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ON THE FAILURE OF CUT-OFF "SHIRASU" SLOPES

切土シラス斜面の崩壊について

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1. INTRODUCTION Collapse of Shirasu slopes has been observed in many forms; slope failures have been classified and the relative frequencies of occurrence of the types compiled (Yamanouchi, 1972). The majority of cases studied (61%) involved mass movements on the shoulder, at the toe, on the face of the slope or total slope. These failures are discussed with reference to mechanisms of mass movement consistent with surfaces of discontinuity observed after collapse.

2. OBSERVED SURFACES OF DISCONTINUITY Mass movements in Shirasu cuts generally occur along two easily recognized boundaries - one sloping approximately parallel to the cut face and the other nearly perpendicular (Plates 1 - 4), although sometimes a transition occurs. For convenience these surfaces of discontinuity will be referred to as the A and B surfaces respectively. When the mass movement involves the total height of the slope a B surface does not limit the extent of the slip; however B surfaces are still apparent on the failed slope (Plate 4). When scour at the toe precedes the mass movement B surfaces are not predominant (Plate 5). The size of A and B surfaces is variable. B surfaces of the order of centimeters create irregularities on the A surface. Major B surfaces are very irregular. While the A surface is generally planar, the intersection of the B surface with the face of the cut may be planar (Plate 4) or curved (Plates 1, 2 and 3). When mass movements occur near the toe of the cut a third surface of discontinuity is most likely present. Where erosion occurs this surface is horizontal, but in other cases it is obscured by the fallen mass. Some shoulder movements exhibit surfaces of discontinuity that do not appear to be either A or B surfaces, but shear slip surfaces. However even some shoulder movements exhibit both A and B surfaces.

3. THEORETICAL SURFACES OF DISCONTINUITY The results of compression tests on undisturbed Shirasu samples are consistent with the rupture theory of Mohr. With appropriate choice of parameters a straight line envelope can be fitted to compressional tests (Coulomb-Navier & Modified Griffith Theories). To incorporate tensile strengths a curved envelope is necessary however. Axial strains at rupture upto 8% (Yamanouchi & Haruyama 1969) have also been observed. Therefore a theoretical study of the surfaces of discontinuity should include rupture surfaces at small strains (brittle cracking) and also large strains (plastic flow or shear). If the unstable mass is assumed to be in the state of critical plastic equilibrium the surface of discontinuity will not appear like either

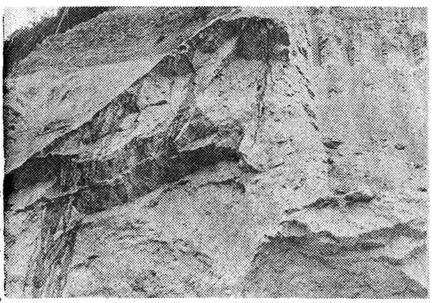

Plate 1.

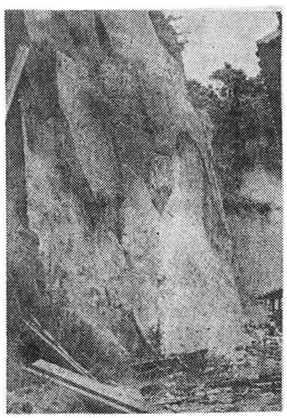

Plate 2.

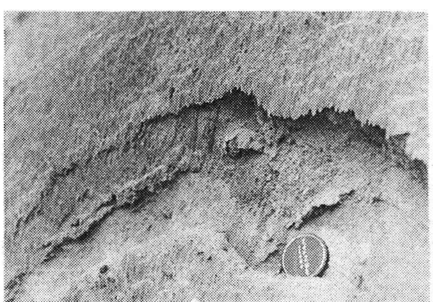

Plate 3.

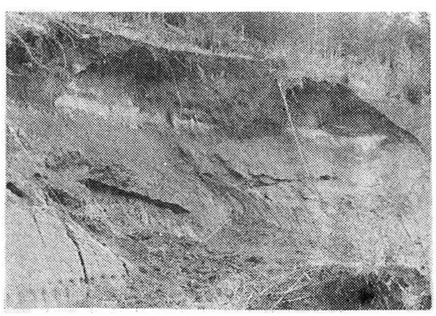

Plate 4.

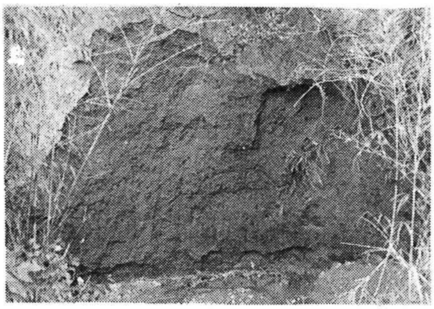

Plate 5.

