Slope Indicator Measurements of Subsurface Movement in Gully Walls

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This article is reprinted from the TRANSACTIONS of the ASAE (Vol. 29, No. 4, pp. 982-987, 1986)
Published by the American Society of Agricultural Engineers, St. Joseph, Michigan

ABSTRACT

SLOPE indicator access tubes were installed in gully banks along an actively eroding channel and upstream of an actively advancing gully headcut in western Iowa. Deflection of these aluminum access tubes due to soil movement was measured with a slope indicator probe capable of sensing small horizontal displacement. Surface soil movement adjacent to the channel was toward the channel; deflections of the tubes at greater depths were generally toward the channel and indicated slab or toppling failure. Bank failure was related to high peak flows and passing channel scarps that decreased bank stability, especially during spring runoff. All recorded bank failures showed greatest displacement at the surface with most of the movement occurring above a depth of 3 to 4 m (10 to 13 ft). At distances of 6 and 10 m (19 and 33 ft) from the channel most soil movement occurred at depths of 3 to 7 m (10 to 24 ft) rather than at the surface. All failure depths were less than the gully depth, while soil movement exceeded gully depth. This indicated that access tubes should be installed as much as 5 m (16 ft) below the channel bottom to record complete movement. Results indicate that this procedure can be used to quantify bank conditions leading to faillure.

INTRODUCTION

Gully erosion occurs throughout the world, and is often severe on loess soils that constitute prime agricultural land in the world. The unique physical properties of these soils make them highly susceptible to gully erosion and cause gully banks to be vertical or nearly vertical.

Failure of gully banks is influenced by many factors (Bradford and Piest, 1977). These include the weight of the soil mass, the weight of water in the soil mass, and seepage forces. The forces resisting failure are determined by cohesive and frictional properties of the soil which, in turn, are affected by wetting-drying and freezing-thawing cycles. The earliest visible signs of bank failure are cracks at the soil surface caused by tensile stresses. These cracks decrease the stability of the bank by reducing the effective resisting surface area of the susceptible soil mass. Infiltrating water reduces the cohesion of the soil below the cracks and increases por water pressures.

Gully Bank failure processes are not well understood. Bradford and Piest (1977) observed that for gullies near Treynor, IA, massive bank slumping was almost always preceded by small scale undercutting at the base of the slope. This undercutting can be caused by the erosive action of flowing surface water, 'popout' failure, seepage, or plunge pool erosion. The passing of an upstream eroding channel scarp increases gully bank instability (Little et al., 1982). The plunge pool action of an advancing scarp forms a deep scour hole which contributes to bank instability, even though it is subsequently backfilled. Any process that causes channel degradation decreases bank stability because stability is inversely proportional to bank height (Lohnes and Handy, 1968). The analysis of bank failure mechanisms is further complicated by structural discontinuities such as vertical cleavage planes, anisotropy in loess derived alluvium, changes in shear strength due to moisture content changes, and, as stated by Handy (1973), the possible collapse of loess upon saturation. Three failure processes commonly occurring in the silty alluvium of western Iowa are: deep seated circular arc failure, slab failure, and a combination of base collapse or "popout failure" and slumping of the undermined bank (Bradford and Piest, 1980).

GROUND MOVEMENT AND IMPENDING FAILURE

Henderson and Matich (1962) stated that, in unstable earth slopes, movement will often start well in advance of failure. Slope indicators were used as a warning device for impending failure and as an indicator of the nature and depth of ground movements. They reported bank movements, near Homer high level bridge in Ontario, of up to 1.0 cm (0.4 in.), which suggested elastic movements in the bank corresponding to changes in canal water levels. Soil movement in Iowa and Ontario will be different since soils and conditions are not the same, but the potential of the slope indicator to measure soil displacement was demonstrated.

The objectives of this study were to evaluate the use of slope indicator tubes for determining gully bank failure and to determine the failure mechanisms that were operative with the passing of a channel scarp. Ground movement near a gully bank may take place prior to the actual failure, and its determination may indicate the

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Article was submitted for publication in January, 1986; reviewed and approved for publication by the Soil and Water Div. of ASAE in May, 1986.

Salaries and research support also provided by State and Federal funds appropriated to the Ohio Agricultural Research and Development Center and the Ohio State University.

