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A Landslide in Glacial soils of New Jersey

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ABSTRACT

On August 13, 2000, a massive landslide occurred in Northern New Jersey following an extreme rainfall event during which at least 381mm (15 in) of precipitation fell during a 4-day period. The composite earth slide-earth flow, with an estimated volume of 22,800 m^3 (29,821 yd^3) traveled up to 365 m (1200 ft) in a short period. While landslides do occasionally occur along the coastal bluffs of the Atlantic Coastal Plain, slides of this magnitude are uncommon in the glacial soils of the New Jersey Highlands section, where the slide occurred.

A geotechnical investigation was undertaken to identify the causative factors of the slide. Soils within the rupture zone were found to be distinctly stratified in a direction parallel with the ground slope, which averaged 15% to 20%. The soil profile consisted of an Upper Till overlying a more compact Lower Till. A rupture surface developed at the stratigraphic contact between the two tills, with the Upper Till failing in translation. A significant factor in the location of the rupture surface was the density difference between the Upper and Lower Tills (averaging 16.11 kN/m^3 (102.5 lb/ft^3) and 20.44 kN/m^3 (130 lb/ft^3), respectively). Grain size analyses confirmed that the dominance of silt and sand in the Upper Till made it especially prone to sliding. Land use of the site was also a factor, since the rupture occurred on a hay field that was within a residential subdivision in the early stages of construction. The beneficial effects of root reinforcement were especially evident around the rupture scar, since headward and lateral migration of the slide were arrested by a bordering forest.

Analyses suggest that the main trigger of the landslide was groundwater perching at the contact between the two tills leading to excess pore pressure which caused failure. Two other conditions contributing to elevated groundwater pressure were a small topographic swale and outcrops of low permeability granite bedrock directly above the rupture zone. The paper concludes with a brief discussion of the implications of the Sparta landslide on the burgeoning development of Northern New Jersey.

INTRODUCTION

Between August 11 and 14, 2000, an extreme rainfall event caused widespread damage to two counties in Northern New Jersey. Doppler radar indicated that total rainfall reached an average of 381 mm (15 in) for the border area between Sussex and Morris Counties (National Weather Service, 2000). Locally, rainfall gages recorded precipitation rates as high as 102 mm (4 in) per hour and 483 mm (19 in) over a 12-hour period during the storm's peak on August 12. A summary of total precipitation during the 4-day storm over Northern New Jersey is shown in Fig. 1, which represents data acquired from 41 gages within the storm area (USGS, 2002). These amounts are a stark contrast to average annual rainfall for Northern New Jersey, which is 1180 mm (46.5 in) per year. The meteorological explanation for the storm was a stalled cell that remained stationary for nearly two days.

As the result of this extreme meteorological event, portions of Sussex and Morris Counties were severely affected by flooding, bridge washouts, dam failures and landslides. The Township of Sparta, located along the eastern border of Sussex County, was particularly hard hit with instances of all four natural disasters somewhere within its borders. A massive landslide in Sparta Township triggered by the storm is the subject of this paper.

The Sparta landslide occurred late in the morning on Sunday, August 13, approximately 16 hours after the heaviest rainfall of the storm had subsided. Intermittent precipitation was to continue for yet another 24 hours. The slide site is located in the lower elevations of the Sparta Mountains as shown on the topographical map in Fig. 2. The Sparta Mountains are within the New Jersey Highlands physiographic province, which is an area of moderate to high relief. While landslides do occasionally occur along the coastal bluffs of the Atlantic Coastal Plain of New Jersey and bordering states (Minard, 1974), slides of this magnitude are uncommon in the glacial soils of the Highlands section. In fact, the Sparta slide is large when compared to slides in California and other more landslide prone regions of the U.S.

This paper reports the results of an investigation of the Sparta slide to determine its causative factors (Talerico, 2003). The paper begins with a description of the slide including its geometry and genetic classification. The results of the field and laboratory investigations of the site soils are also presented. Factors and mechanisms contributing to the landslide are examined next, including land use, soil susceptibility, topography, and groundwater. The paper concludes with a discussion of the implications of the Sparta landslide on the burgeoning development in Northern New Jersey.