Plate 6.

the A surface or the B surface. By confining this stress state near the face the thickness of the plastic zone predicted by the Mohr theory is evident (Fig. 1). However A surfaces are not compressive shear surfaces. The direction of the B surface near the cut face and its roughness is predicted well by a parabolic Mohr envelope. The discontinuity between the A and B surfaces is not predicted by this theory. The restraint conditions at the edges of the unstable mass will control the shape of the intersection between the B surface and the cut face. Greater restraint will cause a curved intersection and less restraint will cause a planar intersection as described (Plates 1, 2, 3, 4).

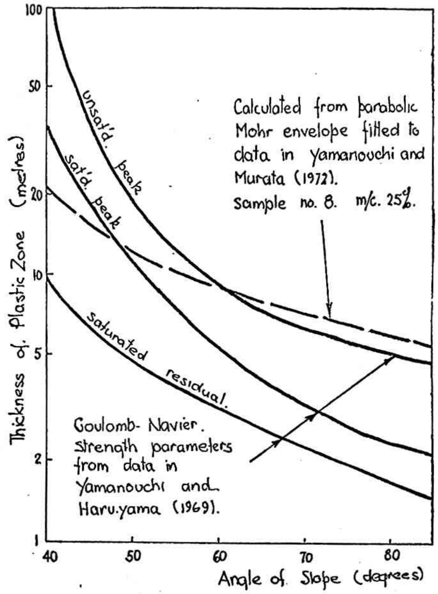

Figure 1.

4. <u>FAILURE MECHANISM IN A COHERENT MASS</u> Failure mechanisms based upon (i) critical plastic equilibrium, (ii) Griffith theory of fracture initiation or (iii) modified Griffith theory applied to rupture conditions - do not predict the observed surfaces of discontinuity except where erosion has occurred at the toe and where the mass movement is confined to the shoulder. The gradual change of strength parameters due to the presence of water, creep strain or weathering will not explain this discrepancy even though the critical presence of water is well known. This last fact indicates that the presence of water is made critical by a further factor. This is considered to be the joint pattern.

5. <u>JOINT PATTERNS IS SHIRASU</u> The presence of a joint systems more or less parallel to the cut face is indicated in Plates 1, 2, 3, & 7. Failures dependent upon this type of joint pattern have been reported for granite (Terzaghi 1962a), weathered granite (Lumb 1962) decomposed granite gneiss (St. John et al. 1969). The critical presence of fissures is noted also for overconsolidated clays (Skempton & LaRochelle 1965). In granite the spacing of sheet joints increases from a few cms. near the face to the order of metres at a distance approximately 12 metres from the cut face (Terzaghi 1962). These joints were open over a large proportion of their total area. In Shirasu similar cracks also persist to some depth (see Plate 7). The increase of crack spacing with depth is also shown in Plates 1 & 3. This crack system in Shirasu would be expected to develop from minute cracks in the original structure due to the reduction in horizontal stress, increased shearing stress behind the cut face and water pressure.

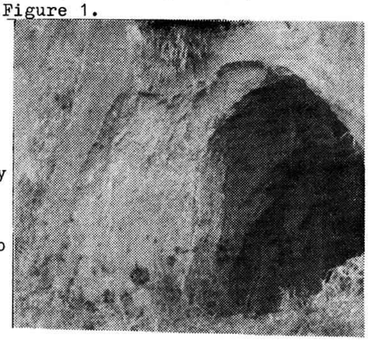

Plate 7.

6. <u>FAILURE MECHANISM INCORPORATING JOINTS</u> This must include both the process of stable crack growth followed by the process of mass movement. The critical stress at which cracks inclined to the direction of major principal stress will propogate, is less than 60% of the laboratory rupture strength (Ingles and Neil 1972). Even when compressive stresses are small cracks would propogate according to the Griffith criterion under water pressure alone (Jaeger 1969). For the strength parameters measured in Shirasu, a head of water less than ½ metre would cause propogation. Glücklich 1971 has demonstrated neutral equilibrium under simple compression of Griffith type material. However the heterogeneous nature of Shirasu would limit crack growth. During periods of rainfall cracks would grow. The cyclic straining due to higher stress and lower strength would cause gradual increase of non-reversible

strain is the coherent material which would eventually fail at residual strength conditions. This mechanism accounts for the time lag between construction and failure, failure under wet conditions, the appearance of the A and B surfaces and the discontinuity between them. The critical defect or crack configuration that will result in mass movement can be defined by considering the equilibrium of the mass shown in Figure 2. Certain conservative simplifying assumptions are made to facilitate calculations:-
the B surface is a pure tensile plane; the A surface is fully developed and has no coherence at the moment of mass movement; the Shirasu is saturated; at the toe of the unstable mass a compressional state of critical plastic equilibrium exists; the failure surface at the base is a plane; large strains have accumulated at the toe prior to the slip, and the resistence to movement along the sides of the mass is small in proportion to the resistance at t he toe. Due to the second, fifth and seventh assumptions, the length of the critical crack above the failure plane will be greater in reality than that predicted. The results of the analysis are given in Figures 3, 4, & 5. Figure 3 indicates the critical crack length at a certain depth. If a crack longer than this intersects the failure plane mass movement will occur. The probability of failure is the probability that