Approved as Ohio State University Journal Article No. 12-86.

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potential for bank failure as well as the depth and the type of failure process. In this study, aluminum slope indicator tubes were installed along two gullies in western Iowa.

SLOPE INDICATOR INSTRUMENT AND MEASUREMENTS

The slope indicator consisted of a pendulum-actuated Wheatstone bridge that measured small horizontal displacement in an access tube. The waterproof cylinder containing the pendulum was lowered in the access tube. The access tube was a four-grooved aluminum casing of 8.6 cm (3.4 in.) diameter installed in a 15 cm (6 in.) borehole which was backfilled with sand. These flexible tubes deflected as soil movement occurred. The instrument was activated with an electrical current closing a relay that completed a circuit between the conductor tip of the pendulum and a precision wound resistance coil. When the circuitry is balanced (no current through the galvanometer) the inclination of the instrument is proportional to the potentiometer dial reading. The accuracy of the series 200-B slope indicator, which was used, was 1:1000 or 3 min. of arc, corresponding to a displacement of 10 mm per 10m (1 in. per 100ft) (Slope Indicator Company, 1962).* Currently (1985) the Slope Indicator Company is quoting the accuracy as 1 mm per 10 m (1 in. per 1000 ft).

Measurements were taken at depth intervals of 0.5, 0.6, or 0.8 m (1.5, 2.0, or 2.5 ft) in each of the four alignment grooves for tube depths of 7 to 12 m (24 to 40 ft). Data were collected at irregular time intervals, mainly after major rainfall and runoff events and snowmelt.

FIELD SITES

Two unstable gully areas in Pottawattamie County, Iowa, were selected for the study. In March/April 1978 seven tubes were installed on the flood plain along Keg Creek, east of McClelland, in the locations shown in Fig.1. Keg Creek is an entrenched 6 to 9m (20 to 30 ft) deep, steep-sided water course with a 230 km²(90 mi²) drainage area above the location of a 1.5m (5 ft) scarp. Tubes were installed to a depth equal to or greater than the channel and the estimated depth of the subsequent scour hole associated with the passing of a channel scarp. Three tubes were placed perpendicular to the channel to determine the area influenced by soil movement.

Five tubes were installed in May 1978 just upstream of the active gully in watershed 1 near Treynor. Their locations are shown in Fig.2. The water way immediately above the 6m (20 ft) deep gully was incised 2 m (7 ft) in the floodplain. Watershed 1 is a 30 ha (74.5 ac) catchment with average slopes of 9 percent and planted to continuous corn on the contour since 1964. It has an actively eroding gully which was fully instrumented to measure runoff and sediment yield (Piest et al., 1975).

Dates and field observations concerning installation, failure, scrap movements, and the expected direction of failure are shown in Table 1 for both sites.

*The use of the product name is included for reader's convenience and does not constitute an endorsement of the equipment by Ohio State University or USDA.

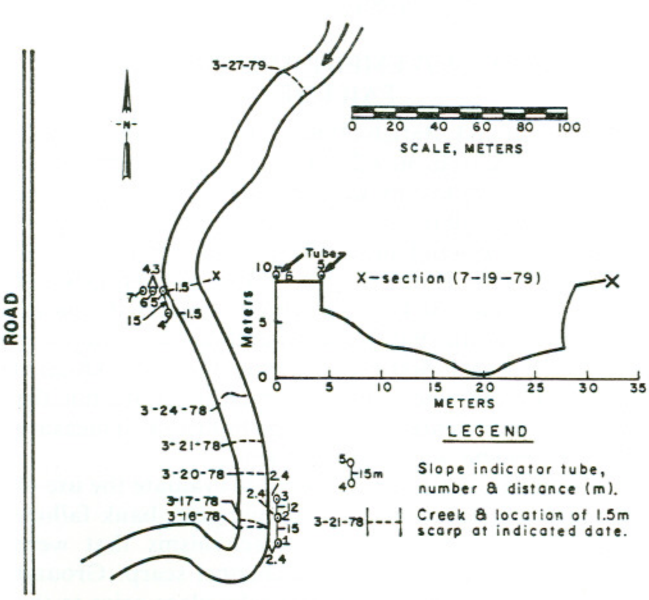

Fig. 1—Location of slope indicator tubes along Keg Creek.