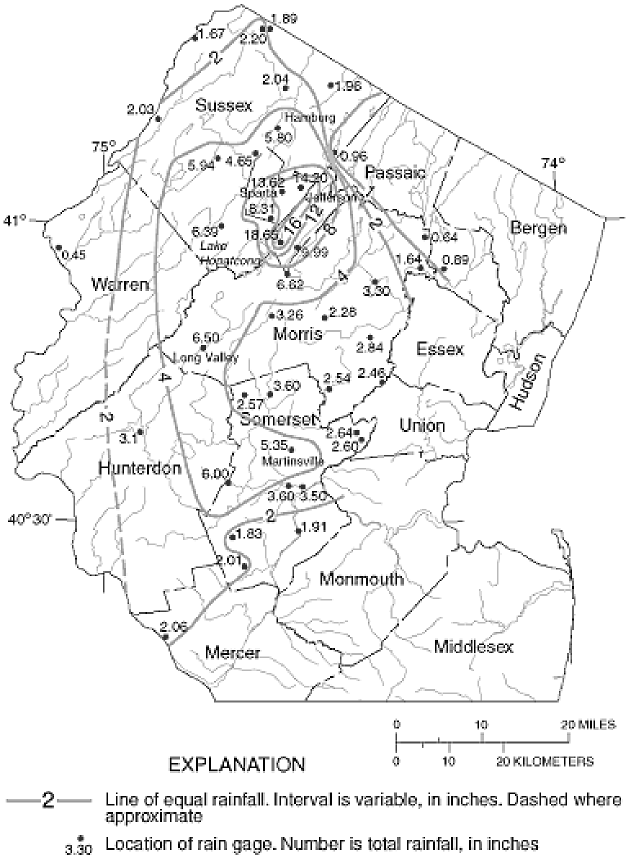

Fig. 1. Rainfall Summary for the August 11-14, 2000 Storm in Northern New Jersey (USGS, 2002).

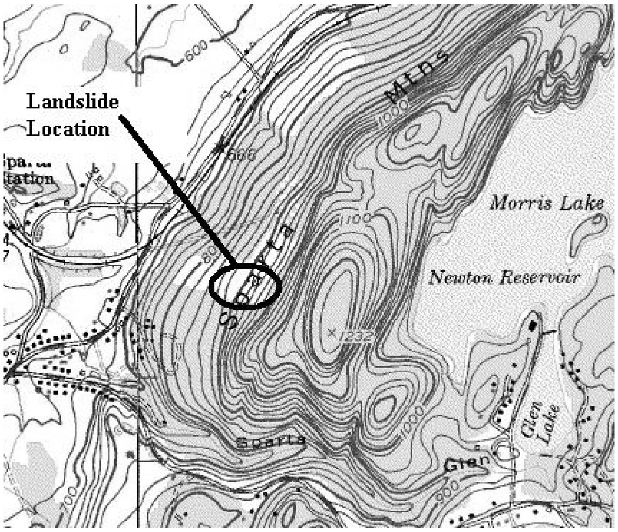

Fig. 2. Topographic quad sheets of Sparta, New Jersey (USGS, 1971).

SLIDE DESCRIPTION

The Sparta landslide occurred on the west side of a north-south trending ridge of the Sparta Mountains, initiating about halfway up the ridge. The slide mass traveled down slope eventually coming to rest at the base of the ridge where the slope flattened considerably. An aerial view of the lower foot of the slide, which was photographed by a private pilot about two hours after the slide, is shown in Fig. 3. It can be seen that the slide engulfed two roadways (Main Street and Route 517 By-pass) and a railroad track (NY Susquehanna & Western), covering them with mud to an average depth of around 1.2 m (3.9 ft). According to an eyewitness account, the slide traveled at a rate such that "one could easily walk fast ahead of the advancing mud." This corresponds to an estimated velocity of around 1 m/sec (3.3 ft/sec), which classifies as "very rapid" on the scale of landslide rate of movement (Varnes, 1978). Fortunately, no injuries were associated with the slide, although traffic on both roadways and a railroad line was interrupted for almost two days. An unoccupied pump house was in the path of the slide and was surrounded by mud up to 1.5 m (4.9 ft). It sustained minimal structural damage consisting only of collapsed doors and windows.

The slide occurred on a parcel of land that was in the early stages of construction for a residential subdivision. Portions of the site had been cleared and graded, and roadway construction was underway. Previous land use of the parcel had been agricultural, although farming activity had been reduced to a minimal level for at least a decade. Figure 4 depicts an aerial photo taken of the area approximately one decade before the slide event showing the vegetative cover to be a patchwork of cleared fields and

Fig. 3. Aerial view of lower foot of Sparta landslide.

