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SOME SLOPE MOVEMENT PROBLEMS IN WINDSOR COUNTY, VERMONT, 1984

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

CONTENTS

ILLUSTRATIONS

TABLES

SOME SLOPE MOVEMENT PROBLEMS IN WINDSOR COUNTY, VERMONT, 1984

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Abstract

An abnormal number of slope movements including flows, slumps, and block slides in tills and glacial-lake deposits blocked main highways, closed secondary roads, and created substantial damage to flood control reservoirs. In one case, stream bank failure due to heavy flooding caused a home and its surrounding land to be carried down a river. These slope movements were triggered by heavy rainfall and the melting of a thick snowpack. A statewide monthly average rainfall of 3.39 inches (8.61 cm) from February through the end of April and an 8.96 inch (22.76 cm) average for May, 1984, contributed to numerous floods and slope movements in the State of Vermont. The monthly rainfall average for the southeastern part of Vermont, which includes Windsor County, during the period February through May was 6.48 inches (16.47 cm).

Mapping and sampling of the 1984 landslides in glacial till and lakebed deposits in Windsor County were carried out to determine the processes involved in these slope movements. Although specific landslide processes varied from site to site, the landslides can be subdivided into groups based on the surficial materials present. The most common slope movement was found to be the earth flow occurring in rhythmite deposits. In clayey till deposits, a mixture of blockslide, slump, and earth flow slope movements were found. Failures involving bedrock can also be found in Windsor County, but none were directly attributable to the 1983-1984 storms.

Introduction

Field studies were made of landslides that occurred during the spring of 1984 in Windsor County, Vermont. Some of these slides were selected for presentation here as representative of the slope movement problems found within the county. The area in which the slides occurred is approximately bounded by the White River valley on the north, the Connecticut River valley on the east, the Green Mountains on the west and the Williams River valley on the south (1,2,3, and 4 respectively in Fig. 1).

The sites chosen for study represent a variety of slope movements involving various types of surficial deposits found in Windsor County. The most extensive surficial deposits include Pleistocene till, glaciofluvial, and glaciolacustrine sediments (Stewart and Mac Clintock, 1969). Regardless of a slope's composition, the above-normal precipitation affected slope stability in all of the soil types studied in the county.

The term slope movement, as used in this report, refers to various types of slides and flows in unconsolidated materials. Although rock falls and topples occurred in the county, they are not included in this report. Slope movements studied in most of the valleys included slides, flows, and complex forms. These variations occurred in relatively small geographic areas, and were primarily the result of differences in materials. Slope movements in the vicinity of the North Hartland and North Springfield reservoirs on the Ottauquechee and Black Rivers respectively, are of particular interest (localities 5,6,7, and 8, Fig. 1) because several types of landslide mechanisms occur at these sites. The slope movement classification used follows Varnes (1978).

New landslides as well as reactivated old landslides were studied. Some of the reactivated slides and flows examined were drilled by soil auger to determine any near surface variation in the materials, as well as to sample the materials present.

Figure 1 about here

Acknowledgements

This landslide research project is a cooperative effort between the Vermont Geological Survey, Agency of Environmental Conservation, and the U.S. Geological Survey. Discussions with Charles A. Ratte', Vermont State Geologist; Frank J. Lanza, Chief Geologist and Dan Cadiz, State of Vermont Agency of Transportation have been very informative. We also wish to thank Michael Curran, Upper Connecticut River Basin Manager, Thomas Coen, Project Manager, North Springfield Dam, and James E. Dyer, Project Manager, North Hartland Dam, New England Division, U. S. Army Corps of Engineers, for their assistance, discussions of reservoir landslide problems and general cooperation on this project. Our gratitude goes out to our colleague, Carl Koteff, U.S.G.S., who took time to accompany us on visits to some of our sites. Discussions with Carl on the glacial history of the area were very enlightening. Special thanks is also due Charles A. Ratte' and William E. Davies for their critical reading and helpful suggestions on the original manuscript. We also appreciate the review and helpful suggestions given the final manuscript by David K. Keefer.

Physiography

Windsor County is located in eastern Vermont, east of the Green Mountains. The county is drained by the White, Ottauquechee, Black, and Williams Rivers, their tributaries; and

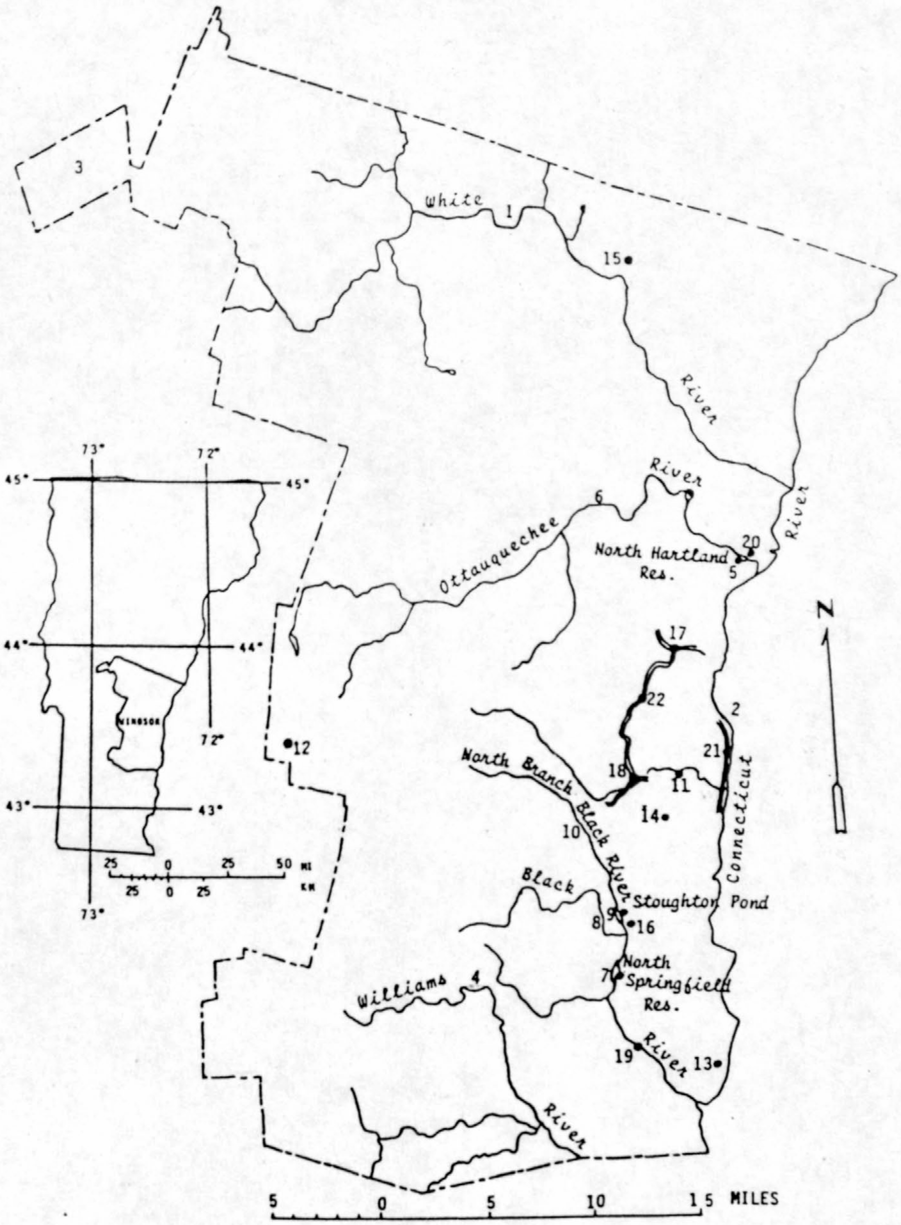


Figure 1. Windsor County, Vermont location map. Numbers indicate places mentioned in the text.

1. White River
2. Connecticut River
3. Green Mountains
4. Williams River
5. North Hartland Reservoir
6. Ottauquechee River
7. North Springfield Reservoir
8. Black River
9. Stoughton Pond
10. North Branch Black River
11. Brook road
12. Salt Ash Mountain
13. Skitchewaug Mountain
14. Mount Ascutney
15. Sharon
16. Butterfield Hill
17. Hartland Four Corners
18. Brownsville
19. Springfield
20. Miller Hill
21. Windsor
22. Holbrook Hill Road

Mill Brook. All of these streams flow eastward into the Connecticut River (loc. 2, Fig. 1). The area is quite hilly, with topography mostly controlled by generally north-south striking bedrock structures. Ridge-crest elevations range from as high as 3286 feet (1002 m) at Salt Ash Mountain (loc. 12, Fig. 1) near the northwest corner of the county , to slightly over 900 feet (274 m) at Skitchewaug Mountain (loc. 13, Fig. 1) along the Connecticut River near the southeast corner of the county. Mount Ascutney (loc. 14, Fig. 1), a monadnock on the east side of Windsor County adjacent to the Connecticut River, is 3144 feet (958 m) in elevation.

Valley-bottom elevations average 1100-1300 feet (335-396 m) in the western part of Windsor County and 300-500 feet (91.4-152 m) in the eastern part.

The entire region has been glaciated, giving much of the topographic surface a rolling aspect in many broad valley areas; the author's observations show that the glacial deposits are thick in valleys and relatively thin on upper parts of ridges and mountain sides.

Geologic setting

The bedrock of Windsor County includes the Precambrian Mount Holly Complex, composed of gneisses, quartzites, and marbles, in the south half of the county. The Devonian Waits River and Mountain Formations which are stratigraphically above the Mount Holly Complex (Hepburn and others, 1984), are mostly found in the north half of the county. The Waits River Formation is composed of three major interbedded rock types: impure marbles, quartzites, and schists. The Gile Mountain Formation consists of micaceous and feldspathic quartzites and mica schists; a marble member; and fine-grained phyllites. Mount Ascutney is composed of Late Jurassic or Early Cretaceous granites, syenites, and volcanics (Faul and others, 1963).

The surficial materials are mostly late Wisconsinan glacial drift (Stewart and Mac Clintock, 1969), and include till, glaciofluvial, and glaciolacustrine deposits. The glaciolacustrine deposits are associated with glacial Lake Hitchcock which covered much of the Connecticut River valley and its tributaries during retreat of the late Wisconsinan ice sheet. Many of the river valleys contain till overlain by lake-bottom rhythmically bedded silt and clay deposits (rhythmites). In some places, the lake-bottom deposits are overlain by late glacial deltas composed of fine sand, cobbles, and gravel and/or by colluvium. Glaciofluvial deposits consisting of sand to coarse gravel are common in the upland valleys.

Weather conditions

Slope stability is closely related to the amount of precipitation that falls in a given time interval (Zaruba and Mencl, 1982). The rate of rainfall coupled with soil or sediment properties of water absorption, infiltration, and retention are the critical hydrogeological factors associated with slope failure. The weather conditions prevailing in New England in general and Windsor County, Vermont in particular for the period September 1, 1983 through June 30, 1984 (NOAA, 1983a-d; 1984a-f), are summarized in Fig. 2.

Figure 2 about here

February 1984 weather records show that the region, including Windsor County, had above normal rainfall and that some snowfall occurred over most of the region from 3 or 4 days to 15 days of the month (NOAA, 1984b).

During the winter and early spring of 1984, the total snowfall recorded at Woodstock, Vermont, in the northern half ofWindsor County, was 95.5 inches (242.6 cm) and was 85.7 inches (217.7 cm) at Cavendish, Vermont, which is in the southern half of the county. This snow cover indicated is roughly equal to 9.6 inches (24.4 cm) and 8.6 inches (21.8 cm), respectively of rainfall.

Abnormal precipitation raised ground-water well levels (Table 1) increasing the moisture content to near saturation of the soil materials in Windsor County during the autumn of 1983 through mid spring 1984. Unusually intense spring storms in late May exacerbated the conditions by increasing the pore water pressure in the sediments, thus triggering slides.

Although Table 1 shows some fluctuation in the ground-water levels, in general, they were above average for the period of interest. It is assumed, based on these well records, that the ground-water levels were higher than normal throughout the county.

Table 1 about here

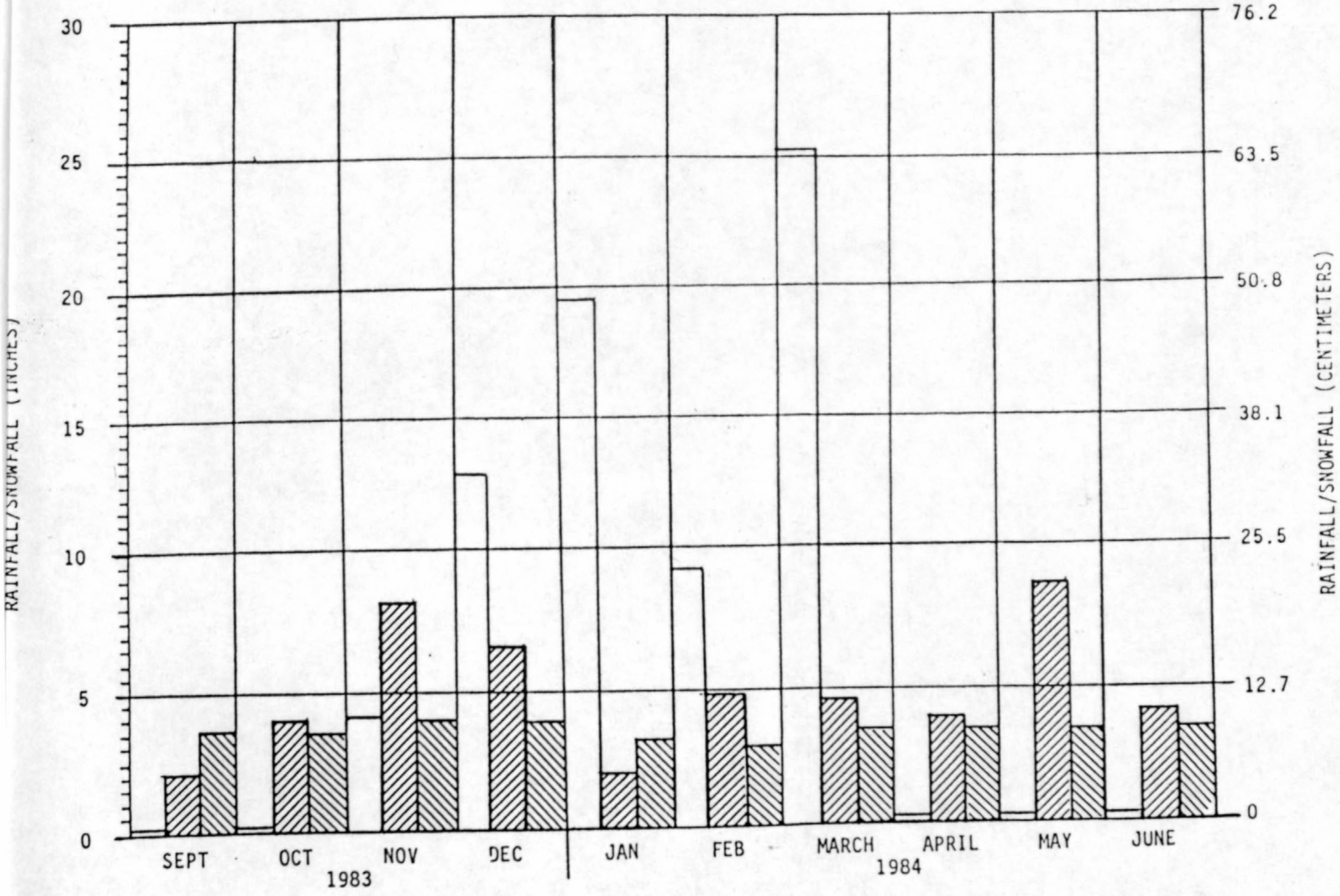


Figure 2. Mean monthly rainfall/snowfall for the period September 1, 1983 to June 30, 1984 for all New England stations. Approximate snowpack equivalent to water is 3.95 inches (10 cm) of snow to 0.395 inches (1 cm) of rain. From left to right at each month the first (open) bar shows total unmelted snow and sleet for the month in New England. The second bar (hachures sloping down to the left) shows the average of total liquid and melted frozen precipitation combined for New England. The third bar (hachures sloping down to the right) shows the normal precipitation in the form of rain for the month. Data from the National Oceanic and Atmospheric Administration Climatological Data reports, 1983a-d; 1984a-f.

