheap to instal if wooden poles and slabs were used. The barriers would need to be placed in trenches dug to the slip surface. Drainage through the barriers must be maintained to prevent the build up of water behind them.

By keeping the piezometric surface low and by piling, it might be possible to maintain stability at least for a period. This may allow the establishment of a tree cover, the roots of which should help contain the movement in the future.

CONCLUSIONS

Drilling in the area around the slip has established that the Launceston Beds dip downhill. The geological sequence comprises basalt talus (at the top), blue-grey fissured clay, red-brown sandy clay and a lower blue-grey clay.

Atterberg limits indicate that the materials in the slip area are inorganic clays of high plasticity, the blue-grey clay having liquid limits of more than 95%.

Groundwater was encountered at two different levels. In the upper aquifer, around the heel of the slip, the water level responded rapidly to heavy rainfall. The water percolates through the basalt talus and the open fissures in the plastic clay. Pump tests on these shallow holes indicate a small but significant rate of flow. The lower aquifer was encountered near the interface between the red-brown sandy clay and the lower blue-grey clay. The water is invariably under pressure, having a head of 1.5-4 m. The piezometric surface of the lower aquifer slopes downhill as a result of water escaping from seepages where the aquifer is near the ground surface. A projection of the sandy clay bed uphill shows that it probably comes into contact with the sand and gravel underneath the basalt. Drilling has confirmed that the lower aquifer does continue uphill; it is thought to be the base failure plane for the large old slip behind the reservoirs.

Vane, shear box and triaxial strength tests have been applied to the landslip materials. The vane tests are useful in performing quick field strength measurements and in measuring the sensitivity of the clays. In general, the blue-grey clays have a sensitivity of between 2 and 4 (i.e. are moderately sensitive). Quick undrained triaxial tests were conducted on a number of samples and generally gave fairly high cohesion values and low angles of internal friction. This method is not suitable for the analysis of failures which are slow moving. The triaxial test with pore pressure measurements on the blue-grey clay gave $c' = 15$ kPa and $\phi' = 18^\circ$ and shear box tests on fully softened samples gave values of $\phi' = 13^\circ-15^\circ$ (assuming the $c' = 0$ condition).

Slope analysis calculations from these values and other information obtained, indicate that the slip has probably moved on the lower aquifer at some time. Reactivation of slip movement on the lower aquifer would have serious results. The likelihood of such movement could be estimated by monitoring the water level in Hole 1. The greatest risk of movement occurs in the months of November and December (fig. 68). A small residual cohesion is seen to have a significant effect on slope stability.

The most useful of the geophysical methods applied to this slip appears to be the refraction seismic investigation which indicated a depth of movement which correlated with other methods. Although the interpretation of the downhole resistivity is not very conclusive at this stage it may be useful in some slips.

Two methods of monitoring subsurface slip movement, a tube with a weighted string and a tube with strain gauge attached, proved very successful in indicating depth of movement.

A study of groundwater chemistry shows that the salinity of the water in the lower aquifer decreases quickly and markedly after heavy rains although the sodium content remains at about the same absolute value. This is expected to increase the percentage of adsorbed sodium ions in the clays with which

it comes into contact. Measurements of adsorbed ions show a relatively low to moderate exchangeable sodium percentage, except in one case. With more controlled sampling, the effects of changes in water chemistry may be indicated in these measurements. The amount of adsorbed magnesium and calcium varies widely from sample to sample.

X-ray diffraction methods have identified montmorillonite and kaolinite as the dominant clay minerals in the slip material. As with such slips in other parts of the world montmorillonite is a common component and its expansive nature and ability to adsorb and exchange large quantities of ions has a marked effect on the stability of an area.

RECOMMENDATIONS

There are probably two levels of slip movement. The upper 3 m of material are intensely disturbed and move after a relatively short period of heavy rain. This movement is fed by surface water and by water in the shallow aquifer above the head of the slip. A system whereby water is siphoned, or pumped from holes during wet periods may aid stability, and will help prevent further cutting back at the head of the slip.

The lower aquifer is considered to be the basal slip plane, both for the present slip, and for the large, old, slip further up the hill. Present movement at this level has not been proved, but such movement would seriously endanger the reservoirs. When the water level in Hole 1 is less than 4.25 m below ground level, the northern tank should be emptied. When the water level is within 3.6 m of the surface close observation is needed.

