Slide Movements on an Inclined Clay Layer in the Avon Gorge in Bristol

Glissements sur une couche inclinée d'argile dans la vallée de l'Avon à Bristol

by D. J. Henkel, Ph.D., B.Sc.(Eng.), A.M.I.C.E. Civil Engineering Department, Imperial College, Exhibition Road, London, S.W.7

Summary

The Carboniferous Limestone Series in the Avon Gorge in Bristol consist of thick beds of jointed limestone interbedded with thin layers of clay. The strata dip roughly parallel to the gorge and the joints in the limestone are coated with thin layers of clay produced by weathering. Movement down the line of dip is prevented by the buttressing effect of the rock but slides can develop in which masses of limestone move obliquely across the clay layer. Surfaces of sliding develop both on the surface of the clay layer and on a series of joint planes.

A recent movement of this type is described and a method of analysis for the quantitative assessment of stability is developed.

Sommaire

Les séries du calcaire carbonifère dans la vallée de l'Avon à Bristol comprennent des couches de calcaire cimenté sur une grande épaisseur, traversées de minces couches d'argile. L'inclinaison des couches est à peu près parallèle à celle du ravin et les joints du calcaire sont remplis de minces couches d'argile d'altération. Un mouvement suivant la ligne de plus grande pente est impossible du fait de la résistance de la roche, mais les masses calcaires peuvent glisser obliquement sur les minces couches d'argile. Des surfaces de glissement se produisent sur les couches d'argile et sur toute une série de joints.

Le rapport décrit un récent mouvement de ce type et une méthode d'analyse pour le calcul de la stabilité.

Introduction

The downward movement of sedimentary rocks on interbedded layers of clay or shale or on joint planes is one of the classical landslide phenomena. Sliding is most likely to occur when the clay layers or joint planes dip directly towards a river valley or excavation. A well known example of sliding on a weaker interbeded layer is the large slide in the Gros Ventre River valley in Wyoming (Alden, 1927). In the great slide on Turtle Mountain in Alberta movement took place on joint planes which dipped steeply towards the river valley (Daly, Miller and Rice, 1912).

Slides can however occur in strata containing interbedded clay layers when the dip is parallel to the valley or excavation. Movement directly down the line of dip is prevented by the buttressing effect of the rock overlying the clay layer but when the rocks are intensively jointed oblique movement can occur. Sliding surfaces develop on the surface of the clay layer as well as on the joint planes in the overlying rock. A recent slip of this kind in the Avon Gorge in Bristol has enabled this phenomenon to be investigated and an approximate method of analysing stability to be developed.

The Site

At the site of the slide the River Avon has cut a gorge some 200 ft. deep in the rocks of the Carboniferous Limestone Series. The strata dip roughly parallel to the face of the gorge at an angle of 33° and consists of thick beds of heavily jointed limestone separated by thin layers of very stiff clay. The joint system is normal to the bedding planes and the sides of the joints have been coated with a red clay derived most probably from the products of weathering of the limestone together with material carried down from the red Triassic rocks which at one time covered the area.

The lower portion of the gorge has an almost vertical face and the flatter upper parts have been terraced by the construction of a number of masonry retaining walls. A general plan of the area, taken from the Ordnance Survey Sheet, is shown in Fig. 1.

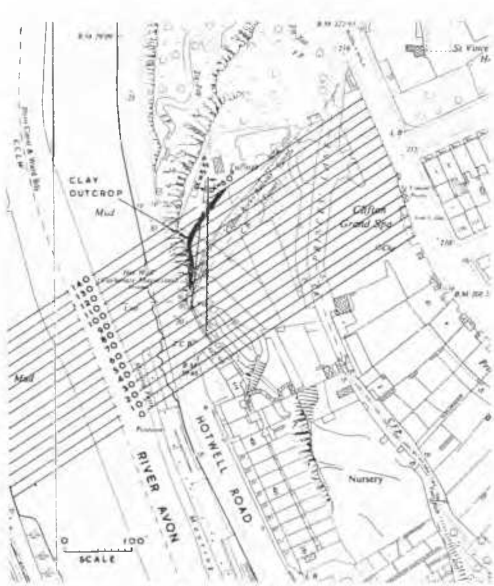

Fig. 1 General plan of area.
Plan d'ensemble.