Table 1

Precipitation and ground water data for Windsor County, Vermont. Precipitation data taken from U.S. Army Corps of Engineers records kept at the North Hartland and North Springfield flood control dam sites. Ground water well readings supplied by David Butterfield of the Vermont Department of Water Resources. Chester, Hartland and Rochester wells are in unconfined aquifers and Queechee-West Hartford is partially confined in bedrock; recharge area is about 100 to 200 feet from this well. All these wells are local quick response types and cover no more than 1000 acre drainage basins; all are within Windsor County (James Ashley, Vermont Department of Water Resources, personal comm., 1986).

Date	Total Precipitation[1] North Hartland	North Springfield	Ground Water Well Readings Chester Well	Hartland Well	Rochester Well	Quechee-West Hartford Well[4]
1983 Sept.	1.97 (5.00)	2.28 (5.79)	6.09[2] (1.86)[2] -0.34[3] (-0.10)[3]	9.60[2] (2.93)[2] -0.21[3] (-0.06)[3]	12.37[2] (3.77)[2] -0.23[3] -(0.07)[3]	5.32[2] (1.62)[2] - -
Oct.	2.66 (6.76)	2.95 (7.49)	5.83 (1.78) -0.48 (-0.15)	9.63 (2.94) -0.26 (-0.08)	12.36 (3.77) -0.95 (-0.29)	6.38 (1.94) - -
Nov.	6.35 (16.13)	6.50 (16.51)	4.74 (1.44) +0.22 (+0.07)	9.29 (2.83) -0.13 (-0.04)	10.12 (3.08) +0.81 (+0.25)	+0.18 (+0.05) - -
Dec.	5.89 (14.96)	6.65 (16.89)	3.40[6] (1.04)[6] +1.60 (+0.49)	7.47 (2.28) +1.31 (+0.40)	6.50 (1.98) +4.08 (+1.24)	+1.35[7] (+0.41)[7] - -
1984 Jan.	0.80 (2.03)	0.59 (1.50)	5.15 (1.01) -0.35 (-0.11)	8.59 (2.62) +0.07 (+0.02)	10.41 (3.17) +0.37 (0.11)	+0.04 (+0.01) - -
Feb.	2.82 (7.16)	2.54 (6.45)	3.30 (1.01) +1.40 (+0.43)	8.17 (2.49) +0.36 (+0.11)	8.08 (2.46) +2.46 (+0.75)	+1.35 (+0.41) - -
March	2.95 (7.49)	3.70 (9.40)	3.84 (1.17) -0.50 (-0.15)	7.96 (2.43) +0.26 (+0.08)	9.44 (2.88) -0.48 (-0.15)	+1.35 (+0.41) - -
April	3.60 (9.14)	4.42 (11.23)	2.98 (0.91) +0.55 (+0.17)	7.01 (2.14) +0.38 (+0.12)	5.41 (1.65) +1.66 (+0.51)	+1.35 (+0.41) - -
May	9.46 (24.03)	9.91 (25.17)	1.57 (0.48) +2.79 (+0.85)	5.96 (1.82) +1.83 (0.56)	4.61[5] (1.41)[5] +4.27 (+1.30)	+1.35 (+0.41) - -
June	1.41 (3.58)	1.64 (4.17)	5.31 (1.62) +0.04 (+0.01)	7.35[5] (2.24)[5] +1.19 (+0.36)	10.41 (3.17) +0.79 (+0.24)	1.77 - - -

1. Includes melted snow and ice in inches and centimeters ().
2. Water level below ground surface in feet and meters ().
3. Departure from average for that month in feet ±, and meters ()±.
4. Flowing well, + readings indicate level above ground surface.
5. New high record.
6. New high record for a December
7. +1.35 feet (0.41) meter readings are for flow from casing slot cut above ground level at that elevation.

NOTES: To save repetition, the values for the four water wells for every month follow the pattern for the values shown for September before the superscripts 2 and 3.

Average for the month can be determined by adding or subtracting the + or - amount indicated by the values before superscript 3 from the water level numbers before superscript 2 for any month.

TABLE 1

Slope failures in Vermont

The entire Green Mountain and Taconic Mountain ranges with their contained river valleys have been found to have slope failures in just about every geologic material and unit encountered. In rock terrane large rock falls have been observed in gneisses, schists, and quartzites; rock slumps in quartzites; topples in marbles, and debris slides in schists. In unconsolidated sediments, earth flows and slumps, debris flows and debris slides are common types of slope movements. In some instances where massive bare rock outcroppings dominate long ridges, rock falls and rock slides have triggered earth and/or debris slides or flows creating complex types of movement. Several hundred landslides have been located in the field, some were just noted on maps others studied in detail, measured, sampled, and tested and many more located and mapped by use of remotely sensed data.

The problem

All the landslides discussed in this report occurred during and immediately following the heavy rains and rapid snowmelt that inundated the New England region during the spring of 1984. The culmination was exceptionally heavy rain that fell during the last few days of May. In Vermont, the damage that resulted from some slope failures involved flood control reservoir slopes, road traffic disruptions, felled trees, and phone lines. Fortunately, there was no loss of life or injuries to persons. Because of the great number of slides that were found there, Windsor County was selected as a primary study site. During a reconnaissance of the county in the first week of July, 1984, it was observed that more than one type of landslide had occurred in the various glacial deposits. The slope movements selected for detailed study were mainly earthflows and block slides.

Rising ground water as a triggering mechanism for slope movements

In every case of slope movement studied in the Windsor County lakebed and till deposits in 1984, above normal amounts of water have played a major role in initiating and sustaining failure.

Above normal precipitation led to elevated ground-water levels which in turn led to increased pore water pressure. Related to the increased pore water pressure, was a decrease in effective normal stress and a corresponding decrease in shearing resistance in the soil (Terzaghi and Peck, 1948, Skempton and DeLory, 1957, Campbell, 1975). Failure occurs when the shearing resistance decreases below a critical level which is dependent on the type of material involved in the failure and the slope geometry.

High water levels behind the North Springfield and North Hartland Flood Control dams helped raise ground-water levels and increase pore water pressures. Schuster (1980) has stated that high water levels behind dams can lead to elevated pore water pressures and cause slope failures in the reservoir. It was noted that all of the slope movements, which occurred in the flood control reservoirs in Windsor County, had head scarps at or below the high water level for the spring of 1984. This fact may be related to rapid drawdown (see Fig. 7 in Terzaghi, 1950). The pore spaces on the reservoir rim are totally filled to the headscarp level. Upon rapid reservoir drawdown, there is a time lag between reservoir level decrease and decrease in the water table surface. This generates high seepage pressures in the toe area producing slope instability and sliding (Terzaghi, 1950)

Man-made slope alterations also played a major role in raising ground-water levels. Old or abandoned unimproved roads and trails which traverse some hillsides as benches, tended to concentrate surface runoff at the low points along these benches. With time, the soil slopes below these low points became saturated and slope failures developed, sometimes beginning as creep. The failure along Route 5 at Windsor (Fig. 1, loc. 21) and those that occurred along Holbrook Hill Road (Fig. 1, loc. 22) near Hartland Four Corners are examples of slope movements which occurred below old roads and trails. Although we don't know the original purpose of these particular roads, many similar roads throughout the state were used for farm access or as logging roads.

Slope movement classification

This paper uses the slope movement classification developed by Varnes (1978), which has become widely accepted by landslide researchers (Table 2). Slope movements are classified according to the type of material involved and the type of movement.

Within the study area, slope movements were diverse and identified as mostly rotational or translational slides, flows, and complex types.

All the materials involved in the slope movements discussed in this study are considered engineering soils. Such soils are unconsolidated, residual or transported inorganic mineral matter and/or rock fragments. The soils ranged from very fine-grained silts and clays, to coarser-grained materials composed of sand, gravel, cobbles and boulders. In this report, the finer-grained soils are referred to as earth, and the coarse mixtures are considered debris as defined by Varnes (1978).

Table 2 about here

Slope movements that occurred during late spring and early summer of 1984 in Windsor County were divided into groups based on the nature of the glacial deposits. The first, and by far the most common group of landslides, occurred in deposits composed of varved silts and clays (rhythmites). The second group of slope failures occurred in glacial till deposits. A few slope movements occurred along the sides of ice-marginal deposits, e.g., kames. One slope movement of special interest, located in Sharon, Vermont (loc.16, Fig. 1), is a complex deposit composed of stream-terrace sediments, above which overlie glaciolacustrine sediments, which in turn overlie esker deposits.

Susceptibility of glacial lake-bottom deposits to sliding

Lake bottom sediments, or rhythmites, represent the greatest landslide problems found in the study area. Rhythmites are generally composed of alternating layers of silty clay and silt to fine sand. Generally, the rhythmite deposits in the county range from nearly pure clays to silts and sand. Where layers of nearly pure clay are found, they are very thin, usually less than 1 inch (2.54 cm). The average thicknesses of glacial lake-bottom deposits, as measured on lateral scarps and headscarps, at the sites investigated is 50 feet (15.24 m). Contained within a few rhythmite sequences are layers of medium to coarse sand and gravel. The medium to coarse sand layers are locally as thick as 4 feet (1.2 m). There are also thin calcite-cemented sand layers at several locations (Fig. 3). These indurated layers are 1/8 - 1/4 inches (.318-.635 cm) thick and spaced 5.12-5.9 inches (13-15 cm) apart.

Figure 3 about here

Some of the rhythmite deposits no longer show their original horizontal bedding (Fig. 3). These materials were deposited on or around stagnant ice blocks. As the ice melted, the depositional units collapsed, an example occurs at the North Springfield Reservoir. Most of these rhythmites dip toward the failure face.

<table>
<tr><th colspan="3" rowspan="3">TYPE OF MOVEMENT</th><th colspan="3">TYPE OF MATERIAL</th></tr>
<tr><th rowspan="2">BEDROCK</th><th colspan="2">ENGINEERING SOILS</th></tr>
<tr><th>Predominantly coarse</th><th>Predominantly fine</th></tr>
<tr><td colspan="3">FALLS</td><td>Rock fall</td><td>Debris fall</td><td>Earth fall</td></tr>
<tr><td colspan="3">TOPPLES</td><td>Rock topple</td><td>Debris topple</td><td>Earth topple</td></tr>
<tr><td rowspan="3">SLIDES</td><td>ROTATIONAL</td><td rowspan="2">FEW UNITS</td><td>Rock slump</td><td>Debris slump</td><td>Earth slump</td></tr>
<tr><td rowspan="2">TRANSLATIONAL</td><td>Rock block slide</td><td>Debris block slide</td><td>Earth block slide</td></tr>
<tr><td>MANY UNITS</td><td>Rock slide</td><td>Debris slide</td><td>Earth slide</td></tr>
<tr><td colspan="3">LATERAL SPREADS</td><td>Rock spread</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="3" rowspan="2">FLOWS</td><td rowspan="2">Rock flow
(deep creep)</td><td>Debris flow</td><td>Earth flow</td></tr>
<tr><td colspan="2">(soil creep)</td></tr>
<tr><td colspan="3">COMPLEX</td><td colspan="3">Combination of two or more principal types of movement</td></tr>
</table>

Classification of slope movements (after Varnes 1978). The terms, Few Units; Many Units, beneath the Type of Movement column, refer to the degree of disruption in a slide, e.g., a few blocks or many blocks.

TABLE 2

Figure 3. Glacial Lake Hitchcock rhythmite deposit at the North Springfield flood control reservoir. The deposit is dipping to the west (left side of photo), and has several calcite-cemented sand layers (hammer rests on one of these).

Ground-water flow within the rhythmite sequences was mainly in the light-colored silt and sand layers. These silts and sands dominated as aquifers because the clayey-silt layers had lower hydraulic conductivities and acted as small aquicludes. When fresh rhythmite surfaces were exposed, either by scraping off surface material or digging small pits into the face, water would leak from the silt and sand layers. As water traveled through any of the silt and sand layers, it slowly saturated and weakened the silty clay layers.

In-situ field strength measurements were taken in these sediments using torvanes and pocket penetrometers (Table 3). The moisture content, as determined in the field, based on visual procedures (ASTM, 1985), of the samples tested ranged from moist to wet; moist indicates damp but no visible water and wet visible free water, no tests were run on completely dry materials. The field tests (Table 3) indicated that some of the materials involved in sliding had relatively uniform engineering characteristics throughout their total thickness, as shown by penetrometer readings (unconfined compression, q_u). At the North Hartland and North Springfield Dam sites, the silty-sand, clayey-silt and silty-clay layers had penetrometer readings that averaged 3.16 tons/ft^2 (kg/cm^2). The low cohesion fine sand at the U.S. Route 5 site had an average penetrometer reading of 1.2 tons/ft^2 (kg/cm^2) and the Vermont Route 11 clays an average of 0.3 tons/ft^2 (kg/cm^2).

Overall, the shear resistance (undrained shear strength, s_u) for all the materials was low; silty-clays and clays with some silt content had greater cohesion and a higher shear strength than other slide materials, e.g. cohesive clay and silt at North Springfield site #1 had an average vane shear of 0.545 tons/ft^2 (kg/cm^2) and the brown clay some silt at North Hartland site #1 averaged 0.423 tons/ft^2 (kg/cm^2). Vane shear readings (Table 3) showed a zone of very low shear resistance 34.5 ft (10.5m) below the top of the headscarp in the rhythmite section at North Hartland Dam site #1. The cross bedded sand stratum in the rhythmite section at site #1 was the thickest measured at North Hartland Dam and, as indicated in Table 3, it was subject to piping. The average torvane reading for the zone referred to above was 0.038 tons/ft^2 (kg/cm^2). This material was sandy, containing very little clay, which gave the layer a very low cohesion. After the earth flow occurred, this unit was extensively piped by ground-water escaping from the scarp along the length of the layer (Fig. 4). The high water conductivity through these sandier layers and parallel to the surfaces of the clay layers, helped add water to the ultimate failure surface.