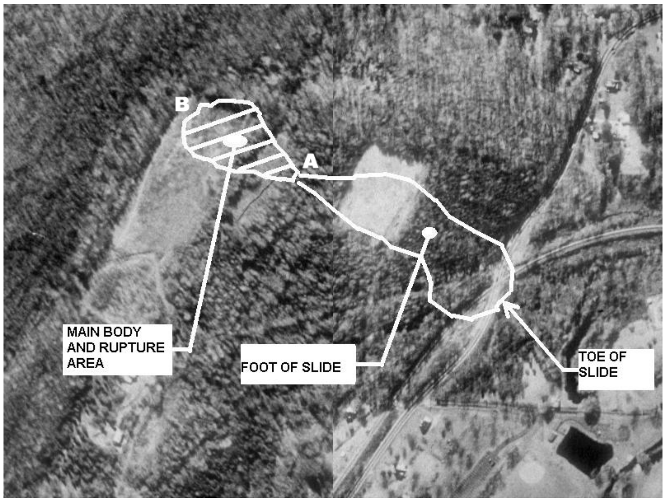

Fig. 4. Aerial photograph of Sparta Mountain showing slide limits (1-meter resolution) (Courtesy of teraserver.microsoft.com) (USGS, 1991).

forested areas. Superimposed on the photo are the limits of the slide including the main body and rupture area, the path of the slide material (or foot), and the toe.

From the perspective of genetic landslide types (Cruden and Varnes, 1996), the Sparta slide is classified as a composite "earth slide-earth flow." The slide apparently began as a progressive translational slide in the rupture area somewhere near point A. The slide then advanced headwardly up slope to the crown located at point B, thereby forming a "zone of depletion." Apparently, as the slide mass became mobilized, its high water content and loss of natural soil cohesion caused it to evolve into an earth flow, which then traveled down the mountain a distance of approximately 365 m (1200 ft). The steepness of the slope, which averaged 19%, furnished the necessary potential energy for the flow. A majority of the slide material followed the alignment of a newly cut roadway, which switch-backed down the side of the ridge.

The rupture zone was visited for the first time the day after the slide. At that time the depleted soil mass within the scar was still fully saturated and totally unstable. A saturation line was observed along the head scarp about 2.5 m (8.2 ft) below the ground surface, and groundwater was daylighting out at several locations to the extent that the noise of running water was audible. The head and side scarps remained nearly vertical, although column-shaped wedges of soil were still sluffing occasionally into the depleted zone. The photo, shown in Fig. 5, taken the day after the slide, provides an additional perspective of the failure. The photo was taken standing at the crown (point B) looking straight down the slide rupture surface towards point A. Note the irregular soil surface and the clumps of detached grassy vegetation.

A topographic survey of the rupture area was conducted to permit more detailed analysis of the slide. Using a total station, spot locations and elevations were taken within and around the slide. These data were compared with the pre-slide topography to develop topographic views of the rupture area before and after the incident, which are shown in Fig. 6. A centerline profile of the slide was also generated and is shown in Fig. 7. The massiveness of the slide becomes readily apparent by comparing these topographical maps. The rupture zone is roughly oval-shaped measuring a maximum of 67 m (220 ft) between flanks and 148 m (485 ft) from crown to toe of surface of rupture. The average depth of the slide as measured from the original ground surface to the failure surface was 4.3 m (14 ft). The total volume of the slide mass is estimated at 22,800 m^3 (29,821 yd^3), of which 17,050 m^3 (22,300 yd^3) of soil traveled down the mountain forming the foot (zone of accumulation), while 5,750 m^3 (7,521 yd^3) of displaced soil remained in the rupture zone (zone of depletion). The original ground slope before the slide ranged from 15% to 20%. The surface slope of the depleted mass after the slide was similar, although the ground surface was hummocky and had been lowered an average of 3 m (10 ft).

Fig. 5. View standing at landslide crown looking down the rupture zone.

GETOECHNICAL INVESTIGATION

Sparta Township and the surrounding region are glaciated terrain formed during the retreat of glacial ice at the end of the Pleistocene Epoch. Reconnaissance geologic information (Stone, *et al*, 2002) indicates that the surficial deposits are part of the Netcong Till, which is a Late Wisconsin deposit consisting of glacial till with occasional zones of residual soil derived from bedrock weathering, especially in steep areas and near summits. The till is dominated by sand and silt with variable amounts of gravel, cobbles, and boulders. Fragipans are encountered in some areas that reduce vertical seepage and restrict root penetration. Small seeps may occur in fragipan areas where there are significant slope changes. The surficial soils are underlain by hornblende granite of the Byram Intrusive Suite, which dates back to the Middle Proterozoic (Drake, *et al*, 1996). The granite is generally competent with slight to moderate weathering and moderate to wide jointing. Depth to bedrock is variable and can range from surface outcrops to depths greater than 10 m (33 ft).