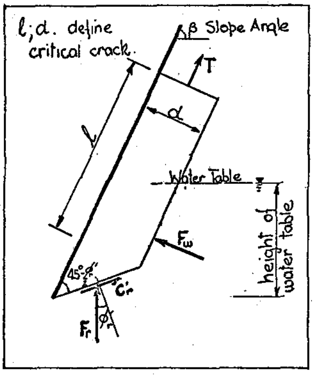

FIG. 2. Stability Analysis Forces

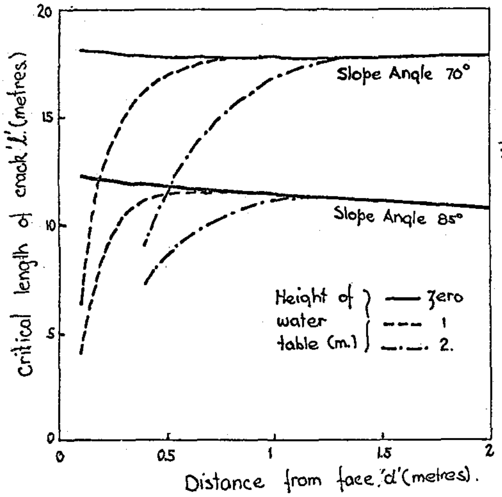

FIG. 3. Critical crack definition. l.'d'.

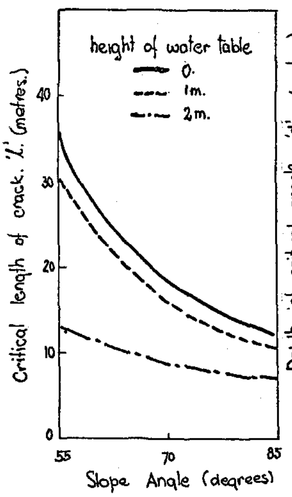

FIG. 4. Crack Length Vs Slope

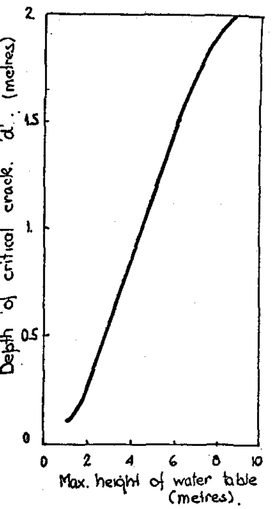

FIG. 5. Limits of analysis.

a crack will propogate to this length. The major effect of water is shown by Fig. 3. and the effect of slope angle is shown in Fig. 4. When a water pressure is present this mechanism predicts the depth of A surface nearer that observed than the prediction based upon critical plastic equilibrium (Fig. 1). A design method for slope drainage can be based upon this type of analysis. For the strength parameters considered the embankment height which would limit stresses to less than the critical value for crack growth is approximately 5 metres. By extending the analysis beyond the limit defined by the assumption of compressive stress on the failure plane (Fig. 5), the curves for different water table heights in Fig. 3 can be extended; a bermed slope can thus be designed with a face drainage system to ensure stability of higher slopes.

7. <u>CONCLUSIONS</u> (a) The surfaces of discontinuity observed after mass movements of Shirasu can be classified into four types;- shear slip surfaces under compression (shoulder failures); shear slip surfaces under tension (failures preceeded by toe erosion); A surfaces; and B surfaces. (b) Mohr's theory of rupture predicts the observed failure planes for shoulder failure (Coulomb-Navier criterion) and toe failures preceeded by erosion (Modified Griffith criterion). The latter case is almost identical to failures in loess reported by Lutton (1969). (c) In order to account for observations of A and B surfaces, a joint system similar to that observed is incorporated into the failure mechanism. This predicts the critical defect (crack) size for failure and the major importance of water. (d) The assumed failure mechanism can be used for the conservative design of stable slopes in brittle material. In order to predict the probability of failure of high undrained slopes, joint surveys in Shirasu slopes are required to define existing

crack patters. (e) The analysis presented can be refined to give a less conservative estimate of slope stability when more information is available regarding the slip surfaces at the base of the toe, the crack patterns in existing cuts, the water table levels due to heavy rain, and the horizontal stresses relieved by excavation.

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