Table 3 about here

Figure 4 about here

Earth flows were the landslide type most commonly associated with the glacial-lake deposits. Some of these slope movements had rotational or slump type movement in the scarp area (slump earth flow) while others had translational or blockslide types of movement. The rhythmite deposits generally contained only minor amounts of gravel and larger detrital fragments. Slope movements occurring in these units were predominately in fine grained materials, best classified as earth as defined by Varnes (1978). In many examples, some gravelly eskers underlie the lake-bottom deposits. Although some of these esker materials became incorporated into the lower parts of the slide mass, they had little or no effect on the overall earth flow character of the slide material, e.g. the Sharon failure site, discussed later in this section, consisted of lake-bottom sediments overlying a gravelly deposit but the earth flow aspect was maintained during the event.

North Hartland flood control reservoir

Many earth flows, some with piping failures, occurred along the rims and walls of tributary stream channels emptying into the North Hartland Reservoir (loc. 5, Fig. 1, Fig. 4, and Fig. 5). Earth flows with piping failures are treated separately here.

Corps of Engineers personnel (personal comm.,1984) reported that during the 1984 flood stage in the reservoir, seiches were observed on the water surface due to subaqueous landslides upstream. It was stated that the sound from upstream was audible at the dam.

Figure 5 about here

Earth flows

A slide located on the northeast valley wall of the reservoir (Fig. 6), near the North Hartland dam emergency spillway was an example of the slump-earth flows encountered. This slope movement occurred in the spring of 1984 along the face of a terrace that formed the northeast valley wall. An unnamed stream flows southwestward into the reservoir from the west flank of Miller Hill (loc. 20, Fig. 1 and Fig. 5A) along the base of the terrace. The toe of the failure temporarily blocked the stream, but by eroding the toe, the stream has reoccupied its original channel.

Table 3

Location	Material	Torvane Readings in T/S/F = (kg/cm^2)	Penetrometer Readings in T/S/F = (kg/cm^2)	Remarks
S. Rt. 5 ndsor, Vt.	Clay	0.1, 0.17	1.3	Readings taken on lateral scarp south side of slide. (moist to wet)
	Dark brown very fine sand.	0.06, 0.16, 0.19	0.7, 1.1, 1.3	
	Dark clay layer	0.19, 0.20, 0.23	1.15, 1.55, 1.65	50' above road.
	Light silty fine sand	0.06, 0.08, 0.08	1.05, 1.15, 1.1	Same elevation as above
orth Hartland ood control dam site #1	Dark brown clayey-silt (moist)	0.13, 0.17, 0.23	1.2, 1.8, 1.8	1 - 2' below top of scarp
	Light brown silty sand	0.21, 0.18, 0.14	3.95, 3.3, 3.25	Slightly below above readings
	Yellowish-brown silty fine sand (moist)	0.07, 0.04, 0.09 0.07	2.5, 2.35, 2.6	4' below top of scarp
	Brown clay some silt	0.43, 0.38, 0.46	2.4, 2.5, 2.15	7' below top of scarp
	Light brown silt (dry to moist)	0.1, 0.06, 0.09 0.096	1.8, 1.45, 1.35, 1.8	9' below top of scarp
	Gray-brown silty-clay	0.20, 0.275, 0.30	2.70, 2.80, 3.2	Piping with earthflow movement 29.5 ft (9 m) below top of scarp.
	Cross-bedded fine brown sand, some silt; upper 3.9 in (10 cm) has interbeds of gray silty-clay	0.037, 0.038 0.039	1.55, 1.45, 1.25	34.5 ft (10.5 m) This unit was subject to piping.
	Gray varved clay and silty-clay with fine sandstone concretions	0.175, 0.28, 0.41	1.9, 2.3, 2.6	42.7 ft (13 m) (moist to wet-no visible water to visible free water+)
	Gray-brown silty-clay	0.21, 0.14, 0.175	2.3, 1.5, 1.7	depth unknown
ite #2	Gray silty-sand	0.225, 0.23, 0.25	2.3, 2.5	Failure scarp on North side of reservo
ite #3	Gray silty-clay	0.42, 0.2, 0.23	1.8, 1.9, 2.0	West of boat ramp
mont Route 11 ingfield, Vt.	Wet clay	-	0.25, 0.3	Water seeps and springs occur in coarse sand layer above the clay at 19.4 ft (5.9 m)
	Non-wet clay	-	0.3, 0.35	
orth Springfield od control dam ite #1	Light-brown cohesive, moist, varved clay and silt	0.54, 0.55	-	14.8 ft (4.5 m) below top of scarp.
	Gray clay layer	-	2.5, 2.8, 3.3	Test made parallel to bedding.
	Gray clay layer		2.55, 3.1	Test made normal to bedding.
ite #2	Dark brown clayey-silt	0.09, 0.1	0.8, 1.25, 1.2	Central reclaimed area
	Both types varves	0.27, 0.28, 0.21	3.0, 2.25, 2.5	Below above sample
	Gray silty-clay with clay layer	0.48, 0.38, 0.32	3.6, 3.5, 3.55	Different location along scarp (12.5' below top of scarp)
	Light yellowish-brown coarse silt and fine sand	-	4.4, 4.2, 3.8	Stratum below above test (13' below top of scarp)
	Dark brown varved clayey-silt	0.29, 0.29, 0.28	3.0, 3.3, 3.15	Same section (14.1' below top of scarp)

* On south side of reservoir 1115.5 feet (340 m) west of intake tower at toe of dam and near boat ramp parking lot.

** On east side of reservoir 4593.4 feet (1400 m) NNE of intake tower and across reservoir ESE of boat ramp.

\+ ASTM, 1985, Designation D2488 in Annual Book of ASTM Standards, Section 4, vol. 04.08 Soil and Rock Building Stones - see Table 3, pg. 415.

Torvane and penetrometer tests taken on four glacial lake-bottom deposits in Windsor County, Sharon excluded.

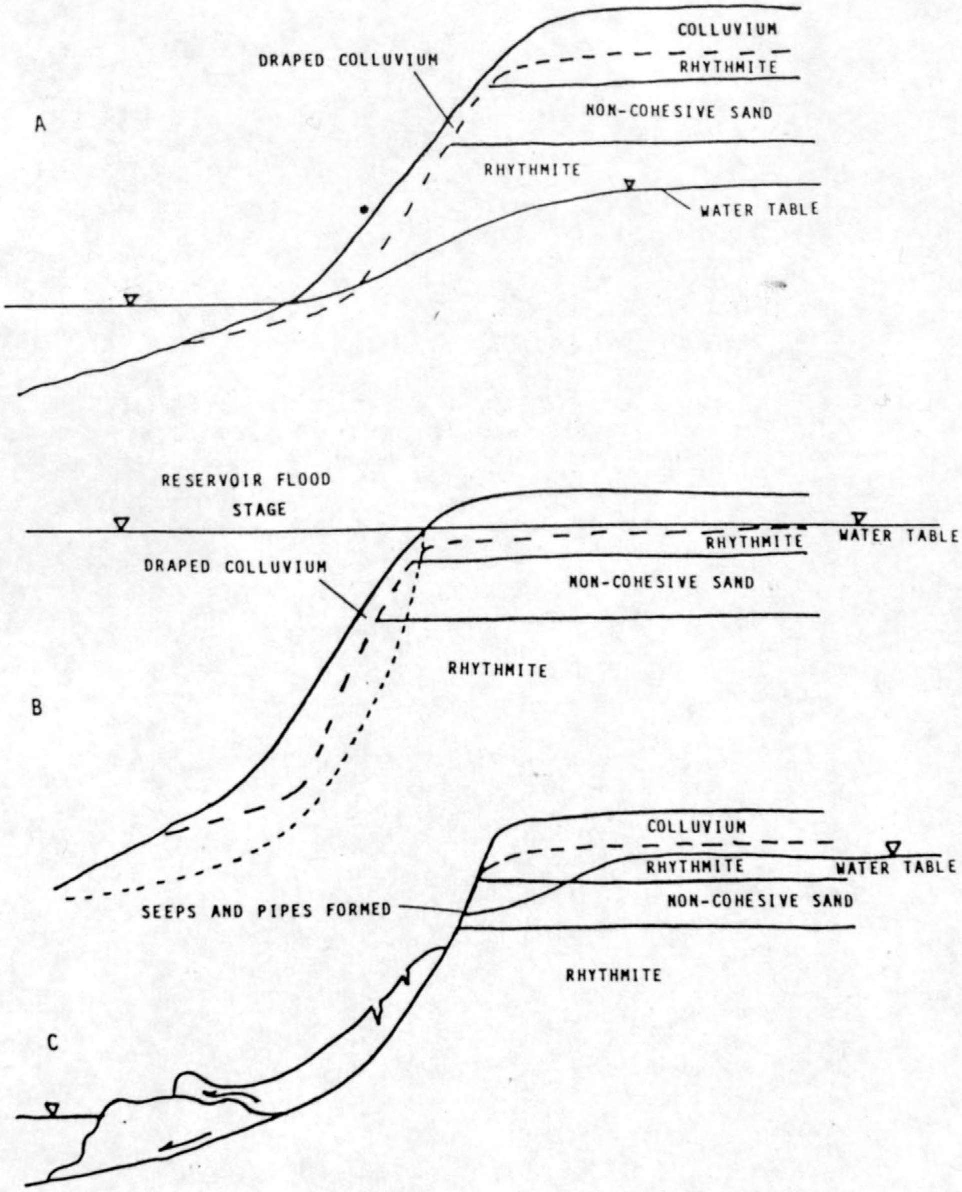
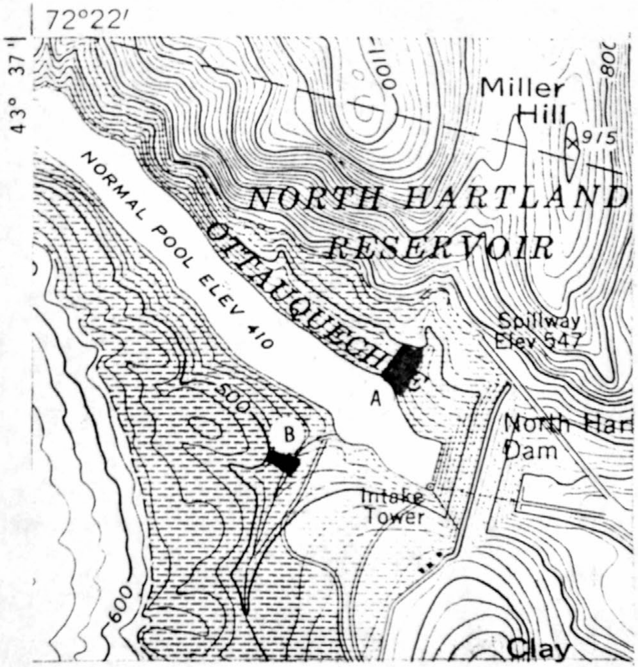


Figure 4. Schematic cross sections of a typical flood reservoir slope configuration in which earth flow and piping failures have developed. A - pre-flooding configuration; B - flood stage; C - post-slide and piping configuration.



Base from U.S. Geological Survey 1:24000

North Hartland, 1959

0 .5 1 KILOMETER

CONTOUR INTERVAL 20 FEET

QUADRANGLE LOCATION

Figure 6 about here

The slope failure had a differential elevation of 110 feet (33.5 m) from head scarp to the toe at the unnamed stream level. The toe of the failure was stopped by the stream channel referred to above just before reaching the lake. The failure length was about 580 feet (176.8 m) from the head scarp to the toe along the axis of sliding, and was 475 feet wide (144.78 m), normal to the axis. The upper boundary of this failure was marked by two undulating scarps. The two scarps (main and minor) had vertical offsets of 2.5 feet (0.76 m) each and horizontal tension openings of 4 to 9 inches (10.16 to 22.86 cm). The slope angle of the scarps ranged from 50° to 62° (119-188%). Slickensides were observed on clay-smeared fresh scarps in July 1984 (Fig. 7), but they were gradually eroded by subsequent rainstorms.

Figure 7 about here

The east side of the failure mass, right side of Fig. 6 just out of view, had numerous en echelon transverse tension gashes with small vertical displacements. The west side of the mass was bounded by an irregular, curving scarp, and one or more lateral shear planes. Except for some tension cracks, the central portion of the slope movement had a relatively smooth upper surface.

The lateral tension cracks seen in the left foreground of Figure 6 resulted from an increase in friction on the basal shear surface of the failure as the fluidized substrate pinched out, placing the basal shear surface in direct contact with the sole of the slide mass. This caused drag on the sole of the slide mass pulling it apart (extension) as shown in Figure 8. Drag on the basal shear surface in the headscarp area generated tension crack openings (tensile stress) normal to the direction of movement during sliding as shown at T in figure 7. The entire upper surface of the slide mass has undergone some extension in the direction of movement. Hummocks and lobes of slide material formed the distal part of the toe of this earth flow. Tension cracks were also found throughout the toe area.

A secondary earth flow developed within the toe area of the main movement. This failure occurred along the western side of the main earthflow where the valley of the unnamed stream widened. The toe of the secondary failure separated into small blocks of intact material riding on a layer of fluid-like

Figure 6. View of slope movement on the northeast wall of the North Hartland flood control reservoir west of the spillway. The headscarp is in the center. Tension cracks on the mid section of the flow can be seen on the lower left. The shrubs on the lower left were mud coated due to high water during reservoir flooding. The smooth area in the foreground is the edge of a grass covered hill on the southeast side of the unnamed stream valley from which the photo was taken.

Figure 7. Photo showing slickensides on a clay-smeared head scarp surface of the slump-earth flow on the northeast valley wall of the North Hartland reservoir. T is the location of a horizontal tension crack.

material. As the blocks came to rest, the fluid material oozed from below the blocks.

In the upper part of the slide mass near the head scarp, the basal zone of liquified material pinched out and was replaced by a planar failure surface (Fig. 8). In the headscarp area of these earth flows some small minor rotational slumps were seen that were separate from the main failure mass.

Failure in both earth flows appeared to have occurred as rafts of intact material riding on layers of fluidized material. Some of the tension cracks referred to above were caused by the extension of the failure mass as discussed previously, but others could have been caused by the bulging and buckling of the surface of the slide mass in the toe area as material piles up.

Figure 8 about here

Piping associated with earth flows

Of the many landslides that occurred on the southwest valley wall of the North Hartland reservoir, one in particular, just west of the boat ramp parking lot had piping associated with the failure (Fig. 6). The site, a terrace, consisted of a rhythmite sequence, covered by a layer of colluvium. Near the top of the terrace, the rhythmite sequence was interrupted by a 4 foot (1.2 m) thick medium sand layer. The non-cohesive sand layer, having had a higher hydraulic conductivity than the surrounding rhythmites, acted as a confined aquifer as shown in Fig. 4.