A feature of the site is the existence of a disused inclined tunnel, which links Hotwell Road on the right bank of the river Avon with the top of Sion Hill. The tunnel portal together with a retaining wall above it extended nearly 50 ft. above the level of Hotwell Road and the first evidence of instability in the area was the discovery, at the end of 1956, of cracks between the masonry of the tunnel portal and the face of the limestone cliffs. Further examination disclosed that a crack some 4 inches wide had opened in the brick lining of the tunnel while cracking and distortion of the steps on the ground surface above the tunnel were also noted. The tunnel portal was shored to prevent further movement and part of the retaining wall, together with loose fill and rock above the portal, were removed. When this work was completed a layer of clay about five feet thick, sandwiched between limestone beds, was found and it appeared that blocks of limestone had been sliding obliquely down the surface of this clay layer.

The photograph, Fig. 2, shows a general view of the cliff face after part of the retaining wall and the fill had been removed, while Figs. 3 and 4 show respectively sections along the centre line of the tunnel and at right angles to the portal and face of the cliff.

Four borings were put down to locate accurately the position of the clay layer, to obtain samples of the clay and to examine the ground water conditions. These borings showed that the top of the clay layer was essentially a plane surface and its position has been shown on Figs. 3 and 4. The outcrop of the clay layer to the north of the tunnel has been indicated on the plan, Fig. 1, and the series of parallel lines show the elevation of the surface of the clay layer above the Ordnance Datum. The dip of the clay layer was found to be 33°.

As can be seen in Fig. 3, the tunnel intersects the clay bed and at this point a considerable quantity of water entered the tunnel. It was evident that the tunnel was acting as a drain for the water moving through the limestone along the impermeable upper surface of the clay layer. Borings in this area confirmed that there was little or no water above the clay layer.

A borehole near the southern wall of the tunnel, about 40 ft. from the portal, showed however that in the vicinity of the slip the ground water was standing four feet above the top of the clay layer. The limestone below the clay was found to be dry and water drained rapidly from the boreholes once the lower limestone had been penetrated.

The samples of clay taken from the boreholes showed that the clay was very hard and fissured. The liquid and plastic limits averaged 40 and 22 respectively, while the natural water content was only 15 per cent. Clay samples were also taken from the face of clay exposed above the tunnel portal. The main mass of clay in the exposure had properties similar to those of the borehole samples, but it was noticed that the upper 1/2 inch of clay in contact with the limestone was of a different nature. This thin zone of clay had been weathered and was in fact very similar to the clay which was found in the joints of the limestone. It had a liquid limit of 51 and a plastic limit of 25.

Drained triaxial shear tests carried out on samples from the main mass of clay gave effective stress shear parameters of $c' = 500$ lb./ft.^{2} and $\Phi' = 22°$. Samples suitable for shear tests could not be obtained from the thin upper zone of material but by comparison with the results obtained from the main mass of material with a lower plasticity index, it was