A subsurface investigation was conducted to characterize the soils in the vicinity of the rupture zone. The first samples were

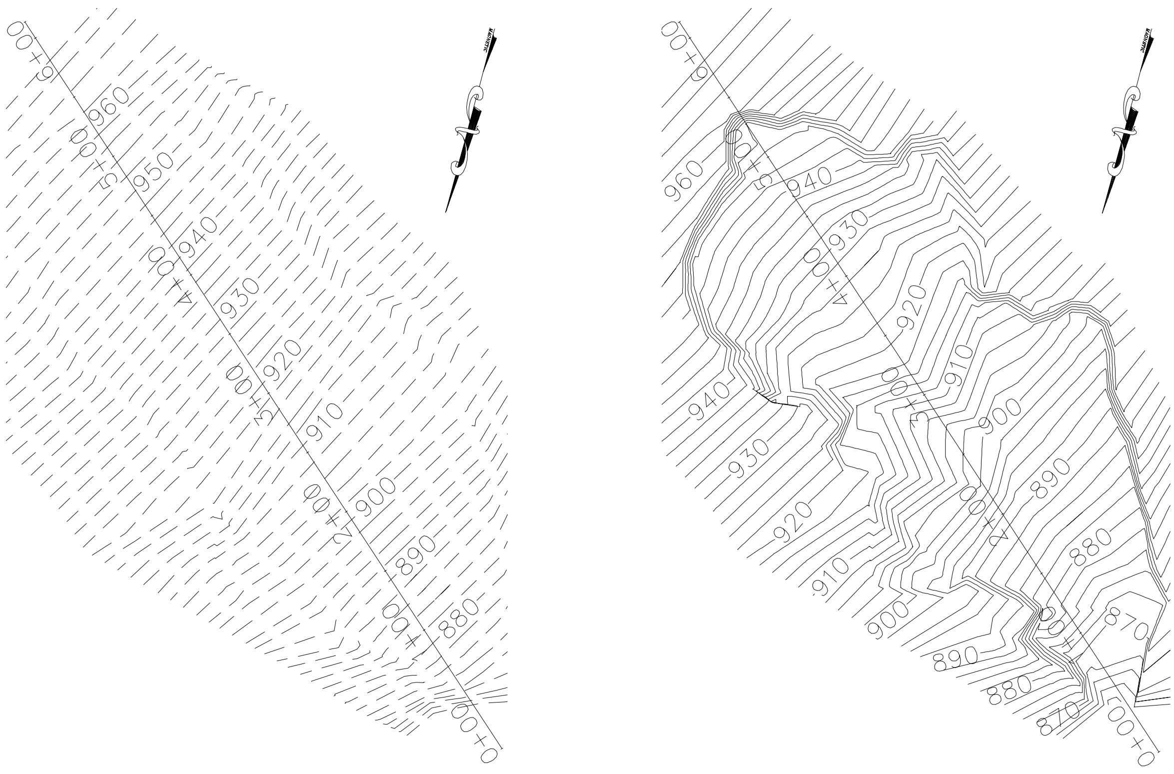

Fig. 6. Topography of rupture zone prior to the slide (left). Topography of rupture zone after the slide (right).

obtained one day after the incident from the toe of the landslide. These were analyzed and the results archived for eventual comparison with the rupture zone soils. The investigative team returned to the slide site months later to investigate the soil profile adjacent to and beneath the rupture zone. During these visits, samples were recovered from test pits excavated with a backhoe, and grab samples were also secured from various locations and depths around the exposed scarp. Soil samples were visually classified, preserved, and then returned to the university laboratory for further analysis.

The field investigation quickly revealed two distinct strata within the rupture zone. A brown sandy till, termed the Upper Till, extended from the ground surface to an average depth of 4.3 m (14 ft). The Upper Till was underlain by a gray sandy till, which contained more frequent cobbles and boulders, and was obviously more compact. Excavation within the slide scar extended a depth of 9.75m (32 ft) below original ground surface without encountering bedrock. The contact between the Upper Till and Lower Till was observed to be distinct and abrupt. Overall, the soils throughout the rupture zone displayed a remarkable degree of textural consistency, both laterally and vertically.