As the water in the reservoir rose during the spring of 1984, water flowed into and through the colluvium, into the sand layer and the rhythmite sequences by way of their silt layers. Eventually, water within the confined sand reached a hydrostatic head roughly equal to the height of the reservoir pool above the confined sand layer. As the water level in the reservoir dropped, the colluvium above the rhythmite sequence maintained a perched water table, and the confined medium grained sand layer held water similar to an artesian aquifer.

The slope failed as an earth flow, which was partially fed by water from the confined sand layer as well as from the saturated colluvium (Fig. 4). The material involved in the failure included the colluvial cover along the slope face as well as some of the rhythmite sequence. It moved as a rapid fluid earth flow across a stream channel and was stopped by the parking lot embankment (see foreground of Fig. 9). The failure removed

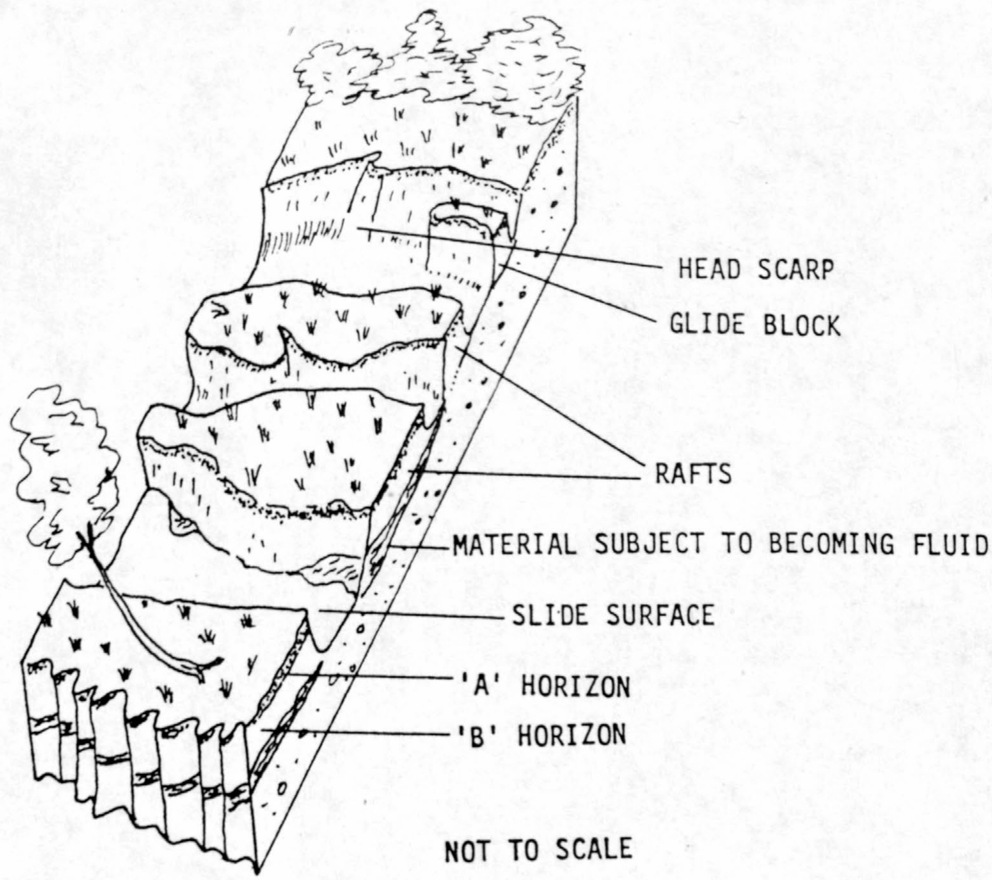


Figure 8. A block diagram showing rafts of intact material sliding on a fluidized substrate which pinches out headward. The failure surface above the pinchout point becomes a planar frictional surface. This friction creates a pulling apart of the slide material on tension cracks, developing some separated glide blocks.

the colluvial cover, exposing the confined sand layer, which allowed the remaining water to escape from this layer. Since the sand had lower cohesion than the surrounding rhythmites, sand was removed by the escaping water. Pipes as much as approximately 4 feet in diameter (1.2 m), developed (Fig. 9 at A). Most of this movement occurred in rapid succession; with the initial earth flow followed closely by the piping phase.

Figure 9 about here

From this example, it was apparent that ground-water flow in the slopes around the North Hartland dam reservoir had a major effect on slope movement. When the reservoir filled, the ground water table rose with it. As the reservoir level was drawn down, the then higher level ground-water flowed toward the reservoir, exiting the slope above normal pool level for some time (Fig. 4). A high moisture content was still evident in the sand unit associated with the pipes. This ground-water flow generated a high water pressure on the potential slide surface (see Costa and Baker, 1981). Slope movement initiation occurred through the increased pressure head created by this new ground-water configuration.

Vermont Route 11

Another earthflow in glacial lake-bottom deposits developed along Vermont Route 11, southeast of the town of Springfield (Loc. 19, Fig. 1 and Fig. 10). The failure occurred on the face of a 80 foot (24.4 m) high terrace on the southwest wall of the Black River valley. Because the failure did not involve the present new alignment of Route 11, no corrective measures were taken, except for the removal of trees on the slide mass which threatened power and telephone lines.

Figure 10 about here

The terrace deposits consist of a medium to coarse sand overlying a rhythmite sequence. The subhorizontal terrace surface is 100 feet (30.5 m) wide back to front. The slope angle of the terrace front is 42° (90%), and the hill slope behind the terrace is 34° (67%).

Numerous springs issue from the bedrock hill above the terrace. The terrace surface has a slight slope back toward the bedrock-defended hill. A small stream drains the swamp area along the proximal side of the terrace surface, and runs easterly

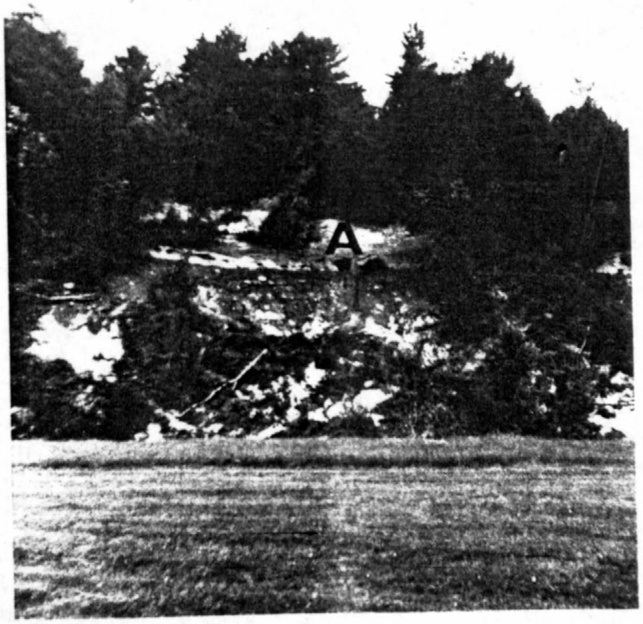


Figure 9. A view of part of the southwest valley wall of North Hartland reservoir showing piping cavities (A) in a sand layer confined between two rhythmite sequences. These cavities are up to 3.9 feet (1.2 m) in diameter.

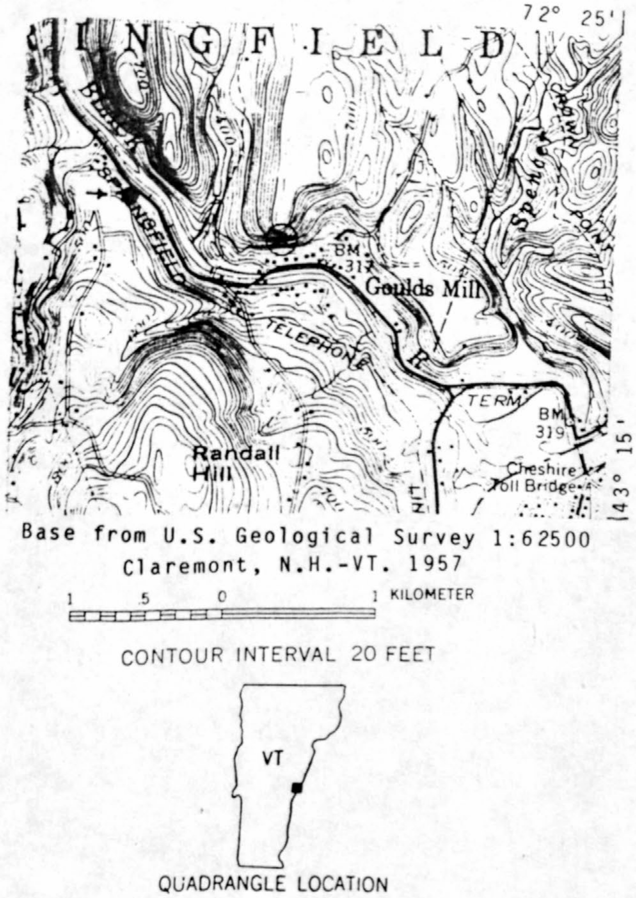


Figure 10. Site 20. Map locating the Vermont Route 11 Slide. Slide is in the upper left of the map at the arrow.

parallel to the bedrock hill. Water from these springs also soaks into the terrace sediments and re-emerges as springs on the terrace front (Fig. 11). In a trench excavated in the scarp face to obtain a clean exposure of the rhythmite sequence, water flowed from the silty sand layers.

Many features of this failure were similar to those of the failure described at North Hartland Reservoir. The head scarp measured 12 feet vertically (3.66 m) and 140 feet (42.67 m) across, normal to the slide axis. The scarp had a steep face, and the failure moved along a single slide plane in the head scarp area; some rotation was also noted. The surface of the failure mass had separated into discrete blocks.

Figure 11 about here

The toe crossed what had been the original alignment and remnant pavement of Route 11. The material in the toe, including blocks containing trees, flowed out over the old pavement without disturbing it. A fluid mass of gray-brown silt came out from under the failed mass and spread over the old road beyond the toe. It was apparent to the authors that the main slide mass moved on a fluidized zone. This fluid layer was fed by seeps issuing from the terrace face at the water table level. Water was still flowing from the failure mass onto the old road at a volume equivalent to a very small creek when the failure was examined in mid July, 1984.

Trees on the slide mass, after the movement, were cut down; ostensibly to prevent their interference with communications lines crossing the site normal to the slide axis should sliding commence again. Examination of tree rings from the stump of one of these cut trees, showed that this area had prior creep movement. The tree rings indicated that during a few years on either side of 1950, asymmetric growth developed, which suggested a period of stress for the tree when the slope may have slipped a bit or at least developed accelerated creep.

The slopes on Route 11 that had not yet failed, showed signs of creep and the pipe-stem tree trunk structure was common. Phipps (1974) suggested that the leaning or curving of tree trunks was the result of geotropic response of the trees. Sharpe (1938) indicated that bent tree trunks may be one of the indicators of slow flowage or creep on slopes. Tree spacing was such that phototropic response could not be a satisfactory answer for the number of trees with these shapes on the unfailed adjacent slopes as well as on the one that failed.

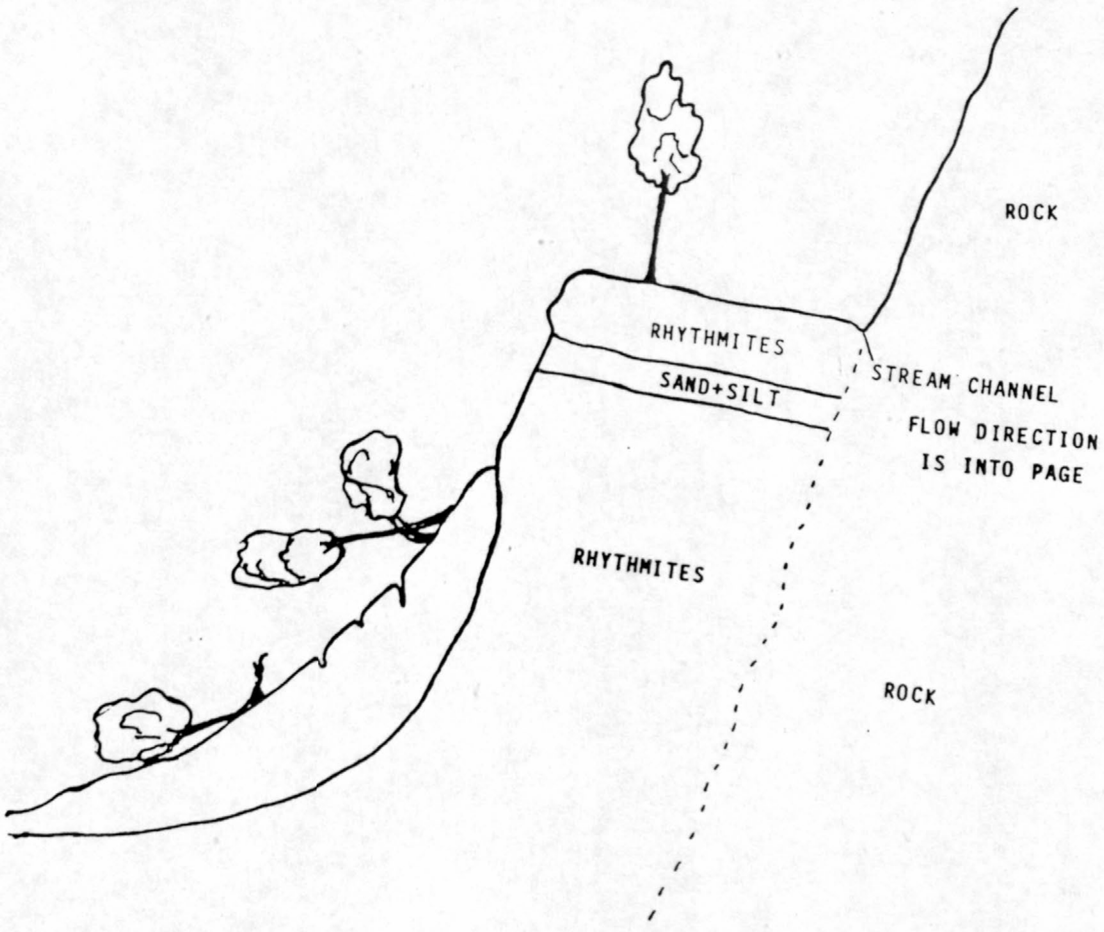


Figure 11. Schematic section of the terrace configuration at Vermont Route 11 slide site showing strata and water flow direction.

Penetrometer tests showed that the rhythmites had extremely low compressive strength. The silt layers yielded readings of 0.3 tons/ft^2 (0.3 kg/cm^2), compared to the average of 2.5 tons/ft^2 (2.5 kg/cm^2) for silts tested in other slope movement areas. Low compressive strength readings at this location may have been the result of the soils being wetter than those encountered at other sites.