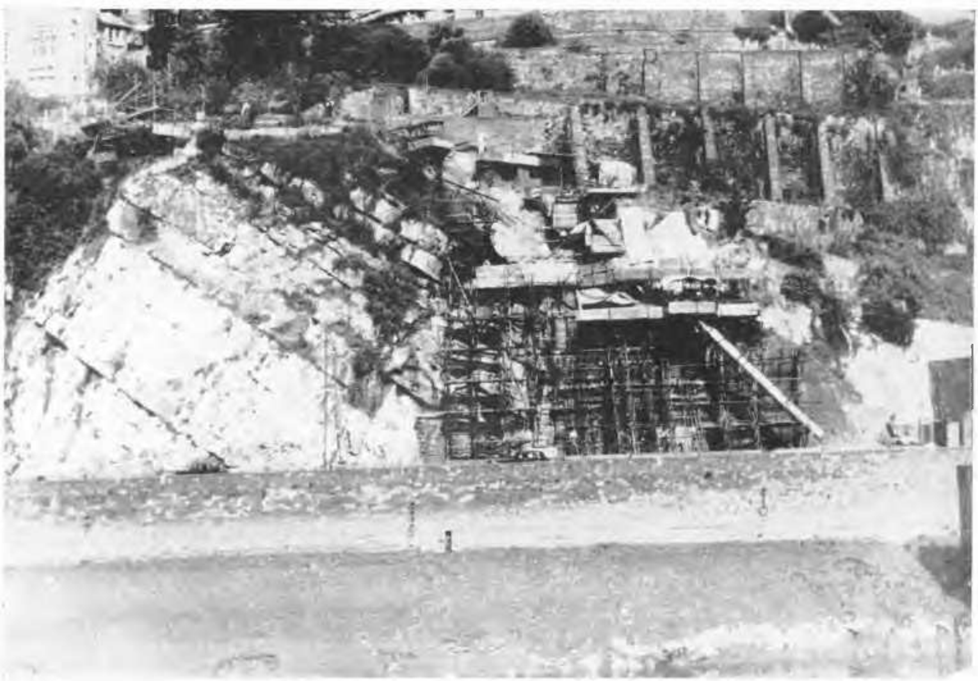

Fig. 2 Elevation of tunnel portal and cliff.
Entrée du tunnel vue de la falaise.

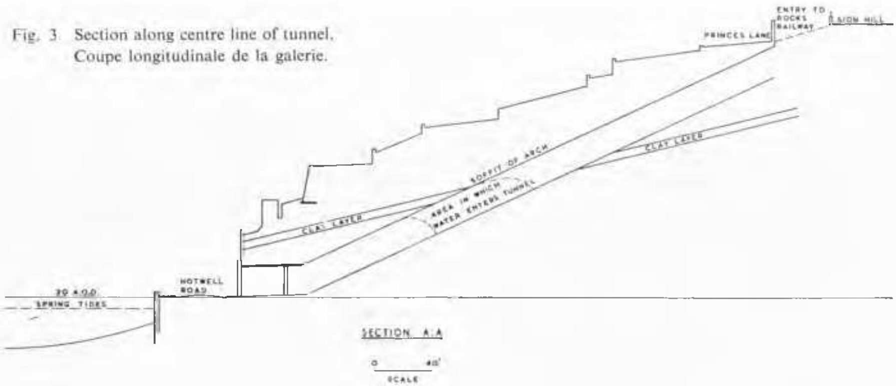

Fig. 3 Section along centre line of tunnel.
Coupe longitudinale de la galerie.

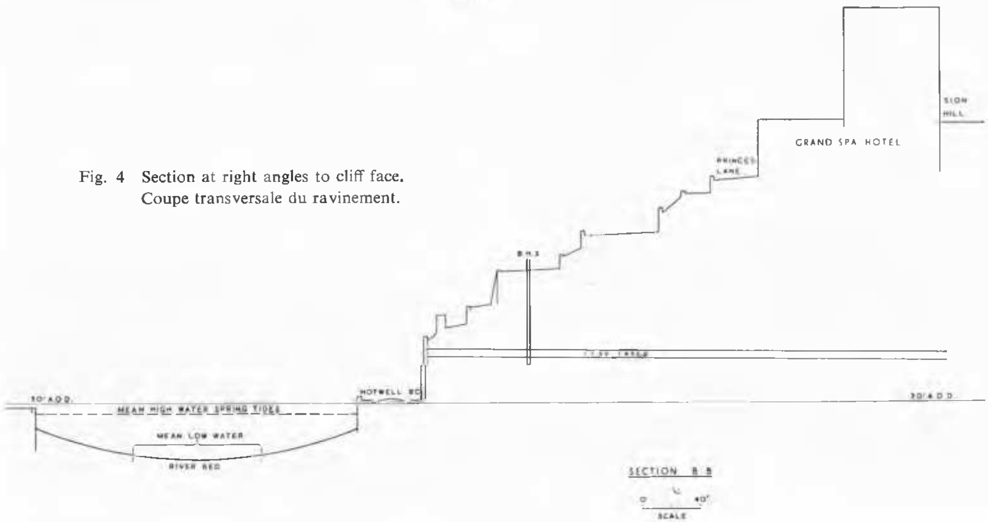

Fig. 4 Section at right angles to cliff face.
Coupe transversale du ravinement.

estimated that the angle of shearing resistance would be about 20°. These angles of shearing resistance are rather low in relation to the plasticity indices of the clays, but they correlate with the results obtained from other clays laid down in Carboniferous times (Henkel and Skempton, 1955).

