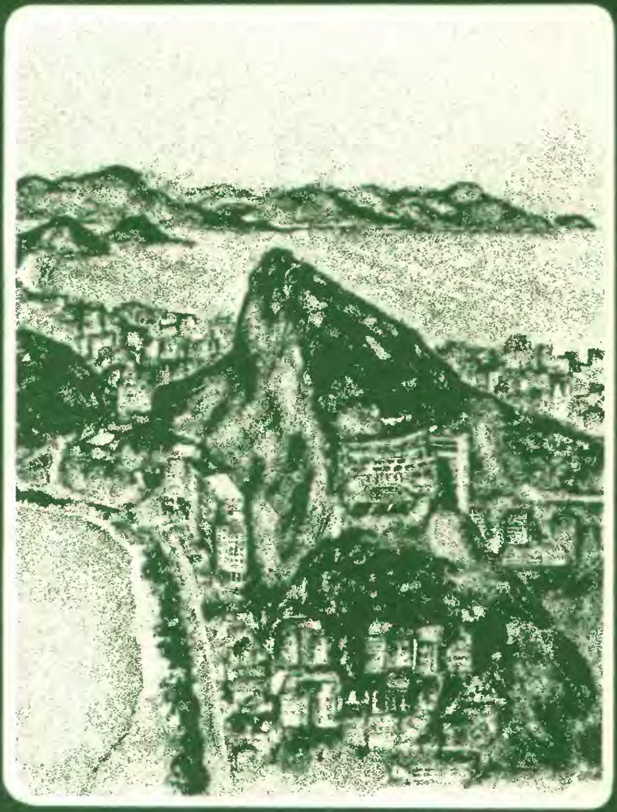
Landslides of Rio de Janeiro and the Serra das Araras Escarpment, Brazil



Prepared in cooperation with the Departamento Nacional da Produção Mineral of Brazil under the auspices of the Agency for International Development, United States Department of State

EOLOGICAL SURVEY PROFESSIONAL PAPER 697

LANDSLIDES OF RIO DE JANEIRO AND THE SERRA DAS ARARAS ESCARPMENT, BRAZIL

Landslide area, in center foreground, in Rio de Janeiro between Cantagalo Rock and Cabritos Hill. Copacabana Beach, Sugar Loaf, Guanabara Bay, and Niterói City in background.

Landslides of Rio de Janeiro and the Serra das Araras Escarpment, Brazil

By FRED O. JONES

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LANDSLIDES OF RIO DE JANEIRO AND THE SERRA DAS ARARAS ESCARPMENT, BRAZIL

By FRED O. JONES

ABSTRACT

Midsouthern Brazil with its south-facing coast is particularly vulnerable to cloudbursts, which result in floods, heavy erosion, and landslides. During the summer season, cold fronts originating in the south polar region move across the South Atlantic Ocean in a rhythmic cycle of about one per week. As the cold fronts mingle with the tropical airmass along the south-facing coast of Brazil, rainstorms develop. Most of the rain falls as cloudbursts. Frequently, many storm centers are operative at the same time.

Unusually heavy rains fell in midsouthern Brazil during the summer seasons of 1966 and 1967. In 1966, the area most affected was the city of Rio de Janeiro and the surrounding vicinity. In 1967, the area most affected was 50 to 70 kilometers west of the city of Rio de Janeiro; it encompassed about 100 square kilometers along the escarpment of the Serra das Araras. The resulting floods and extensive landslides during both seasons caused great loss of life and property damage. The total loss of life in the 1966 floods and landslides may have reached 1,000; in the 1967 floods and landslides, the loss has been estimated as high as 1,700. The damage to property in 1967 and the resulting effects on industry are inestimable.

On the night of January 22 and 23, 1967, a landslide disaster of unbelievable magnitude struck the Serra das Araras region of Brazil. Beginning at about 11:00 p.m., an electrical storm and cloudburst of 3½ hours duration laid waste by landslides and fierce erosion a greater land mass than any ever recorded in geological literature. The area laid waste was 25 kilometers in length and 7 to 8 kilometers in maximum width. A large part of the area of heavy destruction was on the steep slopes of the Serra das Araras escarpment. Thunderbolts from the lightning and the collapse of the hills shook the region like an earthquake. Landslides numbering in the tens of thousands turned the green vegetation-covered hills into wastelands and the valleys into seas of mud. Within the area of most intensive sliding are the Rio Light S.A. generating complex, the principal power supply for Rio de Janeiro, and a section of the Presidente Dutra Highway, the main arterial between Rio de Janeiro and São Paulo. Landslides in the steep canyons above the Rio Light S.A. generating complex turned to mudflows in the valley bottom and buried the main power units.