Windsor Route 5

This landslide was located in the Connecticut River valley on the west side of U.S. Route 5 on the east slope of Horseback Ridge just south of the town of Windsor (Loc. 21, Fig. 1 and Fig. 12). The slope failed just after the heavy rains at the end of May 1984. The headscarp had cut halfway across an old overgrown road which runs parallel to Route 5 about 110 feet (33.5 m) upslope. The slope angle below the old road and along the slide axis measured 30° (58%), and the slope angle above the old road was 36° (73%).

Several old landslide scars were seen to the south of this failure. All the headscarp crowns were at the same elevation. This elevation defined a terrace level that extended to the east of the old road as one proceeded in a southerly direction.

Figure 12 about here

The stratigraphy of the Route 5 slide from the top down is as follows. The topsoil is a spongy dark brown to black silty clay with about 40% fine mica; this layer is about 1 foot (.30 m) thick. Beneath the topsoil is 31.5 inches (.80 m) of rhythmically bedded gray sticky clay, and dark brown very fine sand containing about 30% silt; the top 6 inches (.15 m) of this horizon was saturated. The sand layers were damp but showed no visible water; the clay showed visible water at the time of observation. The next soil unit below contained a fine to medium brown sand with about 30% silt and fine pea gravel. Beneath this layer, which is about 10 feet (3 m) below the top of the scarp, was a saturated dark brown gravelly fine sand and silt. The toe material was a brown to gray silt and clay quite churned up from the sliding.

When we examined the site on July 24, the saturated failed toe area was still exuding water. Springs were noted to be issuing from numerous locations at the base of the headscarp, and in the scarp areas of the older landslides to the south. These springs marked a level along this entire slope just below the terrace top that defined the contact between an upper aquifer

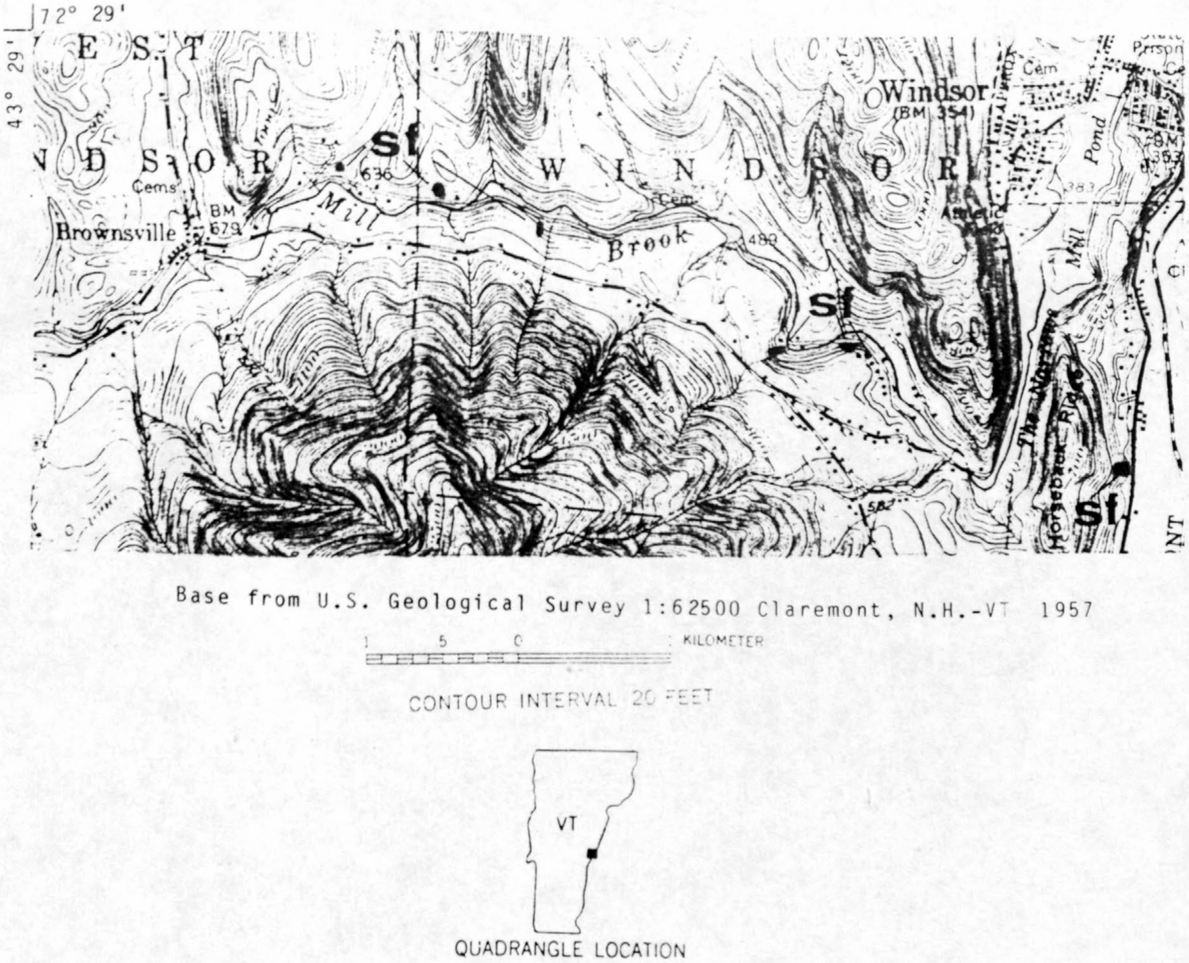


Figure 12. Map locating the Windsor Route 5 and Brook Road Slides. The letters sf point out the slope failures.

composed of the dark brown gravelly fine sand, and a lower layer of gray clay which was observed in the failed head scarp. Heavy flow from these springs after intense precipitation apparently triggered the slides.

Torvane tests taken in the gray sticky clay were 0.10 to 0.17 tons/ft^2 (0.10-0.17 kg/cm^2) and the penetrometer gave a reading of 1.3 tons/ft^2 (1.3 kg/cm^2), indicating both very low shear resistance and compressive strength. The dark brown fine sand was weaker with torvane readings of 0.06 to 0.19 tons/ft^2 (0.06-0.19 kg/cm^2) and penetrometer readings of 0.7 to 1.3 tons/ft^2 (0.7-1.3 kg/cm^2).

The Route 5 slide was an earth flow. The flow mass had a width that varied from 150 to 200 feet (45.7-61 m) and was not channelized. There were no tension gashes as noted in other slides of this type e.g., North Hartland. Some slickensides were visible on both lateral scarps as well as the headscarp. Good evidence for this event having been a flow was the non-descript slush-like toe material which was still issuing water weeks after the slide. Trees on the surface of the slide mass ranged from saplings to 12 to 36 inches (30.5-91.4 cm) in diameter at breast height; most of these had a pipe-stem trunk structure indicating long term creep on the slope.

North Springfield flood control reservoir

Slope movements of serious proportions have been occurring since the first filling of the North Springfield reservoir due to the 1960 floods and all subsequent such events (Michael Curran, oral comm., 1984). Slope movements also occurred prior to construction of the reservoir, as evidenced by old pre-1960 landslide sites. Trees on these old landslide sites showed creep evidence based on "pipe-stem" structure, with their convex sides facing downslope near the bases of their trunks. Eroded slide scarps were also present. Of many old landslides that pre-date the construction of the flood control system, some were reactivated in 1984.

Three older landslide areas on the east slope within the flood pool of the reservoir had been stabilized by the Corps of Engineers. This stabilization was accomplished by grading the slope back to an angle of 26° (approximately a 2 on 1 slope) and the planting of selected types of vegetation. The southern part of the eastern slope was stabilized in two stages beginning in the fall of 1975 and completed in the summer of 1976; the northern part of this slope was stabilized in 1980 (Corps of Engineers resident engineer, (pers. comm., 1985). However, all of these slopes were reactivated in the spring of 1984 along with numerous new slides elsewhere in the basin (Fig. 13).

Fig. 13 about here

The failures at North Springfield reservoir can be best classified as earth flows, with some local variations. Two special features found at North Springfield were the configuration of the slide toes and the nature of the deposit. The deposit at one failure studied on the south-east side of the reservoir (A in figure 13) had a clayey sand, gravel and silt layer at the top. These materials were probably stream deposits laid down after the level of glacial Lake Hitchcock dropped. This would make the material which covered the slope face a reworked soil and/or slope wash. A lake-bottom rhythmite sequence underlies these deposits for some 60 feet (18 m). This latter sequence overlays a coarse gravel, cobble, and sand unit. These lower deposits may be those of an esker. The attitude of this lower unit, and the overlying rhythmites, changed along the slope length from north to south as follows: N. 55° E. dipping 30° NW, N. 60° E. dipping 9° NW, and N. 20° E. with a dip of 75° E. These attitudes indicate collapse structures possibly caused by stagnant ice that subsequently melted beneath these deposits. There exists an angular unconformity between the dipping layers and the top strata.

The bottom coarse gravelly deposits provided a zone of high permeability and high shear resistance beneath the slide mass. As was the case with the piping failures at North Hartland reservoir, water entered the coarse materials when the reservoir level was high. When the lake level was lowered, these coarse deposits provided water to the overlying material which was involved in the failure. The coarse bottom deposits did not become part of the slide mass except for slight mixing along the contact; the sliding mass passed over these materials leaving them almost intact.

Toes on failures at the North Springfield site were somewhat different from what was observed at the North Hartland site. At North Springfield, multiple ridges or hummocks of slide material were aligned parallel to the toe, whereas many of the toe areas at North Hartland had relatively smooth surfaces with en echelon tension gashes normal to the slide axis. At the site which was stabilized by the Corps of Engineers closest to the dam, on the east valley wall (B in Fig. 13), the hummocky toe consisted of a rigid layer which buckled upon sliding; small crevasses formed by the buckling became filled with fine grained fluidized material from beneath the flow (Fig. 14A). This buckled layer had the appearance similar to a rug which has been slid against a wall and folded.

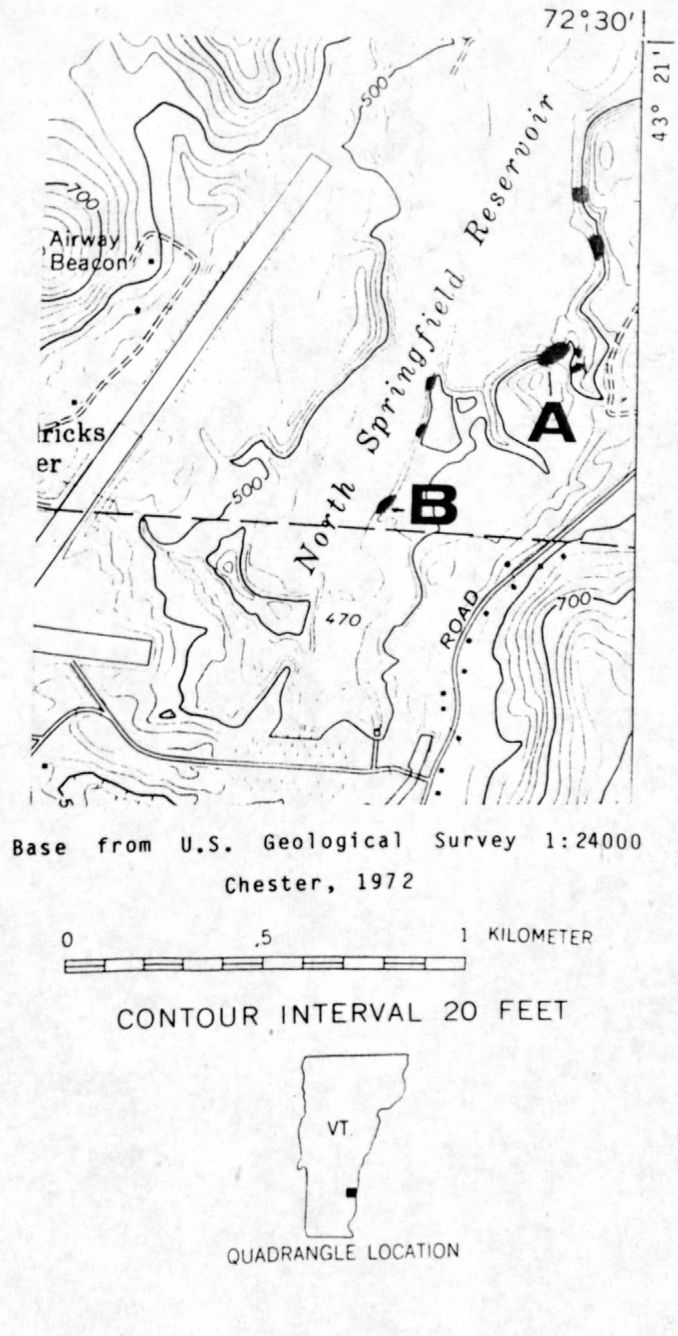


Figure 13. Site 7. Map locating the North Springfield Reservoir slide area. A is the location of the slide on the east side of the reservoir at which changes of attitude of the deposit was noticed over the slide length. B is the site of the Corps of Engineers slope stabilization project.

Figure 14 about here

In some of the toes the buckling appeared to go a step further probably due to a greater velocity or a greater fluidity in the sliding material. As the distal part of the toe stopped moving, slide material in the main track behind the toe would still be travelling on a fluidized substrate. The still moving mass then probably formed an overthrust sheet, and ramped up onto the first sheet. This process apparently repeated itself several times (Fig.14B). At the leading edge of a thrust sheet, a linear trough occurred that was filled with material from the fluidized fine grained substrate.

Sharon slope failure

The Sharon landslide is located in the White River valley on the east side of Vermont Route 14 about 2 miles (3.2 km) north of the village of Sharon (loc. 15, Fig. 1 and Fig. 15). The White River valley has been modified into a U-shaped valley by glacial erosion. While the glacier still occupied the valley, kames and eskers were deposited along the valley walls and bottom. After the glacier receded, the valley was occupied by Glacial Lake Hitchcock. Lake beds were deposited with some deltaic sediments emplaced above them. The present valley configuration was established when the glacial lake drained and the White River eroded the lake bed sediments and other glacial deposits. The White River presently flows along bedrock in this section of the valley.

Fig. 15 about here

The failure occurred in a terrace deposit along the east valley wall. The stratigraphy of the terrace from the top down is as follows: 0-12 in. (0-.305 m) light-brown sandy loam; 12-24 in. (.305-.610 m) tan to grayish-tan silt, with a slight trace of clay and very fine sand; 24-30 in. (.610-.762 m) crossbedded fine to coarse light-brown sand, some fine to medium gravel. This unit varies in thickness parallel to the valley trend, and shows definite foreset and bottomset beds. These deposits unconformably overlie about 56 feet (17.1 m) of rhythmically bedded gray silts and clays. Below the rhythmites is an esker deposit which is composed of stratified cobbly sand and gravel about 25 feet (7.62 m) thick.