Analysis of the Slide

Observations made on the site suggested that the cracking of the tunnel portal had been due to the thrust exerted by the overlying limestone blocks sliding obliquely on the surface of the layer of clay. The form of the analysis adopted was dictated by this assumed mechanism of failure and was carried out primarily to see whether thrusts of a reasonable magnitude would be predicted and to examine the effectiveness of remedial measures.

In order to establish the necessary equations, the equilibrium of a large block of limestone sliding on the clay layer with its lower side in contact with stationary limestone was considered. In view of the heavily jointed nature of the limestone, it was assumed that the contact between the large sliding block and the stationary limestone could be approximated to a plane made up of a series of joints. It was also assumed that the resistance between the fixed and moving limestone was due only to the shear strength of the clay which had been found in the joints.

The problem is illustrated in Fig. 5. A clay layer is shown inclined at an angle β to the horizontal and a block of limestone is assumed to slide obliquely across the surface of the clay against a plane boundary of stationary limestone inclined at an angle α to the strike of the clay stratum. P_n is a horizontal force parallel to the clay layer required to prevent movement.

The normal force exerted on the top of the clay layer by a block of weight W will be $W \cos \beta$ while the weight component down the dip of the clay layer will be $W \sin \beta$. The shearing resistance which can be developed at the contact between the limestone block and the clay layer must act to oppose the motion of the block and it will in consequence be directed away from the face of the cliff inlined at an angle α to the line of strike. This shearing resistance will be called S^α and is given by :

$$S^\alpha = c'bl + P' \tan \Phi'$$

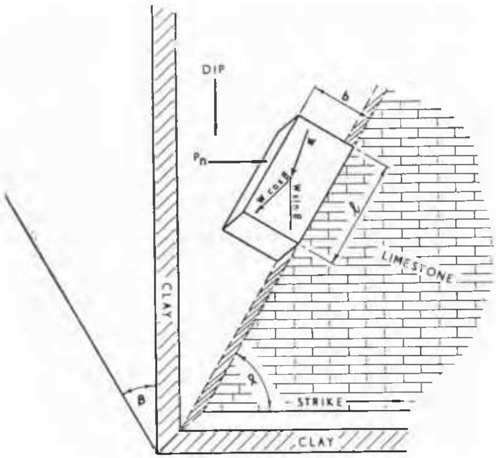

Fig. 5 The mechanism of sliding.
Mécanisme de glissement.

where b and l are respectively the breadth and the length of the block,

P' is the effective force normal to the clay layer,

and c' and Φ' are the effective stress shear parameters.

For convenience in setting up the equations, the pore water pressure at the contact between the base of the limestone block and the clay layer will be expressed in terms of h, the distance normal to the clay layer to which the water would rise. The effective force normal to the clay layer is then :

$$P' = W\cos\beta - blh\gamma_w \cos\beta$$

and $$S^\alpha = c'bl + [W - blh\gamma_w]\cos\beta\tan\Phi'$$

Fig. 6 drawn in the plane of the clay layer shows all the forces which contribute to the equilibrium of the block of limestone.

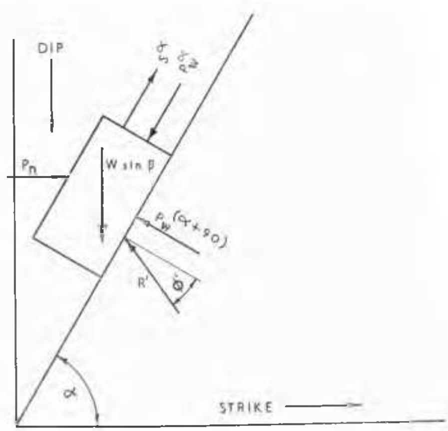

Fig. 6 Forces contributing to equilibrium.
Condition d'équilibre.