Tree planting around the head of the slip and for some distance upslope will produce a soil moisture deficit so that the shallow aquifers will take longer to fill. Tree planting on the basalt plateau may aid the overall stability of the hill.

Surface drains at the head of the slip intercept considerable surface runoff and should be maintained.

Piling is a possible method for arresting slip movement. A number of piles would be required, with shallow barrier between them to prevent the shallow mud flow. The piles would need to be deep enough to penetrate into stable material below the lower aquifer. An engineering analysis is required to establish the feasibility of this method.

ACKNOWLEDGMENTS

Triaxial strength tests, sizing and Atterberg limits were determined by the Public Works Department Materials Research Laboratory, Moonah and chemical analyses of water and adsorbed ions by the Department of Mines laboratory, Launceston. Rivers and Waters Supply Commission employees assisted with many of the field problems that arose during the survey. Drilling was carried out by Technical Officers B. Cox, K. Williams and B. James and survey work by G. Benn of the Department of Mines. X-ray determinations of clay minerals were undertaken by D.J. Matthews, also of the Department of Mines.

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APPENDIX 1

Logs of bore holes

The following abbreviations are used to express test results on bore hole samples:

- | | |
|---|--|
| c' = cohesion intercept, effective | v_p = peak strength, vane test |
| c'_r = cohesion intercept, residual, effective | v_r = residual strength, vane test |
| c_u = cohesion intercept, triaxial undrained test | ϕ' = angle of internal friction, effective |
| LL = liquid limit | ϕ'_r = angle of internal friction, residual, effective |
| m = moisture content | ϕ_u = angle of internal friction, triaxial undrained test |
| PI = plasticity index | |

Hole	Depth (m)	Description	Sample depth (m)	LL (%)	PI (%)	m (%)	c_u (kPa)	c' (kPa)	c'_r (kPa)	ϕ_u (°)	ϕ' (°)	ϕ'_r (°)	v_p (kPa)	v_r (kPa)
1, 1A	0-1.8	Grey-brown fairly plastic clay, small quartz fragments.												
	1.8-4.6	Grey-brown clay, weathered basalt fragments, limonite-cemented silt towards bottom. Small fragments of plastic clay.	2.7	88	69									
			2.95			20	270		6					
	4.6-6.7	Light brown sandy silty material, very fragmental, limonite-cemented areas, perhaps some carbonate.	5.54			28	110				10			
			5.65			31	130		23					
			6.4	95	67									
	6.7-10.9	Light blue-grey plastic clay	9.1	92	67									
			9.2			33	85		11					
			9.3			33	205		1.5					
			9.4			31	150		3.5					
Water level on pulling out was 6.4 m from surface (when hole 1 was re-drilled the water level eventually rose to 4 m).														
2	0-0.9	Dark brown soil, occasional gravel fragments.												
	0.9-1.8	Mid-brown semi-plastic clay, in part fragmental (sandy).	1.2	93	75									
	1.8-2.7	Lighter brown plastic clay, some pebbles of basalt up to 40 mm across.												
	2.7-5.5	Light grey plastic clay with a brownish stain.												
	5.5-7.3	Grey churned-up clay (sandy?). Carbonate band 5.6 m.	5.5	102	76									
			5.62			27	12-		4					
	7.3-8.2	Red iron oxide stained clay with gravel fragments. Limonite and hematite concretions.	8.2	91	67									
			8.32			32	70		6.5					
8.5					3	280		6						
8.2-10.0	Reddish brown material, sandy texture.	10.1	88	65										

LOGS OF BORE HOLES (continued)