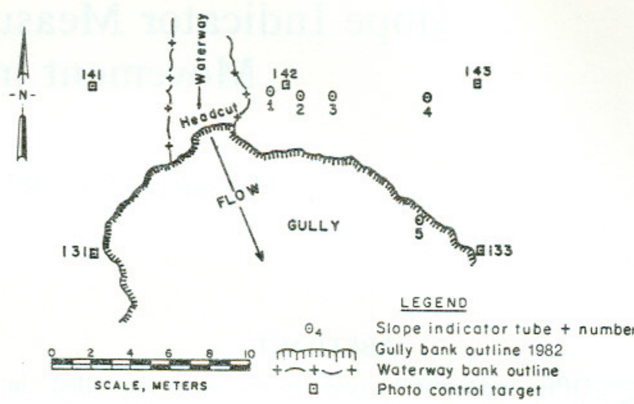

Fig. 2—Location of slope indicator tubes in Watershed 1.

ANALYSIS AND RESULTS

A computer program was used to calculate and plot the deflection with respect to the original position for each tube and for each measurement date as a function of depth. The movement at the surface was plotted for each tube using polar coordinates to show the path followed by the surface portion of the tubes. Shaded areas in these plots represent the accuracy limits of the instrument with respect to the initial position of the tubes.

The following assumptions were made for the analysis:

1. No movement occurred at the base of the tubes.
2. The base of each tube was about one full measurement interval below the lowest reading.
3. The few erroneous values could be replaced by the average of the deflection of the adjoining depths.
4. Some data for the top portions of tubes which were exposed in cracks were obtained by linear interpolation if measurements were taken at later dates. Where this was not possible they show up as vertical lines in the graphs.

Fig.3 shows the horizontal deflection in E-W direction for tube 6 along Keg Creek. The shaded area indicates that most of the deflection in 1978, 1979 and 1980 was attributable to or within the range of instrument inaccuracy. The maximum westward movement away

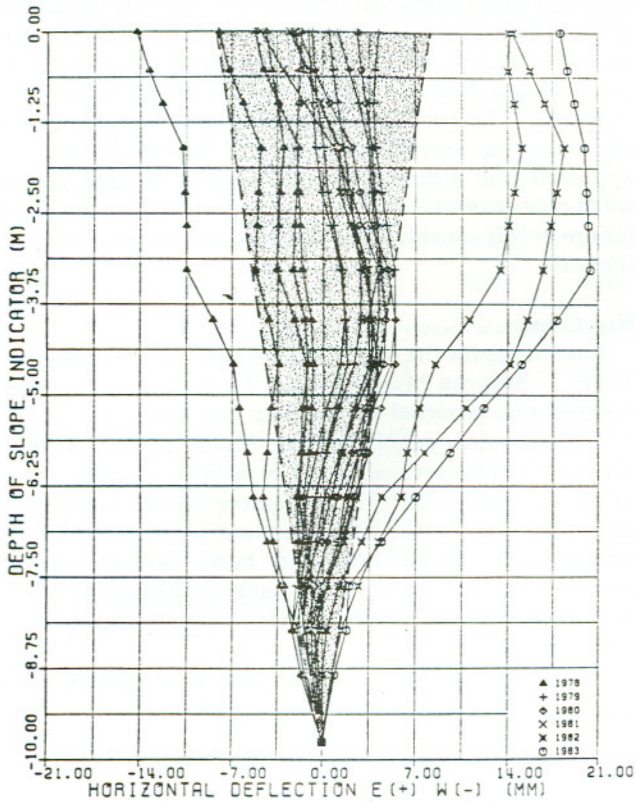

Fig. 3—East-west deflection for tube 6 along Keg Creek.