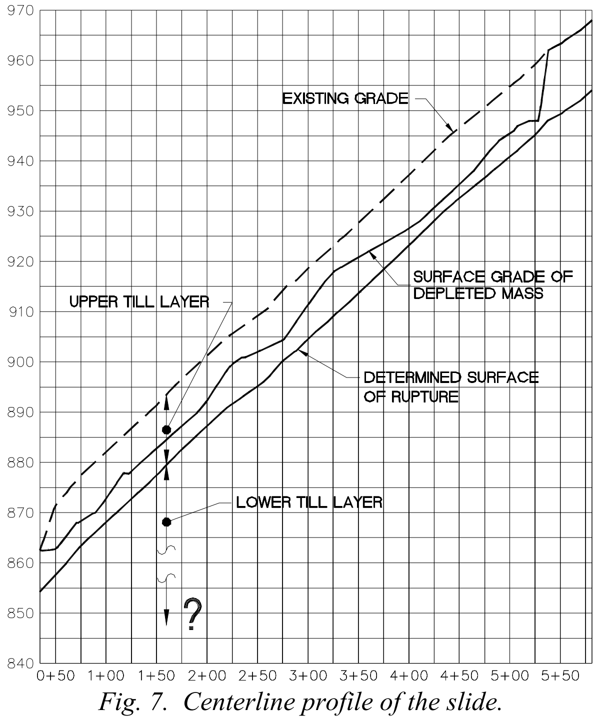

Fig. 7. Centerline profile of the slide.

Laboratory tests were conducted on recovered soil samples to confirm field classifications and to determine index properties. Samples were analyzed for natural moisture content, grain size (both sieve and hydrometer), Atterberg limits, and specific gravity. Standard procedures as published by the American Society of Testing and Materials (ASTM) were followed for all testing. The laboratory classifications for the soils in the rupture zone are summarized in Table 1, and the grain size curves are plotted in Fig. 8. As indicated, the Upper Till is a Silty Sand with a Unified Classification of SM. The texture of the Lower Till is coarser with 22% gravel (compared with 5% gravel in the

Upper Till), and it classifies as a Silty Sand with Gravel, SM. Both tills were found to be non-plastic according to Atterberg limits testing, although field observation suggests that the Upper Till is slightly plastic owing to its ability to hold a near vertical slope over intermediate periods. The specific gravity of all the samples ranged between 2.68 and 2.69.

An interesting trend is evident in Fig. 8 if one compares the grain size curves for the Upper Till (S-1 thru S-3) with those of the slide material recovered from the toe (1A thru 1C). Since the field investigation demonstrated that the slide material originated from the Upper Till, the grain sizes should theoretically be the same. As expected, both soils have the same classification: Silty Sand, SM. However, the grain size curves for the slide material are shifted downward indicating a coarser texture compared with the Upper Till. This shift is attributed to segregation and loss of fines as the soil migrated from its *in situ* location.

Early in the course of the geotechnical investigation, the team began to suspect that the rupture surface was the contact between the Upper Till and the coarser Lower Till. It was therefore decided to compare the unit weights of these strata with a nuclear density meter. Readings were taken on the north flank of the landslide at three different depths, two within the Upper Till and one just within the Lower Till. The density test results are summarized in Table 2, which also gives qualitative estimates of field density recorded during test pit excavation. The measurements showed that the unit weight of the Upper Till, which averaged 16.11 kN/m^3 (102.5 lb/ft^3), was significantly less than the dry unit weight of the Lower Till, which was 20.44 kN/m^3 (110 lb/ft^3). Considering that the specific gravities of the two strata are nearly identical, this represents approximately a 26.8% increase in unit weight, which further confirmed the planar location of the rupture surface.