Hole	Depth (m)	Description	Sample depth (m)	LL (%)	PI (%)	m (%)	c_u (kPa)	c' (kPa)	c'_r (kPa)	ϕ_u (°)	ϕ' (°)	ϕ'_r (°)	v_p (kPa)	v_r (kPa)
3	0-1.8	Brown, fairly plastic clay, a few basalt boulders.												
	1.8-2.7	Lighter brown clay, pebbles and sandy material (not plastic).												
	2.7-6.4	Light grey plastic clay, limonite centres towards bottom.	3.01 3.35 3.6	98	70			15			18			
	6.4-8.2	Pebbly clay, some basalt fragments (collapse material?).	6.4			39	115			4				
	Water struck at 3.7-5.4 m, rose to surface.													
7	0-0.9	Stiff brown plastic clay.												
	0.9-1.8	As above with basalt fragments.												
	1.8-2.7	As above, becoming damper and loose-structured.	2.0			30.3								
	2.7-3.0	Base of basalt clay, loose yellow clay.	2.8			43							55	13.8
	3.0-3.6	Stiff grey, plastic clay.												
Water rose to one metre. Piezometer installed.														
8	0-0.9	Stiff grey clay.				39								
	0.9-1.8	Softer yellow and grey clay.				34.4								
	1.8-2.7	Soft grey plastic clay with yellow partings of more sandy material.	1.86			45	60			1				
			1.96			43	65			1				
			2.0 2.7			33						44.5	23	
	2.7-3.6	Soft brown clay with grey plastic pellets.												
	3.6-7.3	Dry, crumbly brown and red sandy clay with ironstone fragments and nodules.	4.59			30	200			3.5				
	7.3-9.7	As above, but softer.	4.69			30	340			0.5				
9.7	Hard band, stopped drilling.													
9	0-0.9	Grey plastic clay with brown iron staining mixed with dark brown soil.												
	0.9-3.4	Dark brown clay, sandy clay, a little grey clay, basalt boulders.												
	3.4-3.6	Light grey clay, some light brown oxidised areas.												

LOGS OF BORE HOLES (continued)

Hole	Depth (m)	Description	Sample depth (m)	LL (%)	PI (%)	<i>m</i> (%)	<i>c_u</i> (kPa)	<i>c'</i> (kPa)	<i>c'_r</i> (kPa)	ϕ_u (°)	ϕ (°)	ϕ'_r (°)	<i>v_p</i> (kPa)	<i>v_r</i> (kPa)
9	3.6-4.6	Light blue-grey clay, some brown iron oxide stained areas.	3.79			36	75			1				
			3.89			36	95			1				
			3.99			30	100			0				
	4.6-5.5	Light grey clay.												
	5.5-6.4	Grey clay, a little red iron oxide staining.												
	6.4-7.3	Red sandy clay, calcite band 6.9 m, some iron oxide pellets.												
	7.3-8.2	Reddish to khaki coloured sandy clay.												
8.2-12.0	Brown sandy clay.													
		Dry hole.												
10	0-2.7	Brown plastic clay with basalt fragments.												
	2.7-3.6	Stiff grey fissured clay with moist patches.				35								
	3.6-8.2	Stiff grey plastic clay.												
	8.2-10.0	Dry, red crumbly clay containing iron-stone pieces.												
	10.0-11.9	Orange-brown crumbly clay, moist and soft.				30								
	11.9	Dry yellow sand.												
		Dry hole.												
14	0-1.8	Orange-brown crumbly clay and basalt fragments.												
	1.8-2.7	Crumbly grey clay with yellow patches overlying soft crumbly yellow clay.				34								
	2.7-3.8	Yellow soft crumbly clay overlying wet gravelly material.												
	3.8-4.6	Stiff grey clay, very plastic, sticks to the auger.												
			Water intersected 3.4-3.6 m, rose to 1.8 m.											
15	0-1.8	Brown soil and weathered boulders.												
	1.8-2.7	Grey silty clay with crumbly texture.												

LOGS OF BORE HOLES (continued)

