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A Study of a Road Landslide in Puerto Rico

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SYNOPSIS: Numerous landslides have plagued the construction of a 1.3 mile road sector in the mountainous region of central Puerto Rico. The area is underlain by a sequence of landslide deposits overlying a muddy limestone and hard overconsolidated clayey soils. Landslides have occurred in both cuts and fills that have delayed the road construction for a period of more than two years, bringing as a result, great economic losses for the Puerto Rico Highway Authority. The landslide trigger mechanism has been intimately related to high rainfall, commonly observed in this region. The geotechnical and geological studies performed previous to the construction of this road sector were few and meager. These studies did not recognize the presence of unstable deposits along the road sector alignment. As a result, several large slope failures developed during construction that halted the completion of the road. For investigating the slope failures, detailed geological and geotechnical studies were performed, including monitoring of groundwater levels, rainfall, and slope movements followed by laboratory and slope stability analyses. Remedial measures have been provided in the form of excavation, drainage, and stability berms. Renewal of the road construction with the remedial measures is prompt to start.

INTRODUCTION

Numerous landslides have plagued the construction of a 1.3 mile road sector in the mountainous region of central Puerto Rico. The area is underlain by a sequence of landslide deposits overlying a muddy limestone and hard overconsolidated clayey soils. Landslides have occurred in both cuts and fills that have delayed the road construction for a period of more than two years, bringing as a result, great economic losses for the Puerto Rico Highway Authority. The landslide trigger mechanism has been intimately related to high rainfall, commonly observed in this region.

The road sector alignment runs parallel to a high limestone scarp which rises at steep angles to elevations of up to 400 feet above the road level. North of the scarp is a cone-karst terrain characterized by north-south and east-west trending limestone ridges, sinkholes and inter-ridge valleys. The proposed road grade follows a 300 to 600 feet wide bench along the base of the scarp. The bench is underlain by an 80 ft. thick sequence of landslide deposits, hard overconsolidated clayey soils and volcanic rock. The ground surface south of the bench steepens considerably toward a river running 450 feet below. Figure 1 shows a schematic cross section drawn at the road sector.

The geotechnical and geological studies performed previous to the construction of this road sector were few and meager. These studies did not recognize the presence of unstable deposits along the road sector alignment. As a result, several large slope failures developed during construction that halted the completion of the road.

The study of a single slide that occurred in a 40 ft. high cut in the previously mentioned road sector is presented herein. The slide involved a large ground mass of about 1150 feet along the road, 350 feet wide normal to the road, and 40 feet deep (Fig. 2). The landslide consisted of a combined slump lateral spreading slide with rotational characteristics and gravity/burst structures. The failure developed during a heavy rainfall period in the area after the 40 ft. high cuts were performed.

For investigating this slope failure, a detailed geological and geotechnical study was performed. Several deep borings were drilled at and around the sliding mass. Inclinometers and piezometers were installed and monitored for a period of six months. Laboratory testing was conducted on recovered undisturbed soil samples to determine their engineering characteristics. A detailed engineering geologic reconnaissance was performed and slope stability analyses were carried out.

SITE GEOLOGY

The route alignment runs nearly east-west at an elevation of about 1050 ft. above sea level. It is located upon a gently sloping to locally irregular bench 300 to 600 ft. wide which is bounded on the south by the moderately steep, heavily vegetated valley slope of Rio Grande River of Arecibo, which flows about 430 ft.
below, and on the immediate north by the steep rock escarpment (cuesta scarp) of the Lares limestone plateau which extends another 150 to 300 ft. higher (Figure 1). This position places the route alignment right along a precarious condition of a plateau margin (Deere et al. 1987), as shown in Fig. 1.

For most of its alignment, the road sector is underlain by landslide deposits (QL), a muddy limestone unit of the Lares Limestone Formation (TL), hard overconsolidated clayey soils called the San Sebastian Formation (Ts), and a generalized volcanic rock basement (Ty, Ka). Figure 2 shows a typical profile in the failed road sector.