The forces P_w^α and $P_w^{\alpha+90°}$ are the forces due to the water pressure acting respectively on the back and lower side of the sliding block and may be expressed as follows :

$$P_w^\alpha = \tfrac{1}{2}bh^2\gamma_w\cos\beta \quad \text{and} \quad P_w^{\alpha+90°} = \tfrac{1}{2}lh^2\gamma_w\cos\beta$$

It has been assumed that the shear strength of the soft clay which coats the joints in the limestone may be expressed in terms of an angle of shearing resistance only, and that the values of Φ' for the upper $\frac{1}{2}$ inch of the clay layer and for the clay in the joints are the same. The effective stress reaction R' on the interface between the moving block and the fixed limestone will thus be inclined at an angle Φ' to the normal to the interface.

The force diagram is shown in Fig. 7 and by resolving in the horizontal direction the magnitude of the force P_n required for stability is found as follows :

$$P_n = \left| W\sin\beta - (S^\alpha - P_w^\alpha)\sin\alpha - P_w^{\alpha+90°}\cos\alpha \right| \tan(\alpha - \Phi') + P_w^{\alpha+90°}\sin\alpha - (S^\alpha - P_w^\alpha)\cos\alpha.$$

When the values obtained above for S^α, P_w^α and $P_w^{\alpha+90°}$ are substituted in this equation, the following expression is obtained :

$$P_n = \left| W\sin\beta - \left\{ \left| (W - blh\gamma_w)\tan\Phi' - \tfrac{1}{2}bh^2\gamma_w \right| \cos\beta + blc' \right\} \sin\alpha - \tfrac{1}{2}lh^2\gamma_w\cos\beta\cos\alpha \right| \times \tan(\alpha - \Phi') + \tfrac{1}{2}lh^2\gamma_w\cos\beta\sin\alpha - \left| \left\{ (W - blh\gamma_w)\tan\Phi' - \tfrac{1}{2}bh^2\gamma_w \right\}\cos\beta + blc' \right| \times \cos\alpha.$$

In the more general landslide case where there is no problem of thrust against structures, the value of the angle α for limiting equilibrium may be found by putting $P_n = 0$.

In the specific problem on the site the volume of limestone which is able to slide on the surface of the clay layer is limited by the outcrop of the clay on the ground surface and in these circumstances the water force acting behind the sliding mass becomes zero. The sliding mass is not rectangular and the force due to the pore pressure at the contact between the sliding mass and the clay layer is better expressed in terms of the area, A, in contact with the clay and the mean head of water $\bar{h}$. The expression for P_n then becomes :

$$P_n = \left[W\sin\beta - \left\{ (W - A\bar{h}\gamma_w)\tan\Phi'\cos\beta + A\cdot c' \right\} \sin\alpha - \tfrac{1}{2}l\bar{h}^2\gamma_w\cos\beta\cos\alpha \right| \tan(\alpha - \Phi') + \tfrac{1}{2}l\bar{h}^2\gamma_w\cos\beta\sin\alpha - \left| (W - A\bar{h}\gamma_w)\tan\Phi'\cos\beta + Ac' \right| \cos\alpha.$$

This expression has been used to calculate the magnitude of the force which might have been exerted on the retaining wall and the tunnel portal by the mass of limestone overlying the clay. Various values of α, which imply different weights of sliding material, have been considered and the pore pressure has been based on a value of $\bar{h}$ equal to the mean of the measured value near the tunnel portal and zero at the surface of the outcrop. Experience in the long term stability of stiff fissured clays (SUKLJE, 1953 ; HENKEL and SKEMPTON, 1955 ; HENKEL, 1957) has indicated that on a geological time scale the cohesion intercept may reduce to zero and for the relatively shallow slip of the limestone behind the portal it is probable that the shear strength of the clay at the time of the

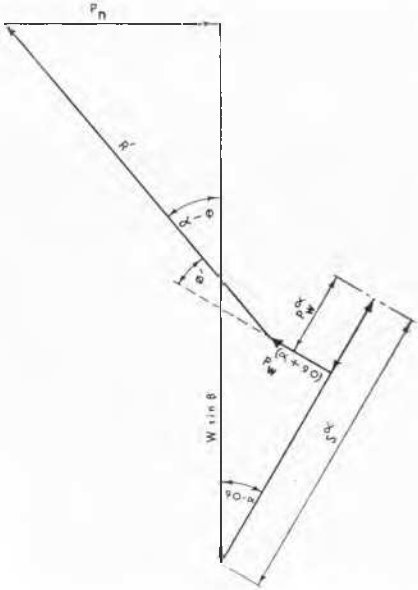

Fig. 7 Force diagram.
Diagramme des forces.