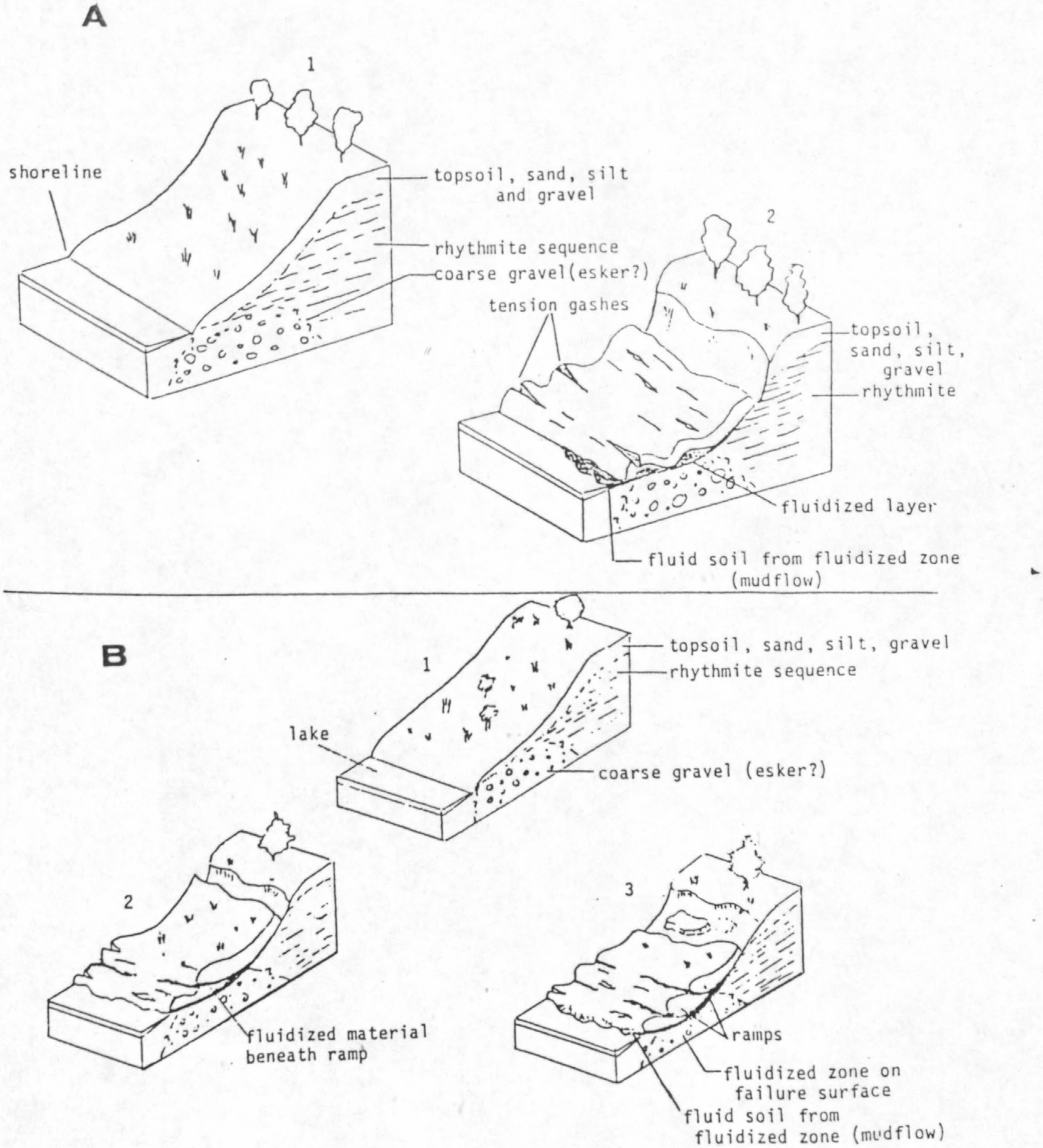


Figure 14. Section sketches depicting the processes for the formation of multiple ridges or hummocks at the east abutment of the North Springfield dam. (A) The hummocks developed in the intact layer are shown with the fine grained fluidized material from beneath penetrating the cracks in the upper layer. (B) Mode of overthrusting and ramping in the toe area of slope movements. These sketches are not to scale.

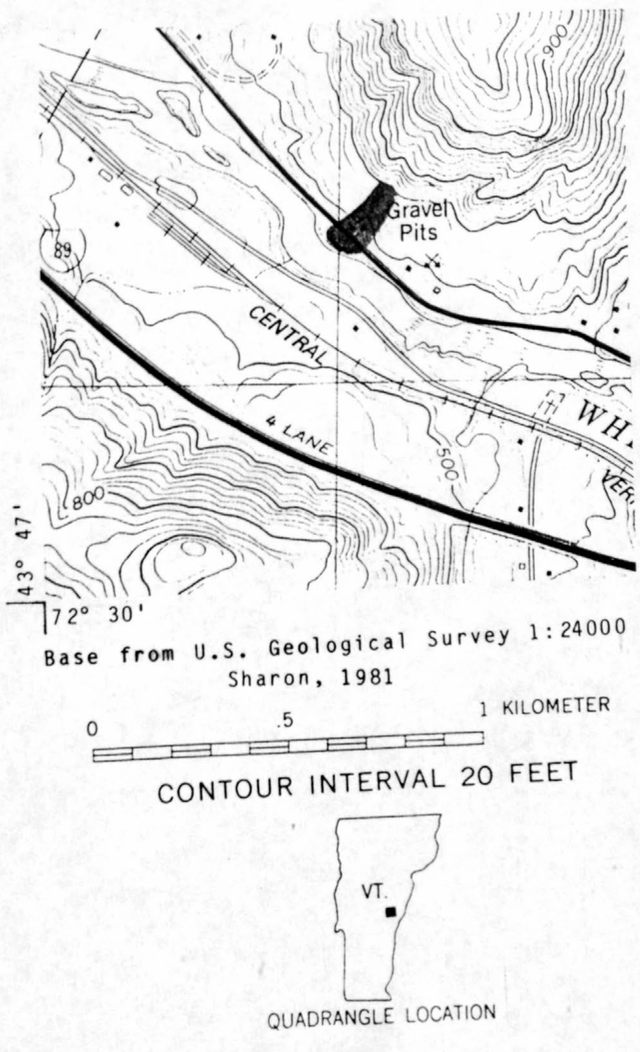


Figure 15. Site 16. Map locating the Sharon slide area.

The rhythmically bedded units at Sharon are glacial Lake Hitchcock bottom sediments. The rhythmite units have a slight dip to the east and are displaced by reverse faults (Fig. 16B) which dip steeply to the west.

Figure 16 about here

The sand units overlying the rhythmites are either deltaic deposits from a lake that formed later than glacial Lake Hitchcock, or stream sediments deposited on the rhythmite surface immediately after Lake Hitchcock drained. In either case, they fill in the low spot along the upper part of the terrace. The sand unit presents a cross section that has a concave downward bottom surface from west to east across the top of the terrace, similar to a section across a stream channel filling.

Thin layers of late or post Wisconsinan colluvium (Koteff, oral comm., 1984) are draped over the the deltaic deposits and rhythmites. A discontinuous clay layer within the colluvium is stretched and, in some instances, pulled apart in boudin-like fashion. These structures are the result of tension in cohesive materials due to downslope creep (Weller, 1960).

Prior to the failure which occurred in 1984, two borrow pits had been excavated into portions of the terrace. The first of these had removed the esker sediments from the lower part of the terrace facing on Vermont Route 14 (Fig. 16 (A)) The other borrow pit was dug into the top of the terrace where the deltaic sediments were the excavated materials. Both pits were inactive when the failure took place.

The width of the failure was approximately 100 feet (30.5 m) across at the headscarp and about 250 feet (76.2 m) across at the toe. At the top, near the headscarp, there are rotated blocks in both the sand units and the rhythmites (note tilted trees in right center part of Fig. 16C). Also in the slide mass are large chunks (± 3 feet (± .9 m)) of the rhythmite that failed and remained on the slope or near the point of failure as disoriented or jumbled blocks; a few of these have been rotated.

Before the excavation of the upper borrow pit, surface water runoff flowed off the terrace and did not saturate the deltaic sediments. This was due, more than likely, to the colluvium, which has a low enough permeability to have acted as a protective cap. After excavation, the upper pit became a catchment basin but there was no out-drainage channel. Water impounded in the pit saturated the sand unit above the rhythmite sequence, which

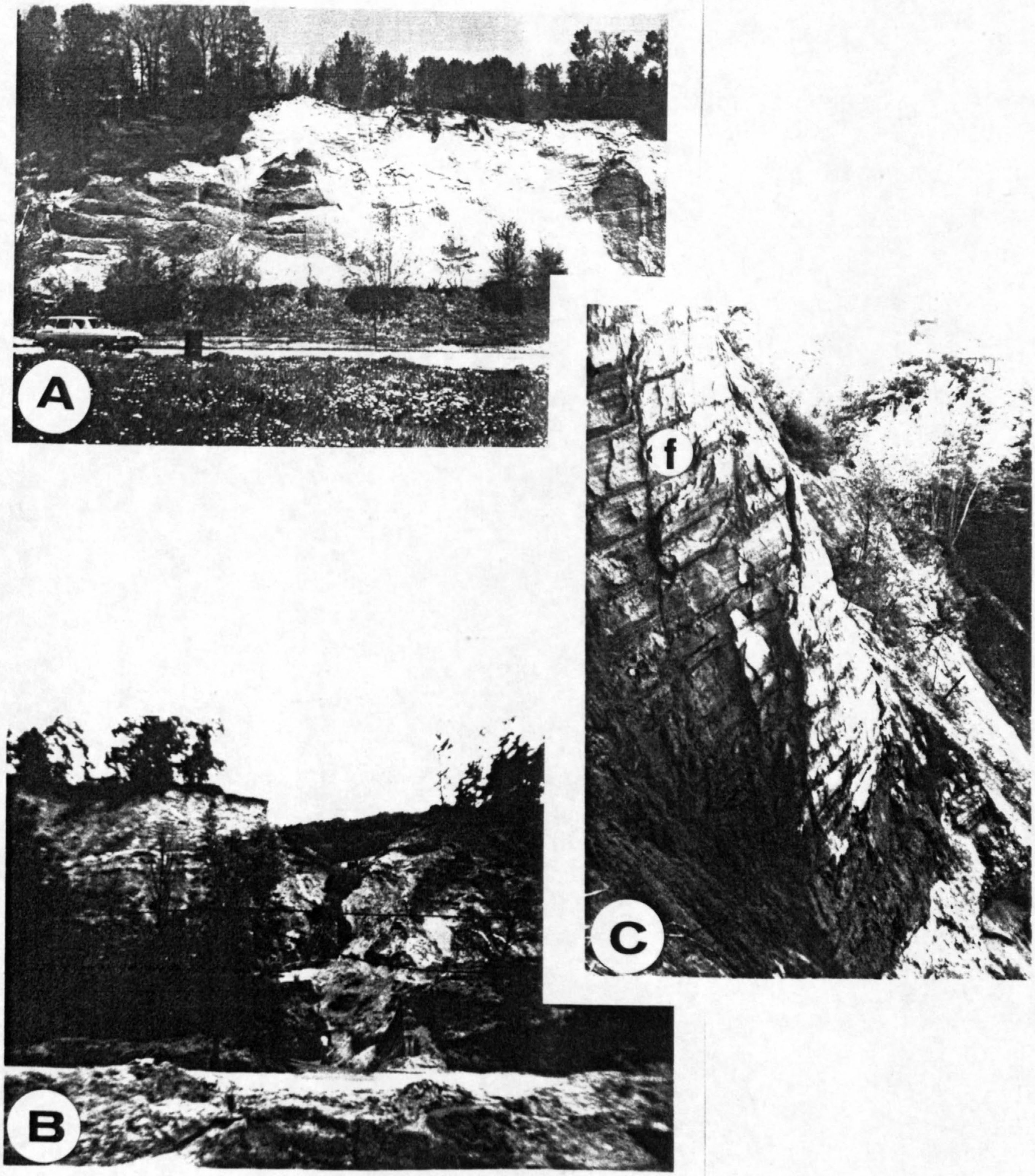


Figure 16. A view of the landslide site north of Sharon, Vt. on route 14. This photo shows how the site looked as a borrow pit facing Route 14 before the failure (A). The breach channel developed during failure is seen left of center in scene (B). The fault (at f in C) is one of several reverse faults exposed at this site. Photo (A) through the courtesy of Charles A. Ratte'.

acted as an impermeable bottom. As water in this pit deepened, it seeped through the rim and overflowed the rhythmite sequence, inundating the slope. Previously, evaporation and underflow drainage along the long axis of the pit, which slopes slightly southward, may have kept an equilibrium between inflow and outflow. However, intense rainfall in late spring 1984 may have completely saturated the sand layers and raised the impounded water level to the rim level at the face of the terrace.

Representative samples were taken down the face of the rhythmite unit. Torvane and penetrometer tests for shear resistance and compressive strength respectively, were performed at each sampling station; these stations were 6.54 to 9.79 feet (2 to 3 m) apart vertically. The tests show a low shear resistance for rhythmites in general, with the lowest resistance in the upper silty clays (Table 4). The clayey-silts have the greatest shear resistance of all the rhythmite units. Shearing resistance in the clays show an increase with decreasing moisture, and the clayey silts show an increase in strength as clay content decreases. The compressive strength of the rhythmite was relatively high--2 to over 5 tons/ft^2 (kg/cm^2).

Two other field tests were used to determine whether the fine grained materials were either predominantly silt or clay. The first of these tests was based on part of the procedure for identifying fine-grained soils test used for plasticity

Table 4 about here

determinations (ASTM D2488, 1985). A small sample of the material was rolled between the palms of the hands to a 1/8 inch (0.32 cm) thread as described in ASTM D2488 (1985) and Mathewson (1981). If the material ccould not be rolled, it was considered non plastic and that silt was dominant. If the material could be rolled easily to its plastic limit (near the 1/8 inch (0.32 cm) diameter) the material was considered plastic and clay dominated. We also used the ASTM Dilatancy Test (1985), see also Costa and Baker (1981). Relative particle size was determined by shaking a small cake of remolded rhythmite material in the hand to see whether water would come to the surface. If the water subsequently disappeared back into the cake, the specimen was mostly silt; if the sample was mostly clay, moisture would remain on the surface of the cake. The results of these tests are shown in Table 4 under the Dominant Particle Size column.

The failure took place in two phases. The first phase was a slump-earth flow along the back face of the lower borrow pit. The failure extended from the top of the terrace to the floor of

Table 4

Depth Below Top of Varve Unit	Field Torvane Readings in T/S/F *	Field Penetrometer Readings in T/S/F *	Dominant Clay/Silt Size
0.40 meters	0.41 0.30	5.0 + 5.0 +	Clay Clayey-silt
1.70 meters	0.15,0.30, 0.26,0.45 -	3.4, 4.3 - 5.0 +	Clay Clayey-silt Sand
3.70 meters	0.09,0.1 -	4.0 5.0 +	Clay Silty-clay
5.70 meters	0.47,0.49, 0.55	3.1, 3.3, 3.35	Clayey-silt
8.70 meters	0.35,0.43 -	2.25, 2.50, 2.75, 2.8 4.0, 4.5	Clay Silty-clay
12.70 meters	0.35,0.37, 0.39	1.8, 2.05, 2.15	Clay and silty-clay
16.40 meters	0.46,0.48, 0.56 0.76,0.07, 0.68	4.3, 4.65 5.0 + 4.3, 4.65	Clayey-silt Fine sand
17.00 meters	-	5.0 +	Very fine sand, some silt 46 to 61 cm thick.