The Lares limestone, which constitutes the northern plateau, consists of a mid-Tertiary upper unit of hard, white to tan, massive to bedded limestone (recrystallized chalk and calcarenite) of 250 to 330 ft. thick, and a 30 ft thick lower unit of softer, thick to medium bedded, tan marly, muddy limestone containing coral beads and calcareous algal fragments. The upper unit has undergone extensive dissolution with many small to large cavities and an elaborate karstic surface with isolated rock cones, steep ridges, and columns separated by elongated and circular sinkhole depressions (Fig. 3).

The Lares Limestone (TL) is underlain conformably by the San Sebastian Formation (Ts), also of mid-Tertiary age, which consists of hard interbedded and lenticular masses of varicolored hard clay, silty clay, and clayey silt with some weathered gravel at the base. This gravel is probably the weathered surface of the underlying volcanic rocks. Some thin lignitic zones occur near the top of the sequence. The San Sebastian formation ranges in thickness from 0 to 6 ft. on the east to about 80 ft on the west end of the studied section.

The above described formations are the two bedrock formations that enter into the construction problem, the resistant Lares limestone at the cuesta scarp and the weaker San Sebastian deposits which underlie and support the limestone at the scarp and beneath the plateau. The bench has been formed in the San Sebastian formation with the limestone having been removed by solutioning, erosion, and ancient landsliding.

The San Sebastian formation rests unconformably on the weathered surface of the volcanic rock basement of early Tertiary age.

The most recent geologic unit is the Quaternary landslide deposits (QL) or colluvium that have accumulated at the base of the limestone scarp and on the bench of the San Sebastian formation over the last few hundred to thousands years. These deposits consist of a heterogeneous mixture of limestone blocks that have fallen or toppled from the scarp, clay and weathered limestone fragments washed out of the limestone joints, and slide debris from block creep, block slides, and rock slumps which contain both limestone blocks and disturbed clays and silts from the underlying San Sebastian formation.

Old slide scarps can be recognized in the field and on aerial photographs in the colluvium, many of which coalesce giving a scalloped appearance to the escarpment. Further weathering and high rainfall have resulted in additional deterioration of the colluvium causing local, small and large debris flows and earth flows, the latter involving the greenish clay from the upper part of the San Sebastian formation which was softened as squeezed out from below the escarpment or which was brought to the surface by rotational slumps.

HYDROGEOLGY

The general area of road sector is humid and tropical with an average annual rainfall of about 6 ft, most of which falls from May to November. Most of the rain that falls on the karstic limestone plateau on the north is collected through the sinkhole system into an internal drainage network. Part of this water emerges as springs from open joints or crevice along the base of the escarpment. A few springs appear on the south side of the bench at the colluvium, at the contact of the
Fig. 2 Soil Profile and Slide Surface at Station 192+10

Fig. 3 Schematic Geologic Cross Section in a North-South Direction
colluvium and the San Sebastian formation, and at the contact of the weathered gravelly San Sebastian and the weathered volcanic bedrock. Part of the water seeps down and along the contact with the San Sebastian clays, giving an opportunity to the clays to absorb water, swell, and soften under the reduced stress beneath and outside the limestone scarp.

The combination of colluvium mixed with clay, resting on a clayey foundation, and of a steady inflow of seepage water from the limestone plateau becomes particularly unfavorable for the sector stability and has been the main cause of the slides developed during construction. Some of the northern sinkholes appear to be partially plugged allowing the development of shallow lakes in them during the wet season. These lakes slowly drain and feed the underground water supply. A small creek runs north of the scarp. The creek has been dammed by a small dike for local use. The resulting small lake may also be an additional source of water for the internal drainage network.

The complex geological and groundwater conditions observed at the project area place this site in a hazardous geological environment.