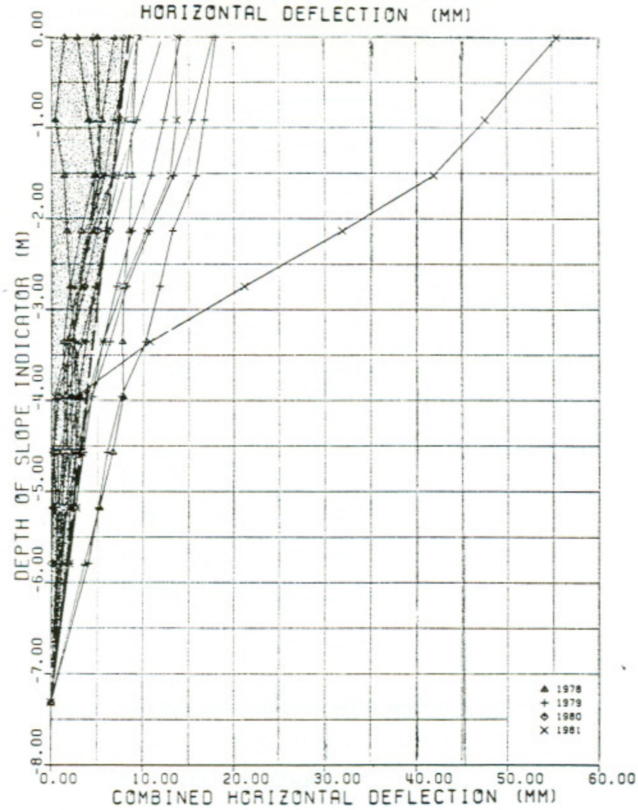

Fig. 4—Total deflection for tube 1 of watershed 1.

from the channel in 1978 (Fig.3) was probably the result of settlement of the sand backfill. Defliction toward the channel in 1981 was probably a valid response to bank failure. The deflictions toward the channel in 1982 and 1983 are not large enough to rule out instrumentation inaccuracy as the possible cause. Fig.4 and 5 show the total horizontal deflections for tube 1 of watershed 1 and tube 5 show the total horizontal deflections for tube 1 of watershed 1 and tube 5 along Keg Creek. The total or combined horizontal deflection-curves generally coincide with the direction which is at right angles to the gully. For tube 1 of watershed 1 (Fig.4) some of the deflection occurred in response to the approaching headcut and total failure took place in August 1981. In Fig.5 the scale has been greatly reduced to display the large deflection for tube 5 of Keg Creek with initial (1979) and final failure in 1982. Fig.6 shows the movement of tube 1 of watershed 1 at the surface assuming straight line movements between points.

Watershed 1

The results of the analysis for watershed 1 are shown in Table 2. The depth of failure was usually between 3 and 4 m (10 and 13 ft) with the maximum displacement taking place at the surface. Final failure of tubes 1, 2 and 5 (Tables 1 and 2) was in the direction expected from the position of the tubes with respect to the gully.

The greatest displacement per unit depth occurred where the failure surface intersected with the tube. In watershed 1 this often occurred at depths between 1.5 and 4 m (5 and 13 ft).

For tubes 1 and 2 the general direction of movement at the surface, during the two years before failure, was in the direction of failure (Fig.6). This could indicate that tension in the ground increased before final failure occurred.

Most failures occurred during spring runoff, sometimes due to snowmelt, oftem in combination with rainfall and a partially frozen soil. Tubes 1 and 2 of watershed 1 failed in August 1981, after a 44 mm (1.72 in.) rainfall. The peak runoff was 0.9 m/s (33 cfs) which