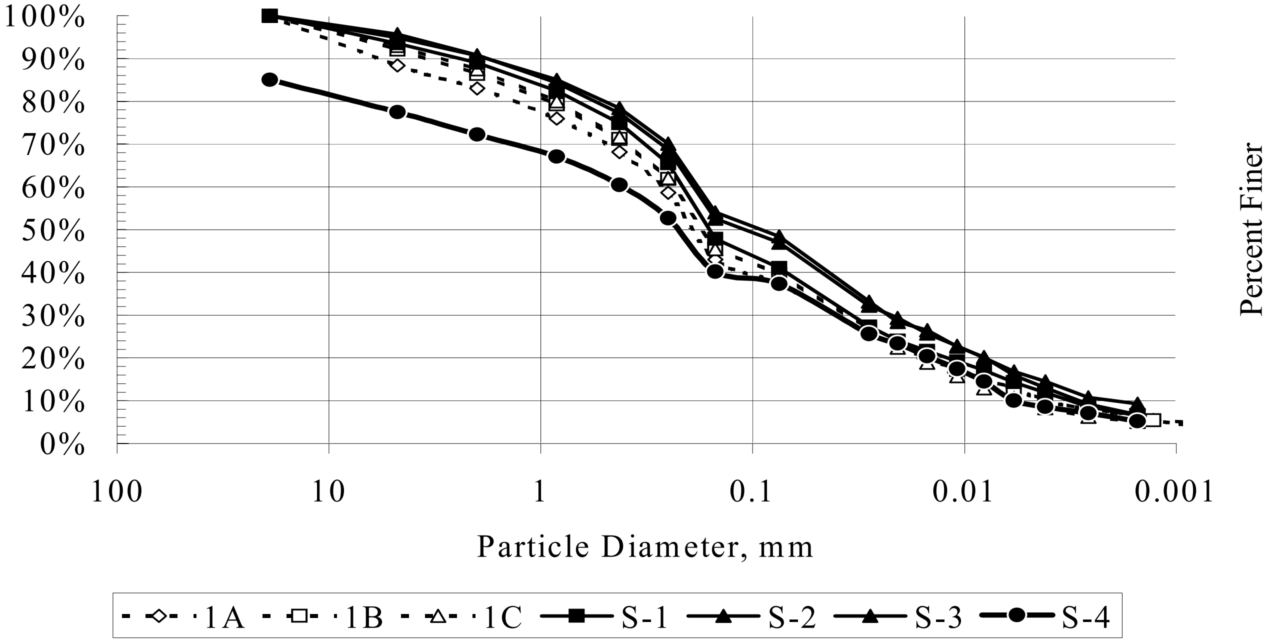

Fig. 8. Summary of grain size curves for rupture zone soils

Table 1. Laboratory test results for soils in the rupture zone.

Stratum	Sample No.	Location	Depth below original ground (m)	Unified Symbol	Textural Description
Upper Till	S-1	North Flank	0.9	SM	Brown Silty Sand
	S-2	North Flank	0.45	SM	Brown Silty Sand
	S-3	North Flank	2.4	SM	Brown Silty Sand
Lower Till	S-4	Middle of Rupture Scar	4.3	SM	Gray Silty Sand with Gravel
Slide Material	1A, 1B, 1C	Toe of Slide	0.3*	SM	Brown Silty Sand

* depth measured below the surface of the slide mass

Table 2. Summary of Field Density Tests.

Stratum	Depth below original ground (m)	Dry Unit Weight (kN/m3)	Field Density Estimate
Upper Till	0.6	14.94	Loose-medium dense
	2.44	17.29	Medium dense
Lower Till	4.57	20.44	Dense

CAUSATIVE FACTORS OF THE SLIDE

Landslides are rarely the result of any single cause, but rather they are the combined result of several causative factors and mechanisms. Probably the most critical factors are the geologic and hydrogeologic conditions of the site, which must be favorable for sliding. As important is the terrain of the site, which must be steep enough to furnish the required potential energy for the particular sliding mechanism. Most mechanisms require a least a moderately steep slope, although certain kinds of slides such as spreads occur on relatively flat terrain. Land use, both past and present, can also factor significantly into landslide events, especially when modifications have been made to slope geometry or natural vegetation. Finally, a triggering event such as intense rainfall or an earthquake is usually required to initiate a slide. In the end, it is a combination of factors that eventually answers the two important engineering questions that surround every landslide investigation: Why did it slide here and not there, and why did it slide now?

This section of the paper discusses the causative factors of the Sparta landslide. Included is an analysis of soil susceptibility, geologic stratification and terrain, land use, and groundwater effects.

Soil Susceptibility

Numerous studies of landslides have established the range of soil grain sizes that are most susceptible to sliding. Soils containing large amounts of clay or gravel are less susceptible, since these soil components have a stabilizing influence on a soil mass. In this context, the texture of the Upper Till at the Sparta slide was analyzed and compared with historical data from nine landslides in the area of San Francisco, California, which occurred as a result of a record storm (Howard, *et al*, 1988). The California landslides are genetically similar to the Sparta slide, i.e., composite slide-flows. The results of the comparative analysis are plotted on the grain size triangle shown in Fig. 9. As indicated, the Upper Till falls within the zone of historic landslide soils, which is centered on silty and sandy soils. This demonstrated that the glacial soils at the Sparta site qualify as landslide prone.