The Presidente Dutra Highway was cut by slides and mudflows in several places. Floods from many tributaries converged in the Floresta Creek valley at the toe of the mountains to form a mudflow which engulfed virtually an entire village and a highway construction camp.

In soils containing montmorillonite clay, the movement of some slides can be halted by installing subsurface drains, channeling all surface runoff into concrete drains, and treating the surface with lime. The lime reacts with the montmorillonite, causing it to stiffen and release ground water downward to the subdrain system. Preliminary tests indicate that many of the soils of Brazil can be induced to drain and stiffen by the application of lime. The possible effect of applying lime to unstable or potentially unstable slopes without providing subsurface drainage is unknown. Study of the soil profiles and the upper rock profiles in the city of Rio de Janeiro indicates that in general the soils are most impermeable at the surface and that permeability increases downward through the soil and decomposed bedrock. The lift seams and related joints in the upper part of bedrock are more permeable than the overlying formation and the underlying firm rock. This sequence in the soil-rock profiles may provide a natural drainage system that could provide escape for ground water from the soil if it is treated with lime.

A reconnaissance survey of the city of Rio de Janeiro was made to study the possibility of increasing the stability of the slopes by application of lime; 183 soil samples were collected and tested. These were taken from various geographic areas and areas of diverse parent bedrock. Of the 183 samples, 24 (or 13 percent) resulted in negative tests; the other 159 (or 87 percent) tested positive. The 87 percent that tested positive were divided into three groups: 16.5 percent showed only fair reaction, 29.0 percent showed good reaction, and 41.5 percent showed excellent reaction.

Much has been done in the past to stabilize decomposed bedrock, dangerous appearing slabs on the exfoliation domes, and weathered out blocks; much work is in progress in the city at present. The identification of potentially unstable rock is essential to the safety of the people and the many fine buildings along the toes of the slopes and is necessary to guide future planning and construction.

More than half of Brazil is made up of geologic formations similar to those in the Rio de Janeiro and Serra das Araras regions. Although topographic forms vary widely, the solutions to slope-stability problems that prove beneficial in these areas should have wide application in other parts of Brazil and perhaps elsewhere in the world.

INTRODUCTION

Unusually heavy rains fell on the city of Rio de Janeiro, Brazil, and the surrounding area during the summer of 1966. The resulting floods and extensive landslides caused great loss of life and property damage. Because of the severity of the catastrophe, a special landslide committee, under the direction of the Brazilian National Research Council, was established to study the problems. Upon the recommendation of the landslide committee, the Brazilian government requested the Agency for International Development, U.S. Department of State, to furnish an engineering geology specialist from the staff of the U.S. Geological Survey to review the landslide and slope stability problems of Rio de Janeiro during the rainy season of 1967. The writer was assigned to the project and remained in Brazil from December 10, 1966, to April 7, 1967.

Again in January 1967 unusually heavy rains struck. The area most affected was 50 to 70 km (kilometers) west of the city of Rio de Janeiro. It encompassed about 100 square kilometers along the escarpment of the Serra das Araras, a subdivision of the Serra do Mar. Included in the area are the Rio Light S.A. (South America) generating complex and the São Paulo-Rio de Janeiro highways; the highways wind through steep canyons between the plains and the summit of the Serra das Araras escarpment (fig. 1 and pl. 1).

In the steep canyons above the Nilo Pecanha underground powerplant, some 40 to 50 landslides turned to mudflows in the valley bottom and buried the main generating units supplying power to Rio de Janeiro. Slides and mudflows in the Lajes Creek canyon filled the tailrace channel of the new Fontes plant of the power complex and temporarily interrupted the inlet of a city water-supply line having a capacity of 5.5 cu m per sec (cubic meters per second).

The Presidente Dutra Highway was cut by slides and mudflows in numerous places. The floods from many tributaries converged in the Floresta Creek valley at the toe of the mountains to form a mudflow which engulfed virtually an entire village and a highway construction camp. Loss of life and property damage were very great. The area was 0.8 to 1.3 km above the confluence of Floresta Creek (Ribeirão da Floresta) and Lajes Creek (Ribeirão das Lajes) (pl. 1). Although the rains were not as widespread in 1967 in Rio de Janeiro as they were in 1966, local cloudbursts struck some areas and caused great loss of life and extensive damage.

The total loss of life in the 1966 floods and landslides may have reached 1,000. In the 1967 floods and landslides, the loss has been estimated as high as 1,700. No exact count can be made when entire villages are wiped out. The damage to property in 1967 and the resulting effects on industry are inestimable.