SLIDE MORPHOLOGY

An engineering geologic mapping and air photo analysis were performed along the road sector alignment and within areas lying north and south. The results of these analyses helped to identify the physical characteristics of the sliding mass and its surroundings. Figure 4 schematically shows these characteristics. The slide consisted of a combined slump-lateral spreading slide with rotational characteristics (near the head) and graben-horst structures. The main body of the slide moved in a horizontal translatory fashion with a horizontal offset estimated at 10 ft. The slide main scarp, 1150 ft. long and 10 to 15 ft. high, was located near the escarpment of the Lares limestone. Secondary scarps and tension cracks were observed within the moving mass and the slide toe was located about 350 ft. south of the main scarp. The toe was characterized by bulging (10 ft. high) and overriding ground. Several springs were observed emerging at the slide toe and green silty clay with high water content (90%) was oozing out and slowly flowing away.

The air photo analysis showed that an old large landslide existed at the road sector before the road construction. The development of this old slide may be associated with the same geologic condition described before. The construction and grading operations for the road, where 40 ft. high cuts were performed, reactivated this old slide with the physical characteristics mentioned above.

GEOTECHNICAL EVALUATION

A detailed geotechnical evaluation was conducted. Several deep borings were drilled at and around the sliding mass. The resulting soil profiles were consistent with the anticipated sequence of geologic strata described before. Figure 2 shows a typical profile of the sliding road sector. For the borings located near the base of the limestone scarp, the upper soil samples could belong to the lower unit of the Lares limestone or to the colluvium accumulated down-slope.
The standard penetration N-values for this material were usually in the range of 25 to 50 blow/ft (higher values were associated with hard inclusions or limestone blocks). The borings also indicated a clear contact of the colluvium with the upper part of the San Sebastian formation marked by a lignite layer overlying 35 ft. or so of hard, green to dark gray, organic clayey silt to silty clay (N-values of 100 bpf or more and natural water contents of 25 to 35%, classification of CL to CH).

The borings in about the middle of the bench did not show the lignite and the underlying green organic clayey silt, both of which were probably removed by erosion or old landsliding. Instead, a layer of calcareous, light to dark brown, clayey silt was found with volcanic and limestone inclusions. This layer was softer and wetter than the organic green layer at the edge of the scarp (N-values ranging from 5 to 30 bpf, natural water contents of 35 to 50%).

Figure 2 shows that the upper part of the San Sebastian formation is underlain by the "typical" San Sebastian formation, which consists of purple, green, brown, and gray clayey silt to silty clay with faint to partially decomposed clasts. The typical layer is hard, with N-values greater than 100 bpf, unconfined compressive strengths of 4.5 taf or greater and moisture contents of about 20 to 30%. The average liquid limit and plasticity index are 50 and 30%, respectively. The typical San Sebastian soil has lower N-values of 30-50 bpf when sampled below the bench, particularly in the uppermost part where swelling has been more important. The soil samples of the formation showed the characteristics of stiff fissured clays of shiny luster and slickensides and polished faces when broken.

The clasts in this formation are less weathered with depth as the volcanic basement is approached (leading to difficulty in distinguishing between the San Sebastian deposit and any gravelly saprolite developed on the volcanic breccia). At this contact, the soil matrix was wetter, perhaps from being in contact with water from the bedrock joints. The transition gravel zone is about 6 ft. thick with some clay matrix.

Ten piezometers and eight inclinometers were installed and monitored for a period of six months for determining groundwater levels and depths of active sliding surfaces. The inclinometers were installed during a relatively dry period where the movements measurements were small (Fig. 5). It is during the period of heavy rains that the rate of movement increased, reaching large displacements in excess of 1 inch where shearing off of some of the inclinometers casings developed (Fig. 5).