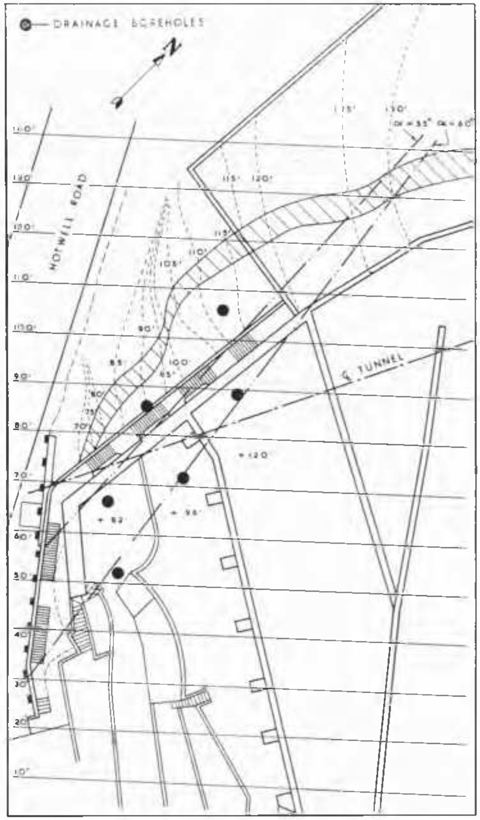

Fig. 8 Large scale plan in vicinity of tunnel portal.
Plan à grande échelle des environs de l'entrée de la galerie.

movement corresponded to the $c' = 0$ case. The significance of the cohesion term in the problem has however been examined in the calculations and the effect of reducing the ground water level by drainage has also been investigated. An angle of shearing resistance, Φ', of 20° has been used in the calculations.

The results of the computations are given in Table 1 below.

Table 1

α°	Wt. of sliding mass) tons	Values of P_n-tons			
		$\bar{h} = 2{\cdot}5$ ft.			$\bar{h} = 0$
		$c' = 0$	$c' = 0{\cdot}05$ t/sq.ft.	$c' = 0{\cdot}1$ t/sq.ft.	$c' = 0$
50	1060	37	− 78	− 140	− 18
55	580	56	− 23	− 101	19
60	268	46	− 2	− 49	22

These calculations indicate that with the measured water levels and assuming that $c' = 0$, a thrust of 56 tons could have been exerted on the portal and wall. This thrust implies a potential plane of movement in the jointed limestone inclined at an angle of 55° to the line of strike of the strata. This plane, commencing at the southern edge of the portal, is shown in Fig. 1 as well as in the larger scale plan, Fig. 8.

It is not possible to estimate with any degree of precision the magnitude of the thrust required to push the tunnel portal away from the cliff face but the calculated maximum value of 56 tons is by no means unreasonable. It will be noted that even a small amount of cohesion is sufficient to make P_n negative, i.e. to ensure stability and the assumption that c' is zero or very small appears to be reasonable.

The position of the plane of movement for $\alpha = 55°$ shown in Fig. 8 corresponds quite well with the area in which damage to the steps and walls above the tunnel were observed and it would seem that the assumed mechanism of movement approximates to the real situation on the site. In these circumstances it is permissible to use the analysis to examine the effect of drainage and, as is shown in Table I, reducing $\bar{h}$ to zero produces a marked reduction in thrust to a value of about 20 tons.

South of the tunnel portal the clay layer dips behind a retaining wall which carries the steps leading up the cliff and finally disappears beneath the level of Hotwell Road on the line where the elevation of the surface of the clay layer is + 30′ *O.D.* The possibility of the slide spreading to involve all the material above this level was then investigated. Calculations were made to find the magnitude of the normal force required for stability in this region and the results are given below in Table II. The maximum measured distance of the water table above the clay layer was used in these calculations.