Torvane and penetrometer tests of the varved deposits on the Sharon, Vermont slope. * T/S/F is numerically equivalent to kg/cm^2 using these instruments.

the borrow pit which is only slightly above the level of Vermont Route 14. The second phase started when the upper pit rim was breached by the first phase failure. A deep channel was cut down the face of the lower borrow pit by a slurry of sandy material as the upper pit drained. The material from this failure crossed Route 14, damaging a heavy trunk telephone cable paralleling the east side of the road as it passed. This second phase failure can be classified as a wet, sandy, earth flow.

Slope movements in ice-marginal deposits

A number of slope failures occurred in ice-marginal deposits at Stoughton Pond. Stoughton pond is part of the U.S. Army Corps of Engineers North Springfield flood control project (loc. 9, Fig. 1 and Fig. 17). Slope angles measured on the east slope of Stoughton Pond averaged 37° (75 %).

The surface of the glacial terrace on the east shore of Stoughton Pond near the dam, contains an elongated closed

Figure 17 about here

depression (kettle) (Fig. 18) that strikes N. 30 E. The floor of the kettle is about 15 feet (4.57 m) above the normal pond level. The crest of the west rim of this depression, which is also the east rim of the reservoir, is approximately 20 feet (6.09 m) above the depression floor. Rim width averages about 15 feet (4.57 m). The rim has been breached several hundred feet (tens of meters) north of the east abutment of the dam (Fig. 18). The breach extends 5 to 6 feet (1.52 to 1.83 m) below the top of the rim.

Figure 18 about here

The terrace materials are crossbedded, fine to coarse, glaciofluvial deposits. Most of these materials contain little silt or clay. The stratigraphic variation from north to south along the east shore is indicated in three descriptions shown in Table 5.

A few elongate lenses, 3.0 feet (.91 m) thick, of fine

Table 5 about here

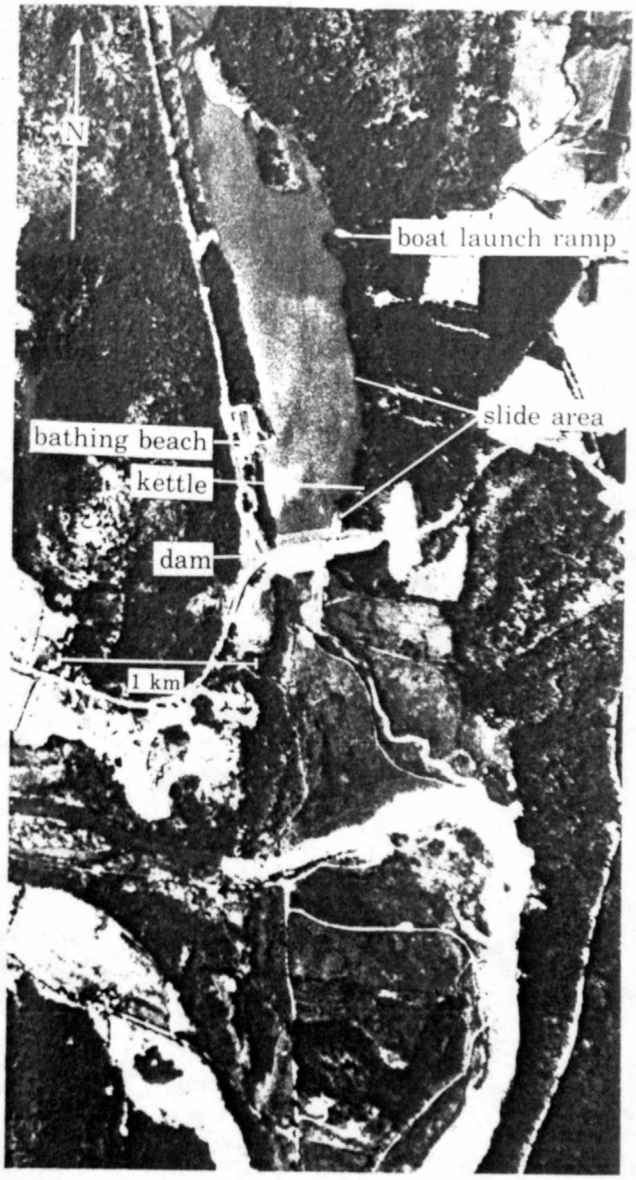


Figure 17. Enlarged portion of an aerial photograph of Stoughton Pond showing the location of slide areas on the east shore. (Photograph courtesy AeroGraphics Corp., Bohemia, N.Y.).

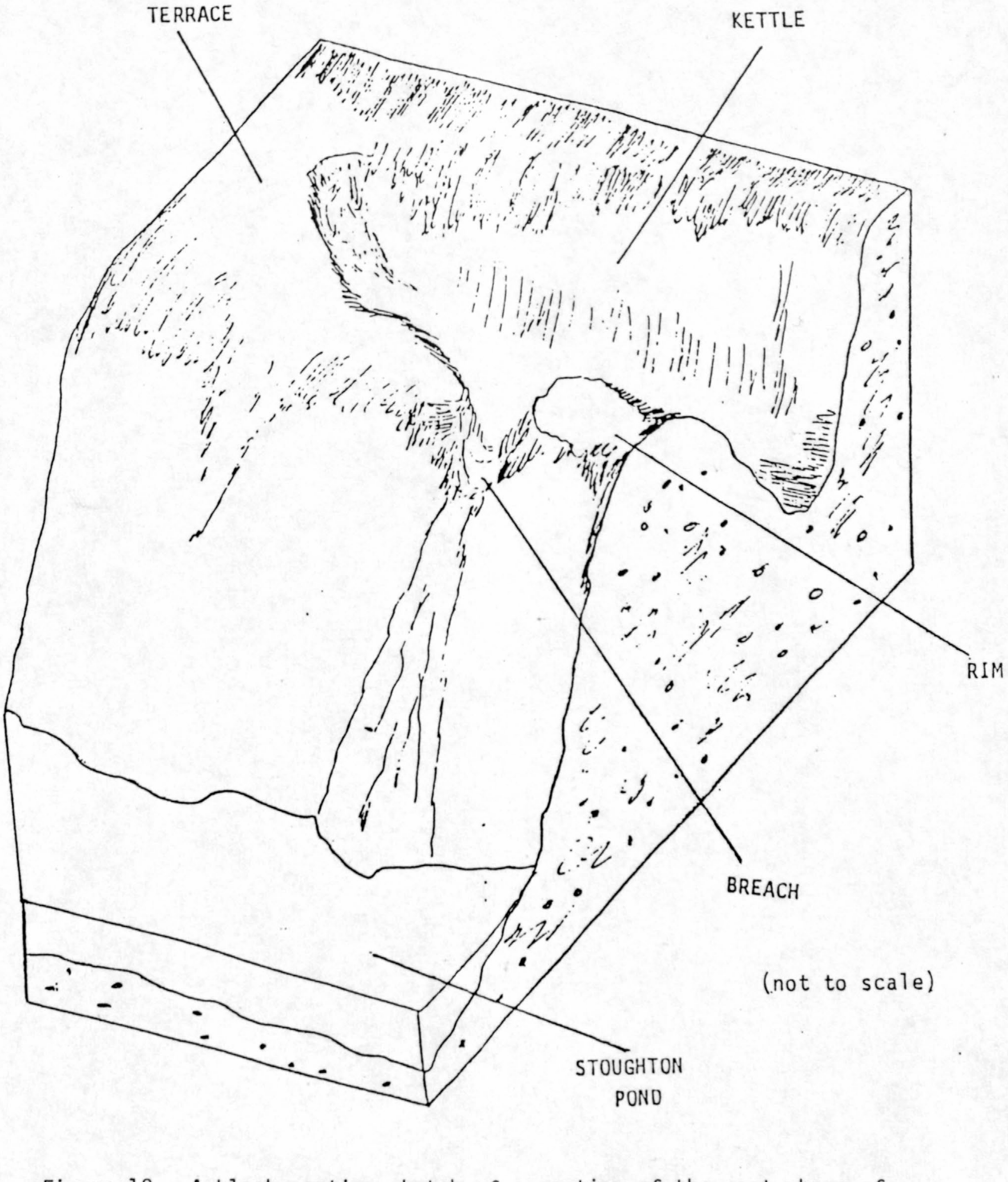


Figure 18. A block-section sketch of a portion of the east shore of Stoughton Pond to show the reservoir terrace kettle rim relationship. This sketch is not to scale.

TABLE 5

North | South

Depth from terrace surface in feet () = m	(1) South side of boat ramp approximately 3937.2 feet (1200 m) north of site (2)	Depth from terrace surface in feet () = m	(2) Approximately 200 feet (61 m) north of east abutment	Depth from terrace surface in feet () = m	(3) Approximately 150 feet (46 m) north of east abutment
0 -.167 (0 -.051)	Brown sandy topsoil	0 -.167 (0 -.051)	Gray-Brown topsoil	0 -.167 (0 -.051)	Gray-brown sandy topsoil
.167-22.95 (.051-6.996)	Dark brown fine to coarse sand, some fine to coarse gravel, trace to some cobbles and boulders, trace of silt	.167-.67 (.051-.203)	Brown silt with a trace of grit and gravel	.167-1.58 (.051-.483)	Yellowish-brown fine sand, some silt, trace of gravel and clay
		.67-1.25 (.203-.381)	Layer of gravel with a trace of cobbles	1.58-3.67 (.483-1.118)	Medium to coarse sand, some gravel, trace of silt
		1.25-22.95 (.381-6.966)	Brown fine to coarse sand, some fine to coarse gravel, trace of silt and boulders	3.67-3.99 (1.118-1.219)	Brown gravel, some coarse sand, trace of cobbles
				3.99-4.17 (1.219-1.270)	Yellowish-brown, cross-bedded, fine to medium sand, some silt, trace of gravel
				4.17-5.83 (1.270-1.778)	Brown cobbly gravel, some boulders and coarse sand - damp
				5.83-6.67 (1.778-2.032)	Coarse to medium brown sand, some gravel trace of silt
				6.67-8.42 (2.032-2.565)	Cobbly gravel, some boulders and coarse brown sand (cobbles and boulders are well rounded)
				8.42-9.09 (2.565-2.769)	Medium and coarse light-gray clean sand, trace of silt becoming more silty toward the base
				9.09-9.58 (2.769-2.921)	Light brown to tan silt and fine sand, trace of clay
				9.58-9.67 (2.921-2.946)	Brown clay
				9.67-10.08 (2.946-3.073)	Tan to white fine sand and silt
				10.08-10.34 (3.073-3.150)	Yellow-brown fine to coarse sand, some silt-damp; white clean fine sand near the bottom-dry
				10.34-10.83 (3.150-3.302)	Tan silt, some fine sand, trace of clay light-gray gravelly medium sand-dry light-gray medium to coarse sand-dry

Soil stratigraphy of three adjacent areas on the east shore of Stoughton Pond. Two near the east abutment of the dam, and one a little farther north near the boat ramp.

red-brown sand containing gray clayey-silt layers several centimeters thick, can be seen in section on some slide surfaces. The lenses range from approximately 16.0 feet (4.88 m) across to as much as the entire width of a failure which may be 100 feet (30 m) across.

Water flow from the reservoir into the kettle through the breach is indicated by broad aprons of cobbles and gravel on the kettle floor leading from the breach. Saplings growing in the kettle were killed by drowning; new leaves had started (spring,1984), but subsequently wilted. Mud on shrubs and tree trunks in the depression indicated that water stood at least 20 feet (6.10 m) deep. There were also indications of backflow into Stoughton Pond from the kettle as pond level was lowered. Distributary channels leading from the breach down the slope on the reservoir side of the rim, contained gravels from which the fines had been winnowed. When the pond level dropped below the floor of the breach, a pool of water about 14 feet (4.28 m) deep remained in the kettle.

The Stoughton Pond slope to the north of the kettle-rim showed evidence of long term creep. Here there were small slope movements of approximately 3.0 to 26.0 feet (.9 to 7.9 m) across, with head scarps 10 to 25 feet (3 - 7.6 m) upslope from pool level.

A piping of the glacial deposits was also observed just south of the kettle slides (Fig. 19). The pipes varied from a little over 1 foot to over 3 feet (0.3 to 1+ m) in diameter. In some of the incipient slide areas, evidence of high velocity underground flow was seen. There were several piping failures beneath the slope surface as evidenced by collapse and/or sagging of the ground surface over some of these pipes. The soil cover over piping tubes was composed of mats of topsoil and vegetation, underlain by a layer of loam, all of which was held together by a network of plant root systems. Beneath these sagging mats were large cavities (Fig. 19). Sand and gravel on the cavity floors had a flow-produced appearance similar to that seen on some large open slope movements.

Figure 19 about here

Sand and gravel deltas have built up along the pond's east shore slope near normal pool level, below where these pipes exit the slope (Fig. 19). Below pond water level off the mouth of these pipe-flow deltas, subaqueous pits were seen. These were obviously excavated by bottom scour of a high velocity slurry composed of water, sand, and gravel concentrated on the lake bottom at the locations of the pipe exits.