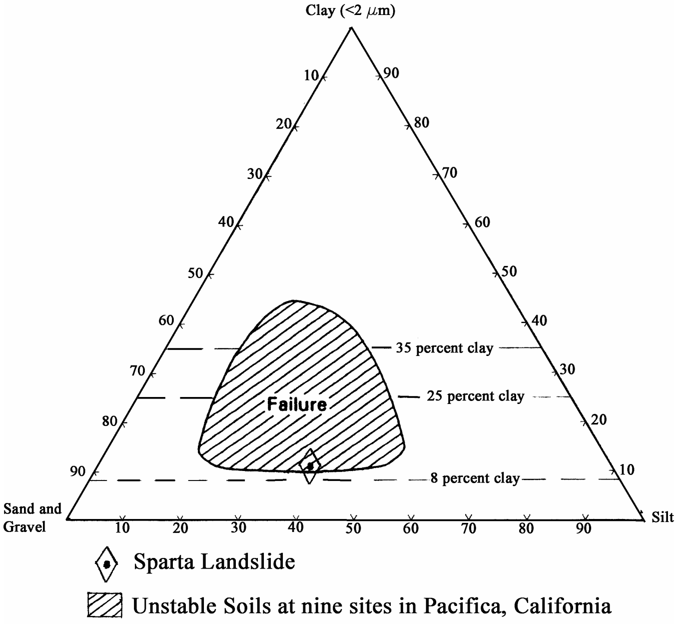

Fig. 9. Correlation of landslide occurrences with soil classification (modified from Howard, et al, 1988).

Stratification and Terrain

The geotechnical investigation established that the glacial soils in the vicinity of the slide rupture zone were distinctly stratified in a direction parallel with the ground slope: a fine-textured Upper Till layer overlying a coarse-textured Lower Till layer (refer back to Fig. 7). Furthermore, field density measurements confirmed that the Lower Till was considerably more compact than the Upper Till. This stratigraphic discontinuity became the rupture surface of the slide. The remarkable uniformity of the two tills with regard to thickness and lateral extent likely explains the massiveness of the slide. The origin of the till layering at the site is apparently the result of complex melting mechanisms of the receding continental glacier in the Sparta area. It is speculated that the layering may reflect a local retreat and re-advance of the ice front, since the compactness of the Lower Till suggests it was subjected to some amount of ice weight (lodgement till), while the looseness of the Upper Till indicates it was dropped directly from the ablating ice (ablation till).

The original ground slope of the rupture zone ranged from 15% to 20%. Such slopes are sufficient for translational slides and earth flows, which typically occur on slopes ranging from 7% to 36% (Sidle, *et al*, 1985).

Land Use

The dominant land use of the Sparta area has been agricultural since it was first settled in the 1700s. More recently, Sparta and the surrounding townships of Sussex County are evolving into bedroom communities for the New York City Metropolitan Area. As previously seen in the aerial photo in Fig. 4, the current vegetative cover of the landslide site consists of a patch work of fields and forests. The presence of stone fences seen winding through adjacent forested areas definitely suggests that farming activity was more intense in the past. Approximately two years prior to the event, construction of a residential subdivision commenced on the parcel of land containing the slide. Development was proceeding slowly according to an approved site plan. At the time of the slide, a limited amount of clearing and grading had been accomplished, and roadway construction was underway.

The possible effect of the ongoing construction activity on the landslide was examined. One influence was the newly constructed pioneer road, which apparently provided a "path of least resistance" for the traveling mud flow. This explains the remarkable length of the landslide foot (365 m, 1200 ft). Another possible influence was a road cut located adjacent to the rupture zone. While the investigative team concluded that the slide could have occurred from the other factors alone, the road cut may have affected the magnitude of the slide. As this paper is written, engineering measures are being evaluated to help protect the site from future earth movements.

The field investigation yielded some striking observations about the ability of root systems to stabilize soil slopes. The rupture area is located on a weedy field of grass that was reportedly used for hay production up until recently. As might be expected, root penetration of the grassy vegetation rarely exceeded 0.5 m (1.5 ft). However, the rupture area is abutted to the east and south by medium-growth forest, and it was along these boundaries that the beneficial influence of root reinforcement was clearly observed. The slide, which had progressed from west to east, was stopped rather abruptly at the two tree lines. A virtual wall of roots, many penetrating in excess of 3 m (10 ft), was seen exposed along the scarp of the crown and south flank. Additional confirmation of the anchoring power of roots was provided by a lone tree left standing near the center of the rupture scar. Apparently, this "tree island" stood fast in a sea of sliding soil.