HISTORICAL BACKGROUND

Midsouthern Brazil with its south-facing coast is particularly vulnerable to cloudbursts, which result in floods, heavy erosion, and landslides. During the summer season, cold fronts originating in the south polar region move across the South Atlantic Ocean in a rhythmic cycle of about one per week. As the cold fronts mingle with the tropical airmass along the south-facing coast of Brazil, rainstorms develop. Most of the rain falls as cloudbursts in areas of varying size. At times many storm centers are operative at the same time.

Historical records describe catastrophic landslides in such widespread cities as Santos, São Paulo, Angra dos Reis, Petrópolis, Niterói, and Rio de Janeiro (fig. 1 and pl. 1), and Curitiba in Paraná, Salvador in Bahia, and Maceió in Alagoas (fig. 2). In Rio de Janeiro, history records that the hillsides have been a problem ever since the city was founded. Because the lowlands consisted of marshes, lagoons, and water-logged land, they were not inviting. Many of the slopes were inhabited during the beginning of the 19th century partly because of yellow-fever epidemics in the low-lying parts. From the very earliest settlement, people took to the hills because they were more desirable and provided a better stronghold against the pirates. Castelo Hill was settled in the 1550's. Several landslides there in 1759 and 1811 led to the eventual removal of the hill for safety. The material was used to fill swampy sections of the city. Other hills have since been removed because the stability problems were impossible to cope with, and the material could be used advantageously for fill elsewhere. Many similar situations exist today.

Most landslides and erosion have occurred at places where the natural relief of the land has been changed by man. Such places are predominantly cuts and fills in slopes of residual soil and decomposed bedrock.

The earliest rainfall record for the city is for the year 1782. Regular observations have been made since 1851 and regular records have been published since 1910. The rainfalls of the two disastrous storms of Rio de Janeiro were not as intense as rainfalls that have been observed elsewhere in the world. The historical records for Rio de Janeiro prior to 1966 show the following maximum durations and amounts:

	Millimeters	*Inches*
1 min	3.3	.13
5 min	19	.75
1 hr	72	2.83
24 hr	290	11.42
72 hr	340	13.38

A rainwater-disposal system became necessary as soon as people began living on the lands around the lagoons which lay at the foot of the hills. Rainwater runoff from the hills had to be channeled around the dwellings. Later, conduits were dug to drain the lagoons. The first one was constructed in 1641 to carry off the waters of Santo Antônio Hill, and by the end of the 19th century all the midtown lagoons had been filled in except Sentinela. The fills created large flat areas of land with poor drainage to the sea.

The need for an overall plan of water disposal became apparent. Engineer J. J. Revy proposed a plan in the 19th century, but it was not put into effect. The first plan which was put into effect was drawn up later by a group of physicians who used guesswork and information from plans adopted in other countries. The physicians themselves felt that the work should have been done by engineers. Many other plans for a runoff system have been suggested and some have been used.

Plans that were put into effect were only piecemeal, and there still is no master plan and set of standards for the laying of rainwater drains. Individual engineers do what they consider best for their clients in each circumstance. It is not surprising that a confused system has resulted. At present, four state bodies are entitled to operate in the same city area.

Years ago it was known that the situation was critical at some places whenever the summer rains came, and water pouring down from the mountains could find no outlet to the sea. The quantity of earth brought down from the hillsides added to the difficulties. As the eroded soil was added to the water, the channels became plugged and runoff was impossible. During one rainstorm in 1942, 36,700 cu m (cubic meters) of material was brought down into the city streets.

Successive laws and decrees have been enacted since 1955 in an effort to control foundation and excavation work and reduce slope failures. The decree of May 15, 1955, required investigations of the safety of sloping land before construction, including consideration of land and buildings lower down on the slope that might be affected by sliding. The General Office of Transport and Public Works was empowered to scale down the size of developments on slopes that might be unstable, and if necessary condemn any hillside-foundation plan that might destroy the balance of the hillsides. From the decree of May 15, 1955, it is apparent that slope-stability problems in Rio de Janeiro had reached alarming proportions even before the excessively heavy rains of 1966 and 1967.

Law No. 948 of November 27, 1959, provides for the preservation of woodlands and establishes forest preserves on most of the mountains and hills of the state above specified altitudes. Its provisions cover land use and developments within the city and in rural areas.

Decree No. 67 of September 18, 1963, provides regulations governing the selection of sites and operations of quarries. This decree was revoked by Decree No. 708 of October 1966, which drastically restricts quarries within the city. For safety and slope-stability purposes, it places a large part of the control of quarries under the Institute for Geological Engineering of the General Office of Transport and Public Works.