Table II

$\alpha°$	Wt. of sliding mass in tons	Values of P_n in tons			
		$\bar{h}$ = 5 ft.		$\bar{h}$ = 0	
		$c' = 0$	$c' = 0{\cdot}1$ t/sq.ft.	$c' = 0$	$c' = 0{\cdot}1$ t/sq.ft.
55	5360	445	− 140	170	− 395
60	3720	521	82	307	− 120
65	1730	394	91	239	− 65

The figures in Table II suggest that with the measured ground water conditions and even with a cohesion intercept of 0·1 t/ft.^{2} appreciable thrusts might be applied to the retaining wall carrying the steps. If the reduction of c' to zero is considered, the thrusts become very large. Drainage would substantially reduce the potential thrusts but with $c' = 0$ the force to be taken by the retaining wall would still be considerable. In view of the fact that the site was adjacent to an important traffic artery, a reasonable margin of safety was desirable. It was therefore considered that a considerable reduction in c' should be allowed for, and in these circumstances remedial measures were required in this area. The trace of the plane which gave the largest thrust, i.e. α — 60° is shown on Figs. 1 and 8.

Remedial measures

In order to reduce the potential thrust in the cheapest manner, it was decided to lower the water level in the limestone overlying the clay in the potentially unsafe area and six boreholes were put down on the river side of the α — 60° plane. These boreholes went through the clay layer into the lower limestone and they were backfilled with gravel so that the water above the clay would be drained into the lower limestone. The positions of these boreholes in plan are shown in Fig. 8.

The lowering of the ground water level was not by itself sufficient to eliminate the possibility of an extension of the movement if a considerable reduction in c' was to be considered. It was therefore decided to strengthen the tunnel portal and the retaining wall carrying the steps down to the point where the upper surface of the clay layer passed below the level of Hotwell Road. This was achieved by tying the tunnel portal and wall to the limestone beneath the clay layer. A horizontal reinforced concrete beam carried on small vertical buttresses was cast in contact with the top of the tunnel portal. The beam was extended down the inclined top of the retaining wall carrying the steps and in this region the beam centre line was located a few feet above the top of the clay layer. Inclined boreholes were drilled through the upper limestone behind the beam and were extended through the clay layer and some 20 to 30 feet into the lower limestone. Steel rods were wedged and grouted into the lower limestone and their upper ends were secured to the reinforced concrete beam above the buttresses which took the vertical component of the pull. The concrete beam and the rods were designed to withstand a horizontal thrust of 200 tons. This thrust is not quite as large as that calculated for the area with $c' = 0$ but it was thought that with the high overburden pressures on the deeper portions of the potential failure wedges complete softening with the reduction of c' to zero was not so likely to occur as in the small slide over the tunnel portal.

Conclusion

While no great accuracy can be claimed for the results of the stability analyses carried out in the paper, they do at least show reasonable agreement with the movements observed on the site. At any particular time the amount of softening or reduction in c' the clay bas undergone is difficult to estimate, but it is considered that the long term stability with $c' = 0$ can be predicted with some confidence.

The analysis developed in the paper may also be used to examine the general problem of stability in the area where no retaining walls are present. The calculations show that in the simple case, when $c' = 0$ and the pore water pressure is zero, limestone blocks located on the riverside of a plane on the surface of the clay layer inclined at 52° to the strike would be unstable. In practice, however, the pore water pressure on the interface between the base of a limestone block and the top of clay would not be zero and for positive pore water pressures the limiting value of α would be smaller. Its precise value would depend on the geometry in a particular case but it is significant that a number of natural ground features in the vicinity of the tunnel portal suggest that in the past large scale slides with values of α a little below 50° have occurred. For example, in Fig. 1 the area just North of the tunnel where a footpath winds up the hill has the appearance of having been formed by a slide of this type on the surface of a clay layer.

The fact that the joints in the limestone are coated with clay makes sliding possible on planes defined by fairly low values of the angle α. The same mechanism of failure would however apply to jointed rocks where a high angle of shearing resistance could be mobilised between the sliding and the stable rock. If in the Avon Gorge an angle of shearing resistance of say 35° could be mobilised across the rock joints, the calculations show that for $c' = 0$ and zero pore water pressure the limiting value of α for stability would be 62°.

It would therefore appear that theoretical consideration in terms of effective stress, of the possibility of the oblique sliding of jointed rocks on an inclined clay layer is of considerable help in understanding the phenomenon and also enables some quantitative deductions regarding the stability of the rocks to be made.

Acknowledgements

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