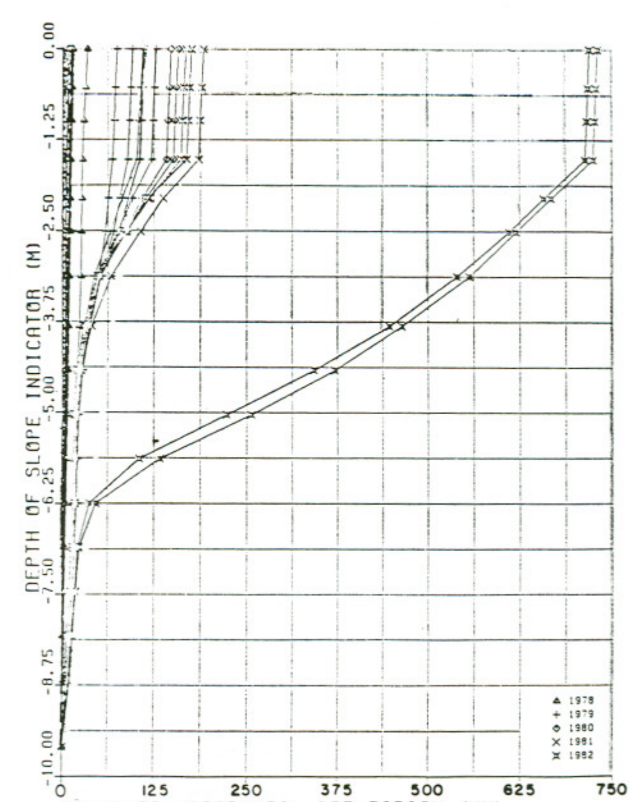

Fig. 5—Total deflection for tube 5 along Keg Creek.

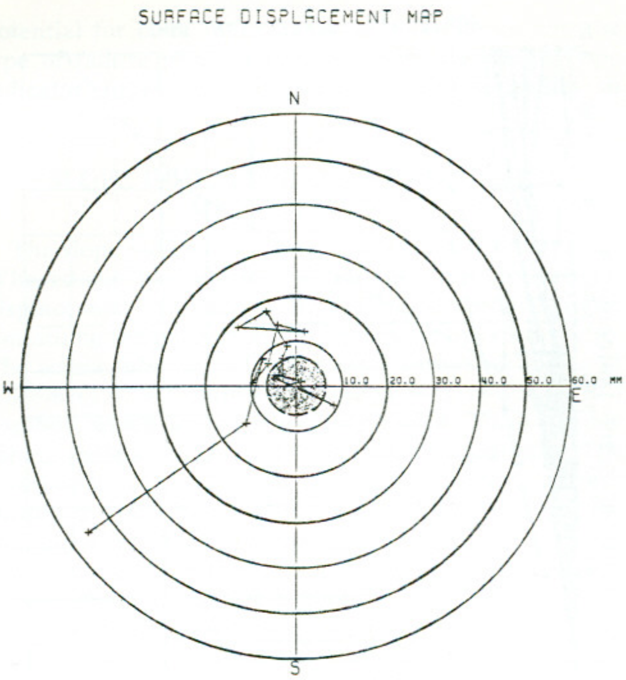

Fig. 6—Path of surface deflections for tube 1 of watershed 1.

was exceeded 10 times in the period 1978-1982 indicating bank failure was not related to peak flow or season. The general direction of movement for tubes 1 and 2 was in the expected direction during the one to two years prior to failure. This period of tube movement in the direction of failure was considerably shorter for other tubes. It appeared that spring snowmelt favored sudden failure while other runoff/rainfall events later in the year caused failure only if considerable tension was already present in the soil.

Keg Creek

The results for the tubes along Keg Creek are shown in Table 3. Between March 18 and 24, 1978 massive bank failures were reported for the area near tubes 1,2 and 3. A large snowmelt runoff event on March 18 and 19, 1978 caused these failures while a 1.5 m (5 ft) channel scarp moved upstream 70m (225 ft) passing tubes 2 and 3. The passing of the scarp with attendant [3 m (10 ft) field measurement] scour hole and bank failures caused ground movement toward the gully resulting in a new channel equilibrium. Tube 3 failed with the top 3 m (10 ft) completely exposed.

On March 17 or 18, 1979 the area near tubes 4, 5, 6 and 7 was subjected to massive bank failures due to

TABLE 1. SLOPE INDICATOR TUBES OBSERVATIONS AND DATES FOR WATERSHED 1 AND KEG CREEK

Tube no. —	Tube depth, m	Measurement period	Initial failure date	Exposed depth, m	Final failure date	Date scarp passed	Expected failure direction
Watershed 1:							
1	7.3	5-78/11-80	Aug. 81	1.5	3-19-82	NA	SSW
2	7.3	5-78/11-81	Aug. 81	1.5	3-19-82	NA	SSW
3	7.3	5-78/11-81	3-19-82	1.5	<July 83	NA	SSW
4	7.3	5-78/ 7-83	—	—	—	NA	SW
5	7.3	5-78/11-81	May 78	2.0	spring 82	NA	SW
Keg Creek:							
1	9.7	3-78/ 4-79	—	—	—	<3-16-78	W
2	12.2	3-78/ 4-79	—	—	—	3-17-78	W
3	9.7	3-78/ 6-78	—	3.0	3-19-78	3-19-78	W
4	9.6	4-78/11-78	—	—	3-19-79	3-18-79	E
5	9.6	4-78/ 8-82	3-18-79	3.0	3-25-82	3-18-79	E
6	9.7	4-78/ 7-83	—	—	—	3-18-79	E
7	9.7	4-78/ 7-83	—	—	—	3-18-79	E