Hole	Depth (m)	Description	Sample depth (m)	LL (%)	PI (%)	m (%)	c_u (kPa)	c' (kPa)	c'_r (kPa)	ϕ_u (°)	ϕ' (°)	ϕ'_r (°)	v_p (kPa)	v_r (kPa)
15	2.7	Grey and yellow clay with a crumbly texture. Patchy, ranges from very soft and wet, to stiff.				34							110	12
	2.7-3.6	Very soft, no auger sample.												
	3.6-4.6	Stiff grey clay.												
	4.6-5.5	Stiff yellow and grey plastic clay. Rather crumbly, small ironstone fragments.				37							134	48
	5.5-7.3	Stiff grey plastic clay.												
	7.3	Very stiff, grey, homogeneous clay.				39							144	48
	Water intersected at 2.7 m, rose to 2 m.													
16	0-1.8	Brown clay with occasional basalt fragments.												
	1.8-2.7	Fairly soft grey clay	2.7						15			14		
	2.7-4.1	Soft grey and yellow crumbly clay.												
	4.1-4.6	Fairly soft bright yellow and grey plastic clay.	4.6						9			12		
	4.6-6.4	Fairly stiff grey and yellow plastic clay.				39								
	6.4-8.3	Yellow plastic clay.	8.2						0			15		
	Water entered slowly; hole collapsed.													
17	0-1.8	Very soft wet gritty clay with basalt fragments.	1.8									53		
	1.8-2.7	Soft, crumbly grey clay with travertine fragments.												
	2.7-3.6	Firm grey clay.												
	3.6-4.3	Hard, sandy clay.												
	4.3	Band of hematite, stopped auger.												
	Water rose to surface.													
18	0-0.9	Basalt boulders, 150 mm across, above medium hard plastic grey and light brown clay.												
	0.9-1.8	Brown iron-stained fragmental clay, some grey medium plastic clay.												

LOGS OF BORE HOLES (continued)

Hole	Depth (m)	Description	Sample depth (m)	LL (%)	PI (%)	m (%)	c_u (kPa)	c' (kPa)	c'_r (kPa)	ϕ_u (°)	ϕ' (°)	ϕ'_r (°)	v_p (kPa)	v_r (kPa)
18	1.8-2.7	Light grey soft to medium-hard, plastic clay, stained pinkish, flaky structure.												
	2.7-3.6	Light grey medium plastic sheared clay.	2.8			36							63.4	12.4
	3.6-4.6	Light grey (pink stained soft to medium-hard plastic clay.												
	4.6-5.5	Light grey medium-soft plastic silty clay; some iron staining.												
	5.5-6.4	Brown clay, fairly soft and silty, limonite nodule.	5.5			36							58	13.4
	6.4-7.3	Silty brown clay, medium-hard plastic.												
	7.3-9.2	Light grey clay, brown silty, flaky structure.	9.2			45								
	Dry hole.													
19	0-0.9	Brown soil and clay, some basalt fragments.												
	0.9-1.8	Hard brown clay, in parts greenish, hematite band.												
	1.8-2.7	Light brown silty clay, flaky structure.												
	2.7-3.6	Silty sandy fragmental light brown clay.	2.7			31								
	3.6-5.0	Brown silty sandy material.												
20, 21	0-1.8	Soft grey-brown disturbed clay. Brown clay as from weathered basalt, with grey areas and pellets.												
	1.8-2.7	Dry, friable, red sandy clay with limonite fragments.												
	2.7-3.6	Yellow-orange friable sandy clay with small limonite fragments.												
	3.6-6.4	Yellow-orange friable sandy clay with small limonite fragments.												
	6.4-7.3	More plastic, orange clay with limonite fragments about 10 cm in diameter.												
	7.3-8.2	Yellow-orange crumbly clay.												

LOGS OF BORE HOLES (continued)