Groundwater Effects

While it is clear that the main trigger of the landslide was the intense rainfall event, the investigation sought to determine the failure mechanism more precisely. A drainage study showed that the tributary drainage area of the rupture zone is approximately 3.4 ha (8.3 ac). Since the runoff generated by the rainfall was computed to be approximately a 1,000-year storm (USGS, 2002), the resulting infiltration would have been more than sufficient to cause full soil saturation in the rupture zone, i.e., groundwater table at the ground surface. For the predominantly granular tills present at this site, full saturation will reduce effective soil stress and global stability by around 50% owing to buoyancy effects. However, this is certainly not the first time that full soil saturation has occurred, and yet there is no record of any previous major slides at the site.

A closer look at the geologic and hydrogeologic conditions was undertaken to gain insight into slide trigger. It is recalled that the Lower Till was considerably more compact than the Upper Till. Since both tills have similar fine contents, an increase in packing density will reduce soil permeability. The resulting effect would be ground water perching on the surface of the Lower Till. And since the tills are inclined at an average slope of 19%, the ground water will move down slope at a significant velocity. It is therefore speculated that as the storm intensity and infiltration increased, pore pressures in excess of static head conditions were created. The excess pore pressure, in turn, reduced the effective stress in the soil.

A stability analysis utilizing the infinite slope method was conducted to examine the role of excess pore pressure on the failure. Estimates of the angles of internal friction were made for the tills using standard correlations with grain size and unit weight. Cohesion was assumed at zero. Based on the knowledge that the failure did occur, the factor of safety was set equal to 1.0, and a regressive analysis was conducted over a range of probable friction angles. The analysis showed that while the slope would have been stable under static groundwater conditions, excess pressure heads as small as 1.5 m (5 ft) could have led to sliding failure at the till interface. The analysis results strongly suggest that the final culprit of the Sparta slide was excess ground water pressure.

Two other conditions likely exacerbated the build-up of groundwater pressure. First, a small, but definite, topographic swale was observed directly above the rupture zone (see photo in Fig. 10). Minor topographic deviations can concentrate infiltration and increase groundwater pressures locally, and are often associated with slope failures (Domenico and Schwartz, 1998). Such swales, which are often non-obvious on topographic maps, help to answer the question: why did the slope fail here and not there? A second condition that likely contributed to groundwater build-up was the bedrock outcrops located on the slope above the rupture zone. The granite bedrock, with its characteristic low permeability, likely concentrated the groundwater in the overlying tills.

Fig. 10. Photograph of natural swale located above the crown of landslide.

CONCLUSIONS

In August 2000, a major landslide occurred in Sparta, New Jersey as a result of an extreme rainfall event. The composite earth slide-earth flow, with an estimated volume of 22,800 m^3 (29,821 yd^3), was massive by any standard. The purpose of this paper was to describe the slide and identify its causative factors.

The geotechnical investigation revealed that the stratification of the site soils played an important role in the slide. Failure occurred at the contact between two glacial tills, an Upper Till and a more compact Lower Till. The dominance of silt and sand in the Upper Till made it especially prone to sliding. Another contributing factor was the land use of the site: the rupture zone was a hay field without significant root reinforcement, and construction of a residential subdivision had begun on portions of the site. The final trigger of the slide was attributed to groundwater effects, and it is speculated that groundwater perching at the contact of the tills elevated the pore water pressure to the point where effective stress was reduced to zero.

As this paper aptly demonstrates, landslides are usually the result of a complex combination of causes and conditions. At first glance, the Sparta slide might appear to be a very random occurrence, given the lack of precedent for such slides in the glacial soils of New Jersey. Upon closer examination, however, the Sparta slide may actually be a wake-up call for engineers, developers, and regulatory agencies in the region. There is little doubt that extreme meteorological events like the storm of August 2000 will occur again, and based on recent climate trends, the frequency and intensity of these storms appear to be increasing. Such storms are the typical triggers for landslides along on the East Coast.

A second cautionary note is related to the pattern of the burgeoning development within the Tri-State region. Residential subdivisions and commercial centers are spreading ever deeper into the New Jersey Highlands and the adjacent Folded Appalachians, as available property closer to New York disappears. The topography of these areas is often severe, causing significant design challenges from a grading point of view. Even so, only relatively few municipalities have adopted steep slope ordinances and those that have usually apply them for population density control. Municipalities do not normally require designers to examine issues of global stability. New Jersey and the surrounding states could benefit by applying the well-established principles of landslide prevention. Adoption of ordinances that require more thorough geotechnical investigations for steep slope sites would be an important first step.

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