TABLE 2. RESULTS FOR TUBES OF WATERSHED 1

Item	Watershed 1 tube number 1	2	3	4	5
Greatest displacement measured, mm	56	25	9	14	28
Depth at which the greatest displacement occurred, m	0	0	0	0	0
Depth at which failure took place, m	4	4	—	—	3
The depth at which the slope of the tube had changed most, m	1.5-4	0-1.5	0-2	2-4	1-3
Inclination of the tube at its bottom end, %	0.03	0.04	0.04	0.02	0.02
Direction and displacement (mm) distances during given periods					
initial	ESE 8	NE 15	ESE 9	SW 8	WNW 10
5-78/11-78	NW 13	WNW 18	NW 10	E 8	SSW 25
11-78/ 4-79	—	—	—	—	—
4-79/12-79	—	—	—	—	—
12-79/ 4-80	SSW 8	—	—	—	NE 8
4-80/ 9-80	—	—	—	—	—
9-80/ 4-81	—	—	—	—	—
4-81/11-81	SSW 15	—	S 8	—	—
11-81/ 7-82	—	—	—	—	—
7-82/ 8-82	—	—	—	—	—
8-82/ 7-83	—	—	—	—	—
failure	SW 42	SSW 18	—	—	SSW 14

TABLE 3. RESULTS FOR TUBES ALONG KEG CREEK

Item	1	2	3	4	5	6	7
			Keg Creek tube number				
Greatest displacement measured, mm	8	30	46	36	732	20	23
Depth at which the greatest displacement occurred, m	3.7	0	0	0	0	3.3	3.3
Depth at which failure took place, m	—	3	8.5	6.4	—	—	—
The depth at which the slope of the tube changed most, m	6-10	8-11	0-3	0-8.5	0-6	3-7	3-6
Inclination of the tube at its bottom end, %	0.03	0.03	0.03	0.02	0.10	0.02	0.03
Direction and displacement distanct (mm) during given periods							
Initial	—	—	W 41	—	SE 8	WNW 8	—
5-78/11-78	—	—	SW 8	—	ESE 25	NNW 13	WSW 13
11-78/ 4-79	—	—	—	—	E 43	E 8	ESE 10
4-79/12-79	—	—	—	—	SE 51	SSW 13	—
12-79/ 4-80	—	—	—	—	SE 20	—	—
4-80/ 9-80	—	—	—	—	E 10	—	—
9-80/ 4-81	—	—	—	—	SE 10	—	—
4-81/11-81	—	—	—	—	SE 8	—	—
11-81/ 7-82	—	—	—	—	ESE 546	E 18	—
7-82/ 8-82	—	—	—	—	SSE 15	—	—
8-82/ 7-83	—	—	—	—	—	—	NNE 8
failure	—	WNW 25	--	E 30	ESE 646	—	—

snowmelt, thawing of ground frost, light rain, and a 1.5 m (5 ft) channel scarp advancing through this channel reach. Tube 5 experienced an initial failure and a crack developed which ran through the centerline of the tube. This is represented by the vertical line from 0 to 1.5 m (0-5 ft) depth in Fig.5. In the period preceding failure (5-8-1978/11-29-1978) tube 5 showed movement of about 25 mm (1 in.) in the direction of the failure. This displacement may be seen as an indicator of tension in the ground and as a possible warning for impending failure.

During the period when the March 1979 failures occurred, tubes 6 and 7 showed a movement of 8-10 mm (0.3-0.4 in) towards the gully (Table 3). Tube 6 showed a more significant displacement of 18 mm (0.7 in) in spring 1982 (Table 3) when the big failure of tube 5 occurred.