Hole	Depth (m)	Description	Hole	Depth (m)	Description
20, 21	8.2-9.2	Red-orange damp sandy clay.	25	0-0.9	Dark brown soil.
		Dry hole. Strain gauge monitoring pipe installed.		0.9-3.6	Light brown sandy silty fragmental material.
22	0-0.9	Wet dark brown sandy soil.		3.6-4.6	As above, but darker, and brown plastic clay.
	0.9-1.8	Light brown sandy material, some basalt boulders.		4.6-6.4	Light grey fairly soft flaky plastic clay, abundant carbonates in upper part.
	1.8-4.6	Light brown sandy, silty fragmental material.			No water after drilling, 0.5 m the next day.
	4.6-9.2	Darker brown sandy silty fragmental material, some calcite at bottom.	26	0-0.9	Dark brown clayey sandy soil.
	9.2-11.9	Grey hard plastic clay (some soft material at top, passing into hard grey clay). Slip surfaces, red pin-head sized spots.		0.9-4.5	Light brown sandy material at 3.7-4.5 m, very soft.
		Water level 8.7 m.		4.5-6.4	Brown, oxidised, sheared, very fragmental clay.
23		Poor recovery: material not as fragmental as that of Hole 22.		6.4-7.3	Grey medium-soft plastic clay, rather fragmented due to oxidation, some slip planes.
	0-2.7	Dark brown soil and clay, sandy, a few small basalt boulders.		7.3-9.2	Fragmental sandy material, with a higher clay content than the overlying material.
	2.7-3.6	A little lighter brown sandy clay.		9.2-9.3	Grey clay, soft area at top, limonite pisoliths in clay.
	3.6-4.6	Medium brown sandy clay.			Water level, 5.0 m.
	4.6-6.4	Medium brown fairly fragmental sandy silty clay. Some grey clay towards bottom.	27	0-0.9	Dark brown soil and clay.
	6.4-8.2	Very soft grey clay (limonite stained), small limonitic centres, some slip surfaces, hard clay at 8.2 m. Calcite areas towards bottom.		0.9-1.8	Wet, chocolate sandy material.
24	0-0.9	Dark brown soil and boulders.		1.8-2.7	Brown fairly damp sandy material.
	0.9-1.8	Dark brown plastic clay.		2.7-3.6	Brown and grey clay, some medium-hard plastic sandy-textured material, slip surfaces, carbonate fragments.
	1.8-2.7	Lighter brown sandy silty clayey material.		3.6-5.5	Brown sandy fragmental material.
	2.7-3.6	Even lighter brown sandy silty clayey material.		5.5-7.3	Lighter brown sandy material. Water struck at bottom.
	3.6-5.1	A little darker brown sandy silty clayey material.			Water level, 6.5 m.
	5.1-6.4	Very soft light brown clay, sandy and silty, a little oxidised.	28	0-0.9	Brown reconstituted grey clay and soil.
	6.4-7.3	Yellow and red oxidised clay, sheared, small pisolitic centres (spots).		0.9-1.8	Grey clay, basalt boulders.
		Water level rose to 3.5 m.		1.8-2.7	Light grey-brown sandy silty clayey material.
				2.7-4.6	Light brown sandy silty clayey material, some carbonate fragments 25 mm in diameter from 2.7-3.7 m.
				4.6-9.2	Brown fragmental sand, hard and dry, from 7.3-9.1 m. Many carbonate fragments.
					No water.

LOGS OF BORE HOLES (continued)

Hole	Depth (m)	Description
30	0-4.6	Rounded quartz gravel and sand mixed with clay, hard and dry.
	4.6-6.0	Dry feldspathic sand.
	6.0-8.5	Dry orange sandy clay.
	8.5-9.0	Wet sandy clay.
	9.0-11.8	Grey plastic clay.

Water intersected at about 9 m, rose to 8.65 m after the winter rains.

APPENDIX 2

Sizing analysis and Atterberg limits of bore hole samples.

Hole No.	3		7		8	
Reference No.	3/1	3/2	7/1D	7/2D	7/3D	8/1D
Depth (m)	3.01	5.5-6.4	2.0	2.9	4.3	1.5
Particle Size	Percentage Finer					
20 mm			100	100		
6 mm		100	83	85		
2 mm		98	80	81		100
600 μm		96	79	79	100	95
200 μm	100	94	78	76	99	89
60 μm	99	88	77	67	92	78
20 μm	96	83	73	56	86	70
6 μm	88	76	64	44	78	63
2 μm	74	69	53	34	66	54
Density (kg/m ³)	2540	2590	2800	2760	2680	2800
*LL (%)	98	110	118	138	100	87
*PI (%)	70	85	93	116	77	65
*LS (%)	20	21			20	

Hole No.	8			9		
Reference No.	8/2D	8/4D	9/1D	9/2D	9/3D	9/4D
Depth (m)	2.1	7.3-9.1	3.4-3.7	5.5-5.8	8.2-8.5	11.9-12.2
Particle Size	Percentage Finer					
20 mm				100		
6 mm	100		100	98		
2 mm	97	100	98	97	100	100
600 μm	94	96	96	96	99	98
200 μm	91	86	95	96	90	92
60 μm	86	72	91	95	79	62
20 μm	82	62	83	90	71	54
6 μm	74	53	75	82	58	45
2 μm	66	44	64	71	45	36
Density (kg/m ³)	2720	2780	2720	2680	2780	2800
*LL (%)	94	95	109	102	84	74
*PL (%)	72	74	88	77	61	56
*LS (%)		23		21	20	20

*Test Method: A.S. A89-1966; tests 2A, 3, 4 and 5.