The depth and shape of the sliding surface was determined with the inclinometer data and the field characteristics of the moving mass. The sliding surface starts at the head scarp and follows the contact between the organic and "typical" layers of the San Sebastian formation. The depth of the sliding surface as determined by the off-sets in the inclinometers was about 40 ft. The sliding mass included the base of the muddy limestone, the colluvium and the underlying overconsolidated clays. The sliding mass has a volume of about 0.6 million cubic yards. Figures 2 and 6 show two profiles indicating the position of the sliding surface and the observed groundwater levels.
STABILITY EVALUATION

To evaluate the stability conditions of the slide, back-calculating and parametric analyses were performed varying the position of the water levels, the depth of the sliding surface, and strength parameters. The back analyses used the residual friction value along the sliding surface. Results from direct shear tests on the San Sebastian deposits indicated a residual friction angle of 16 to 18 degrees. An assumption was made in these analyses that during the heavy rainfalls at the time of failure the water levels rose near the surface. Although reasonable, the assumption was not confirmed by the piezometers, as difficulties were encountered to measure during the rain. However, large quantities of water were observed seeping at several sectors of the existing ground surface at higher elevations than the slide toe. By using this information, the assumed water levels were defined.

The conclusions of the stability evaluation indicated that the causes in reactivating the old slide were the following:

1) The performance of large cuts (40 ft-high) to reach the desired road grading. These cuts deprived the sliding mass of resisting weight.

2) The geologic conditions and strength characteristics of the ground mass, particularly the combination of colluvium resting on an overconsolidated clayey foundation and the presence of the old landslide.

3) The presence of large amount of water seeping into the sliding mass as a result of heavy rainfall and the development of high water pressures associated with the nearby sinkhole system.

A detailed geological and geotechnical study previous to the road construction would have helped in defining the steps required to avoid the reactivation of the old slide. Such steps could consist of smaller cuts, incorporation of drainage schemes, and possible relocation of the road.

REMEDIAL MEASURES

The results of the stability evaluation and the field information were used to draw the remedial measures needed to stabilize the sliding mass and proceed with the road construction.

The recommended solution alternatives involve several forms of subsurface drainage, improvement of the soil conditions at the slide toe area, and incorporation of a weighting berm (to increase the resisting forces and reduce the effect of the large cuts for grading operations). The following remedial alternatives have been proposed for this project (Fig. 7):

- Stabilizing drainage key
- Solution (a) with upslope drainage trenches
- Solution (b) with 8 ft. high berm
- Solution (c) with horizontal drains
- Drainage gallery with horizontal drains
- Permanent wells with horizontal drains
- Combination of some of the above

Fig. 6 Soil Profile and Slide Surface at Station 193+65
The major stabilising element will be the "stabilization drainage key", an excavated drainage ditch near the toe of the slide and to the downslope side of the new highway. The proposed key is up to 50 ft. deep, backfilled with gravel and with a filter fabric lining (Fig. 7). The key will extend a few meters below the determined sliding plane and will increase the factor of safety from 1.0 (rainy season potential condition) to about 1.4. Prior to building the key, it is required to lower the existing water level, considering the disturbed and fissured nature of the slide mass. Studies are presently being made of two procedures for lowering of the water level: (1) parallel small, drainage trenches or ditches (labeled B in Fig. 7) at two or three locations between the new highway and the scarp (excavated and backfilled in small lengths), or (2) 10 ft. to 13 ft. diameter drainage wells (or shaft) near the scarp with horizontal drain holes drilled from the shaft at all wet zones. Also, borings are presently being made in the karstic northern limestone to evaluate the possibility of partially draining the sinkhole system to reduce the feeding of water to the lower colluvium and the San Sebastian formation.

The remedial measure of shifting the alignment either to the right or left of the bench is considered difficult to carry out due to the presence of the large cuesta scarp (on the north) and the steep sloping ground (on the south). Also, previous construction operations performed at other road sectors restrain the realignment of this road sector to its present location.

In conclusion, this case history illustrates the difficulty of road construction in a hazardous geological environment such as this, where the presence of an old slide and colluvium resting on clayey foundation make the road sector a very unstable area. For locations as this, a detailed preliminary evaluation of the area is mandatory and appropriate geological and geotechnical studies previous to road construction are necessary to define the proper construction scheme required to avoid the reactivation of existing old landslides. The use of field instrumentation should not be overlooked and the evaluation of the general area surrounding the troublesome location shall also be included.

REFERENCES