For tubes 1, 6 and 7 the maximum displacement occurred at depths of 3.7 and 3.3 m (12, and 11 ft). The top 2.0 to 3.5 m (7 to 11ft) of tubes 6 and 7 were displaced by an almost equal horizontal distance toward the gully while most of the movement took place between 3 and 7 m (11 and 24 ft). For tube 2 the maximum displacement per unit depth occurred between 8 and 11 m (27 and 37 ft) and for tube 1 between 6 and 10 m (20 and 32 ft). Only tube 5 showed movement which was fairly uniform with depth and reached depths of about 6 m (20 ft) (Fig.5). Displacement during failure seemed to differ from ground movement before failure, especially at greater distances from the gully, where more movement toward the gully occurred at depths of about 3.5 m (11 ft) than at the surface. A more complete description including deflection graphs of all tubes was presented by Van der Poel (1985).

GENERAL OBSERVATIONS

The initial movements of the tubes were fairly random and could indicate an adjustment of the position of the tube due to shifting of the sand which was used to fill the space between the casing and the borehole wall.

The assumption of no movement at the bottom of the tubes seemed to be invalid in several cases where the profile gradients at the greatest depth were large. This was most obvious for tubes 2 and 3 of watershed 1, and tubes 1,2, 5 and 7 along Keg Creek. To check whether basal displacement of the tubes took place, the locations of the tops of tubes 4, 5, 6 and 7 along Keg Creek were surveyed. Although only a limited amount of data was collected, the results seemed to indicate a shift of the base of the tubes toward the gully.

The movement of the ground close to a gully head or bank was toward the gully. The deflections at greater depths were mostly in the same direction as those at the surface,but of smaller magnitude. The top portion of the graphs for tubes which were partly exposed in cracks were not considered as showing the actual ground movement.

Failures of the gully bank were observed to be related to high runoff events, especially those during spring snowmelt, and to the passing of an upstream- advancing scarp. Several failures along Keg Creek were related to the passing of a channel scarp that decreased the stability of the gully banks due to increased bank height.

In several cases there was evidence of ground movement toward the gully in the period preceding the final failure. This indicated a build-up of tension in the ground, which in some cases also manifestd itself by visible cracking at the surface. In the two cases where measurements were taken after the initial failure there was a continuing movement toward the gully.

All the recorded failures showed the greatest displacement at the surface and a fairly definite depth above which most of the movement due to failure took place. This depth varied between 3 and 4 m (10 and 13 ft) for watershed 1 and for tube 3 along Keg Creek, and was 6.3 m (21 ft) for tube 5 along Keg Creek .This, as well as the development of cracks, indicated failure due to the build-up of tension and possibly slab failure. Rotational slip failure did not seem to be a likely process here since, for rotational slips, tension cracks would not usually develop prior to failure but only during failure or immeditately prior to failure. Cracks, however, were observed regularly before actual failure took place. In rotational slip failure the highest stress occurs near the base of the failure mass; once localized failure develops, it may slowly propagate upwards along the failure plane until complete failure occurs.

At greater distances from the gully bank, most of the movement occurred at depths between 3 and 7.3 m (10 and 24 ft) rather than on the surface. All failure depths were less than the depth of the gully, while ground movement exceeded the gully depth. The 3 m (10 ft) scour hole associated with the passing channel scarp effectively increased gully bank height and reduced gully bank stability, which may account for ground movement that exceeded gully depth.

CONCLUSIONS AND RECOMMENDATIONS

Slope indicator measurements indicated movements in the ground prior to failure and revealed depths of failure which were less than the gully depth, while ground movement took place at depths exceeding the gully depth. The measurements and observations indicated slab failure rather than rotational slip failure. Failures were often found to occur during the brief periods of snowmelt and passing of scraps that increased gully bank conditions leading to failure. Full development of this potential, however, will depend upon continued procedural evaluations.

In further research, slope indicator tubes should be installed deeper - at least 5 m(16 ft) below the bottom of the gully. Deflectons should be measured at regular intervals, e.g. once every two weeks if no major runoff event occurs. Random movement can then be more easily distinguished from movement related to impending or actual failure. To evaluate movement due to swelling and shrinking of the soil, soil moisture should be measured along with slope indicator deflections.

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