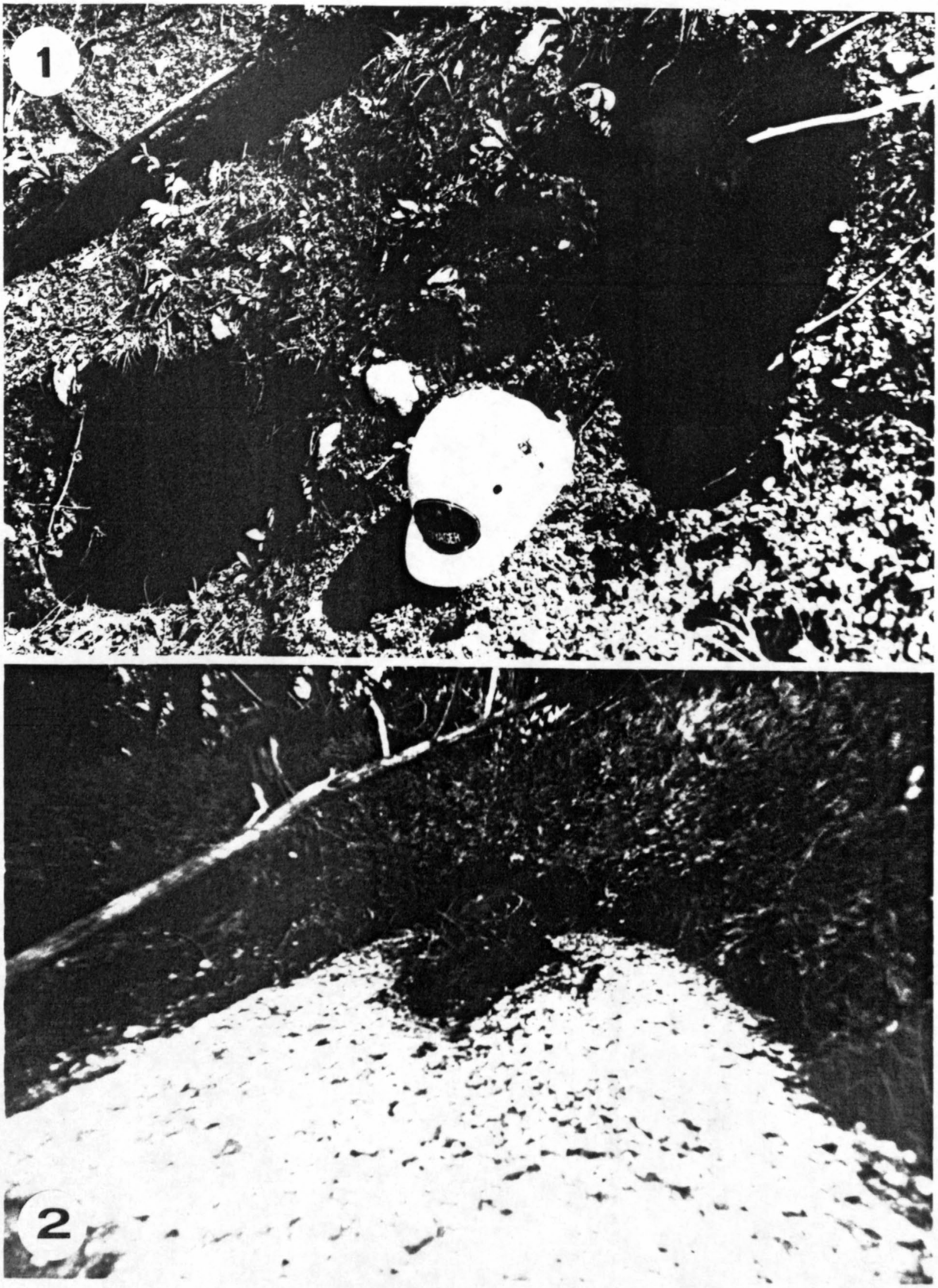


Figure 19. Photographs illustrating piping failures in the east slope of Stoughton Pond, an impoundment on the North Branch Black River. (1) Collapse pits over pipes--hardhat gives scale. (2) Outflow delta deposits from mouth of a pipe at pond level.

Slope movements at Stoughton Pond were mainly debris flows, approximately 3 feet (.9 m) to 25 feet (7.6 m) wide, and were composed of sands, gravels, boulders and vegetation. The failures were initiated by the drawdown of the high water in the reservoir created by the May, 1984 flooding. Wave erosion along the shoreline at normal pool level had oversteepened the slopes (noted at the time of our study) aiding instability. The red-brown sand lenses have a much lower permeability than the surrounding sands and gravels. Localized high pore water pressure zones formed in the materials immediately above the lenses and initiated slope movement along lens contacts.

Narrow distributary channels crossing the slide toe area and floored with gravel and cobbles, suggested a winnowing out of fines, topsoil, silt, and fine sand by relatively rapid ground-water outflow following reservoir drawdown.

The drawdown of the flood-filled reservoir was rapid as compared to the drop in the new high ground-water level in the slopes surrounding the pond. The soils were probably already near saturation due to spring snowmelt and rains prior to reservoir flooding.

As the reservoir was drawn down, the water table remained high due to a lag in the discharge rate from the soil. This situation caused excess pore water pressure that aided in a decrease in shear resistance of the slope materials (see Table 3). The high pore water pressures were also fed by the water which had ponded in the kettle. The pressure head provided by the water in the kettle, along with increased pore pressure in the bank soils allowed subsequent drawdown to weaken the materials on the slope. Failures were then initiated along the south-east rim of Stoughton Pond.

Other ice-marginal deposits occurred throughout eastern Vermont. These deposits should be considered to have similar failure characteristics as those at Stoughton Pond.

Slope movement in till deposits

Till deposits were involved in slope failures at two locations within the county. The first location was along Brook Road between Brownsville, and Windsor, Vermont (loc. 11, 18, and 21, Fig 1), and the other along Holbrook Hill Road between Hartland Four Corners and Brownsville (loc. 17 and 18, Fig. 1 and Fig. 20). The latter site is in the vicinity of the Hartland-West Windsor town line.

Brook Road

Along Brook Road (loc. 11, Fig. 1 and Fig. 12), five slope movements were examined that appear to have been active at various times during the last few years; all of which were reactivated in 1984. The materials at these failures were basal or lodgement tills which varied from dark gray-brown and gray clayey till to dark brown fine to medium sand and silt, some fine to coarse gravel, cobbles and boulders with a trace to some clay; there were extensive variations throughout these deposits. An ablation till lacking silt and clay overlaid the lodgement till. The natural slope angles along Brook Road averaged 32° (62%) to 40° (84%).

Figure 20 about here

Half a mile east of Brownsville along Brook Road was a small slump. The failure was 100 feet (30.5 m) wide and extended from the road 55 feet (16.8 m) vertically up slope. The scarp was about 9 feet (2.7 m) high and had an angle of 76° (well over 100%). The material in the scarp was dry to moist ablation till. Seeps and springs were common in the toe area of the failure and these appeared to be emerging along the contact between the upper ablation and a lower basal till unit.

A large landslide occurred about 0.4 miles west of the east end of Brook Road. The failure was a series of shallow block slides. The slope angle was 43° (93%) and the failure measured 200 feet (60.9 m) wide by about 50 feet (15.2 m) upslope. The material was a gray-brown sand and silt, with some gravel to boulder sized fragments and a trace of clay. At the level of the road, the material had piled up and rotated slightly. Periodically, highway crews had been removing the toe material which had slid out onto the road.

The other slope movements along Brook Road were in the same till sequence but were not as thick and rested on steeply dipping bedrock surfaces. These tills apparently absorbed large amounts of water as a result of the above average precipitation (Table 1) during the period beginning in the fall of 1983 and ending in the spring of 1984. Additional heavy rains in late spring (May 27 through 31 in particular) precipitated sliding by saturating the soil, thus reducing frictional forces.

Holbrook Hill Road

The materials involved in the Holbrook Hill Road slides (loc. 22, Fig. 1 and Fig. 20) were very compact lodgement tills overlain by relatively loose and permeable ablation till with a variable thickness of approximately 60 to over 100 feet (18 to 30.5+ m). Numerous landslides have occurred previously in this valley as indicated by hummocky profiles on the slopes. We noted

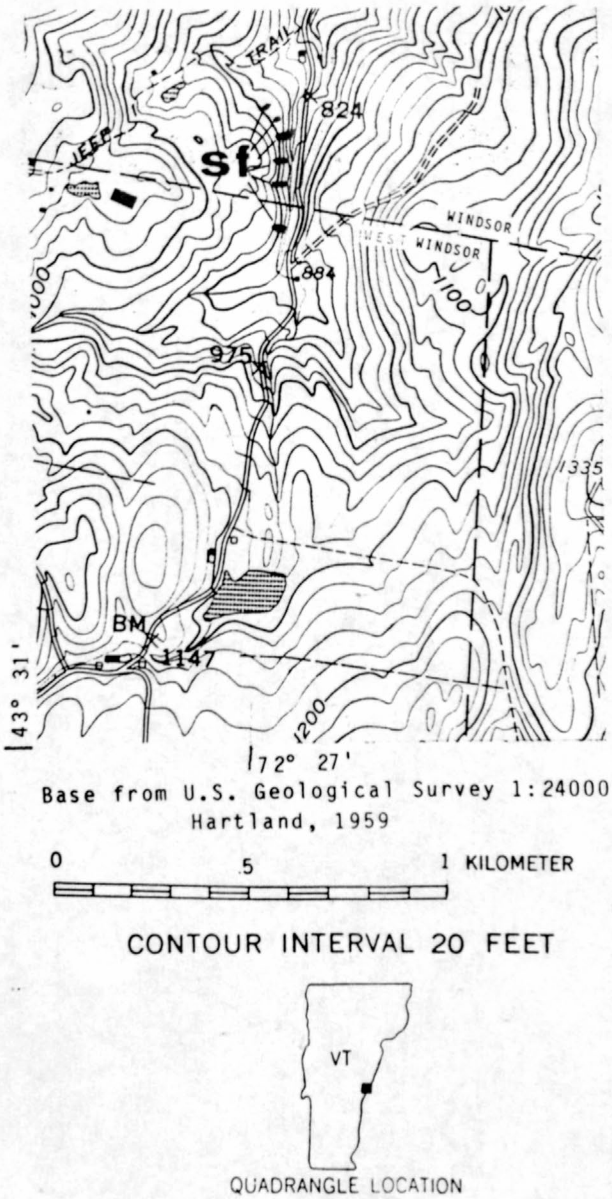


Figure 20. Site 23. Map locating the Holbrook Road slide area. The letters sf point out the slope failures.

that several slides in this hummocky terrane were reactivated in the spring of 1984, one of which took out a telephone pole. The head scarp of this latter slide is at the edge of an old abandoned road that is part of a larger interconnected network of abandoned roads upslope of the failure. The road appears to have channeled water from higher elevations into the permeable ablation tills. The ablation till extended for at least 100 feet (30.5 m) upslope from the slide and was composed of a dark brown fine to coarse sand, with 5% (trace) to 30% (some) silt, and fine to coarse gravel and cobbles. These soils were damp at the time of sampling and they had a loose, open texture. The lodgement till underlying the ablation till was composed of gray sticky clay with a trace to some fine to medium sand and gravel, and some cobbles and small boulders.

Within a distance of 0.2 miles (0.322 km), six active slides were observed; the largest of these was 60 feet (18.3 m) wide and 105 feet (32 m) upslope. Many trees up to 1 foot (.305 m) in diameter at breast height were taken down by the failure. After the failure, water was seeping out of the head scarp along the contact between the ablation and lodgement tills, and the slide plane was a wet slick mud.

Although there is a small stream at the toe of the slope, it apparently had not cut the toe and thus it was not the cause of failure. This appeared to be the case for other slope movements in similar basal till deposits in the Towns of Hartland and West Windsor. The streams in this area appeared to erode till with difficulty; whereas, slower moving ground water soaks these soils a few millimeters at a time. The loose open textured ablation tills had a high hydraulic conductivity. Ground-water flow through the ablation tills eventually soaked into the lodgement till for a short distance beneath the contact, producing a thin layer of soupy, sticky mud. This layer formed the zone of failure and allowed the overlying materials to move downslope. The actual slope movement was a combination of earth flow and block slide.

Summary and conclusions

Slope movements studied in Windsor County, Vermont, indicated that there is a high susceptibility to slope instability in practically every soil type in the area, especially when large volumes of water are added rapidly. The greater than normal precipitation in Windsor County for November 1983 through April 1984 (Table 1) saturated slope soils. The absence of significant drying during the period along with abnormal rainfall between May 29 and 31, 1984 exacerbated the problem (Table 1 and NOAA, 1984e). The occurrence of multiple failures during and immediately following the intense rainstorms of May, 1984, (J.E. Dyer, Proj. Mgr. North Hartland, and Thomas Coen, Proj. Mgr. North Springfield flood control dams U.S. Army

Corps of Engineers, pers. comm.; C.A. Ratte' State Geol., pers. comm.) indicates that the landslides were triggered by a buildup of pore pressure resulting from very high water tables.

Lake bottom sediments or rhythmites were found to present the greatest landslide problem in the study area. Earth flows were the landslide type most commonly associated with these deposits. The earth flows occurred as rafts of intact material riding on layers of fluidized material. Some failures had either rotational or slump movement in the scarp area, others had either translational or block slide movement. The surface layer of slide material at the North Springfield flood control reservoir had buckled in the toe area. The velocity of the slide mass and fluidity of the material in some instances developed overthrust sheets that would ramp up onto the sheets ahead that had slowed or stopped in their advance downslope. At the leading edge of these thrust sheets a trough parallel to this edge contained the fluidized fine grained substrate.

Ground-water flow in the reservoir slopes had a major effect on movement in these slopes. Water flow in the rhythmite deposits in these slopes was found to be confined to the silt and sand layers; there were instances of piping associated with some of the earth flows. At both reservoirs, reservoir filling due to heavy rain and snowmelt runoff raised the water table. As the reservoir was drawn down, the higher ground-water level flowed toward the reservoir, exiting the slope above pool level for some time. Where thick, non-cohesive sand layers were exposed by slope failures along the reservoir rim, sand was removed as the water flowed out forming pipes.

At several locations, pipe stem structure on trees was observed. Pipe stem structure can be a phototropic response by the trees or it can be caused by hillslope creep. The number of trees involved at the sites investigated indicates the latter to be the case. This is supported by tree ring data from the Route 11 landslide.

The slope failure at Sharon appears to have occurred in two phases. The first, a slump-earth flow, took place along the back face of the lower borrow pit. An impermeable clayey rhythmite acted as a floor for the upper borrow pit, separating it from the coarse deposits in the lower pit, allowing the upper pit to fill with water. The second phase failure began when the upper pit rim was breached by the first phase failure, releasing water contained in that pit. A deep channel was cut down the face of the lower pit resulting from the second failure as a slurry of sandy material ran down when the upper pit drained.

Slope movements in the ice-marginal deposits were mainly debris flows initiated by the drawdown of the high waters in reservoirs after the May, 1984 flooding. These failures were accompanied by piping in places. At the Stoughton Pond site, a high pressure head was maintained by water ponded in the terrace kettle on the reservoir's east rim which probably aided the piping there. Drawdown of the reservoirs was rapid as compared to the rate the water table level declined in the surrounding slopes. Excess pore water pressure, thus created, triggered slope failures.

Slope movements in till deposits at the Brook Road site resulted from reduced frictional forces brought on by saturation after the prolonged and intense precipitation infiltrating these sediments that were on bedrock slopes. At the Holbrook Hill Road site, the till deposits were a combination of an ablation till overlying a clayey lodgement till. Water traveling through the open network, high conductivity ablation tills saturated the surface of the clayey lodgement till below creating a layer of soupy, sticky mud which became the slide surface.

Some of the significance in these studies is in the similarity of failed material types over a great distance relative to grain size and engineering characteristics. The shear strengths in the various types of deposits tested ranged from a low of 0.032 tons/ft^2 (kg/cm^2) to over 0.5 tons/ft^2 (kg/cm^2) with the average shear resistance being 0.208 tons/ft^2 (kg/cm^2). The finer sediments also had the greatest cohesiveness, whereas the sandier layers had the least. Since the sandier layers have a higher hydraulic conductivity than the finer sediments, they would behave as aquifers. After slope failure occurred, it was common to find water seeping from the more sandy layers. If the sandy layer was thick enough, and became exposed during slope failure, it was subject to piping by escaping ground-water.

Compressive strengths are related to moisture content and grain size of the materials; whether the field tests were taken normal or parallel to the bedding, seemed to have no affect on the results. Overall, the silty-sands, silty-clays, and clayey-silts had the highest compressive strengths, averaging 3.16 tons/ft^2 (kg/cm^2).

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