Samples were oven dried at 50°C and dry sieved.

Hole No.	1			2			
Reference No.	1/1	1/2	1/3	2/1	2/2	2/3	2/4
Depth (m)	2.7	6.4	9.1	1.2	5.5	8.2	10.1
<i>Particle Size</i>	<i>Percentage Finer</i>						
6 mm	97	100				100	100
2 mm	94	99	100	100		95	97
600 μm	92	82	96	99	100	92	96
200 μm	91	68	92	98	99	83	90
60 μm	86	55	90	95	97	74	82
20 μm	81	47	87	90	93	70	74
6 μm	68	38	80	80	85	62	65
2 μm	58	31	70	72	77	52	56
Dry Density (kg/m^3)	2690	2720	2680	2720	2640	2830	2730
*LL (%)	88	95	92	93	102	91	88
*PL (%)	69	70	67	75	76	67	65
*LS (%)	20	24	20	24	20	20	20

*Test Method: A.S. A89-1966; tests 2A, 3, 4 and 5
 Samples in natural state.

APPENDIX 3

Classification of Tamar clays.

Location	Ref. No.	Material (Condition as received)	Atterberg Tests				Dry Density (kg/m ³)	Particle Size Analysis							Class	
			LL (%)	PI (%)	LS (%)	Sample condition		% finer than (mm)								
							6.0	2.0	0.6	0.2	0.06	0.02	0.006	0.002		
Evandale	L1	Soft yellow brown clay	93	71	22.5	O.D.	2730		100	98	95	86	78	70	63	CH
Quarantine Rd	L2	Soft grey, red and yellow mottled clay	110	78	20	O.D.	2680		100	98	97	94	91	78		CH
Wanstead Farm	L3	Stiff yellow & brown clay	77	54	17.5	O.D.	2720			100	97	90	86	81	65	CH
St Leonards	L4	Very soft yellow clay	103	72	23	Natural	2810	100	96	93	88	79	71	62	57	CH
Danbury Point	L6A	Dry brown clay	90	59	20	A.D.	2700			100	94	86	83	81	77	CH
Freshwater Point	L7A	Friable red brown and yellow clay	71	49	17	O.D.	2670			100	96	87	74	65	58	CH
Freshwater Point	L7B	Grey and yellow friable clay	68	46	16	O.D.	2650		100	98	84	64	60	56	49	CH
Browns Jetty	L8	Stiff yellow & grey clay with carbonaceous bands	79	53	18	O.D.	2660			100	96	92	81	71	62	CH
Rosevears	L9	Friable grey and yellow clay	82	60	20	O.D.	2710				100	94	80	68	55	CH
Deviot	L12	Hard grey & yellow clay desiccated & weathered	73	49	17	O.D.	2660				100	97	87	66	50	CH
Beauty Point	L13	Very soft yellow & grey clay	73	54	18.5	Natural	2720		100	99	90	79	70	60	45	CH
Tamar Avenue	L15	Soft grey clay with roots	76	54	17.5	Natural	2690				100	97	89	70	48	CH
Birralee	L16	Brecciated claystone*	81	54	17	A.D.	2680				100	96	94	85	68	CH
St Peters Oval	L17A	Soft mudstone*	85	64	21	A.D.	2700			100	89	73	66	58	52	CH
	L17B	Soft mudstone*	89	70	22	A.D.	2690				100	96	85	77	65	CH
Abels Hill	L18	Friable krasnozem clay	92	51	21	O.D.	2940			100	97	94	89	82	75	CH
Launceston Area	L19	Stiff yellow brown clay	73	44	14	O.D.	2690				100	94	88	80	70	CH
	L20		82	53	22	Natural	2820	95	91	80	80	67	54	43	37	CH
Craigbourne	M1	Soft grey clay		93	21	Natural	2610				100	92	83	78	74	CH
	M2		45	31	14	A.D.	2680				100	90	82	69	48	CL
Rear Batman Bridge	5m		69	53	21	A.C.	2780				100	95	82	64	48	CH

O.D., over dried at 50°C; A.C., air dried; * breaks down completely after soaking in water.