Ordinance No. SOP 13 of October 30, 1964, establishes regulations and foundation specifications for the use of tie beams and retaining walls which are used so extensively in construction on the slopes. It provides for official review and aproval of all plans and field examinations of the construction.

Decree No. 417 of July 14, 1965, extends in detail the ordinance of 1964 and outlines the geological and engineering data required to secure a license or permit to construct buildings on slopes.

Since the decree of July 1965, many other regulations have been established. With the catastrophic rains of 1966 and 1967, officials have been forced to make drainage and slope stability a prime factor in engineering planning and management. The problems are not easily solved. Solutions for some problems are certainly possible in time to avert disaster, but for others there is no solution until disaster strikes.

PRESENT INVESTIGATIONS

The inadequacies of the water-disposal system were brought sharply into focus in the rainy season of 1966. There was a change in the pattern of rain-

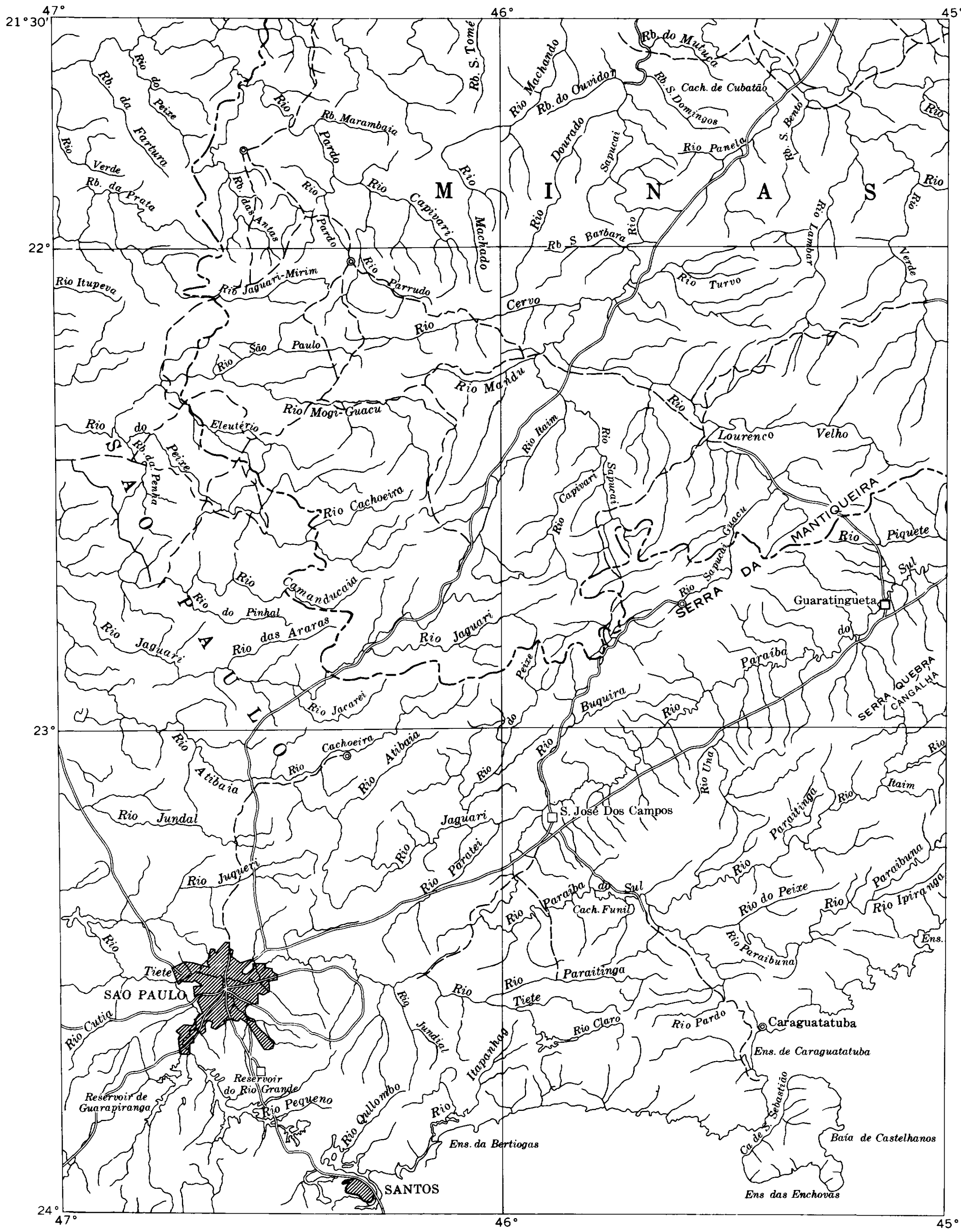
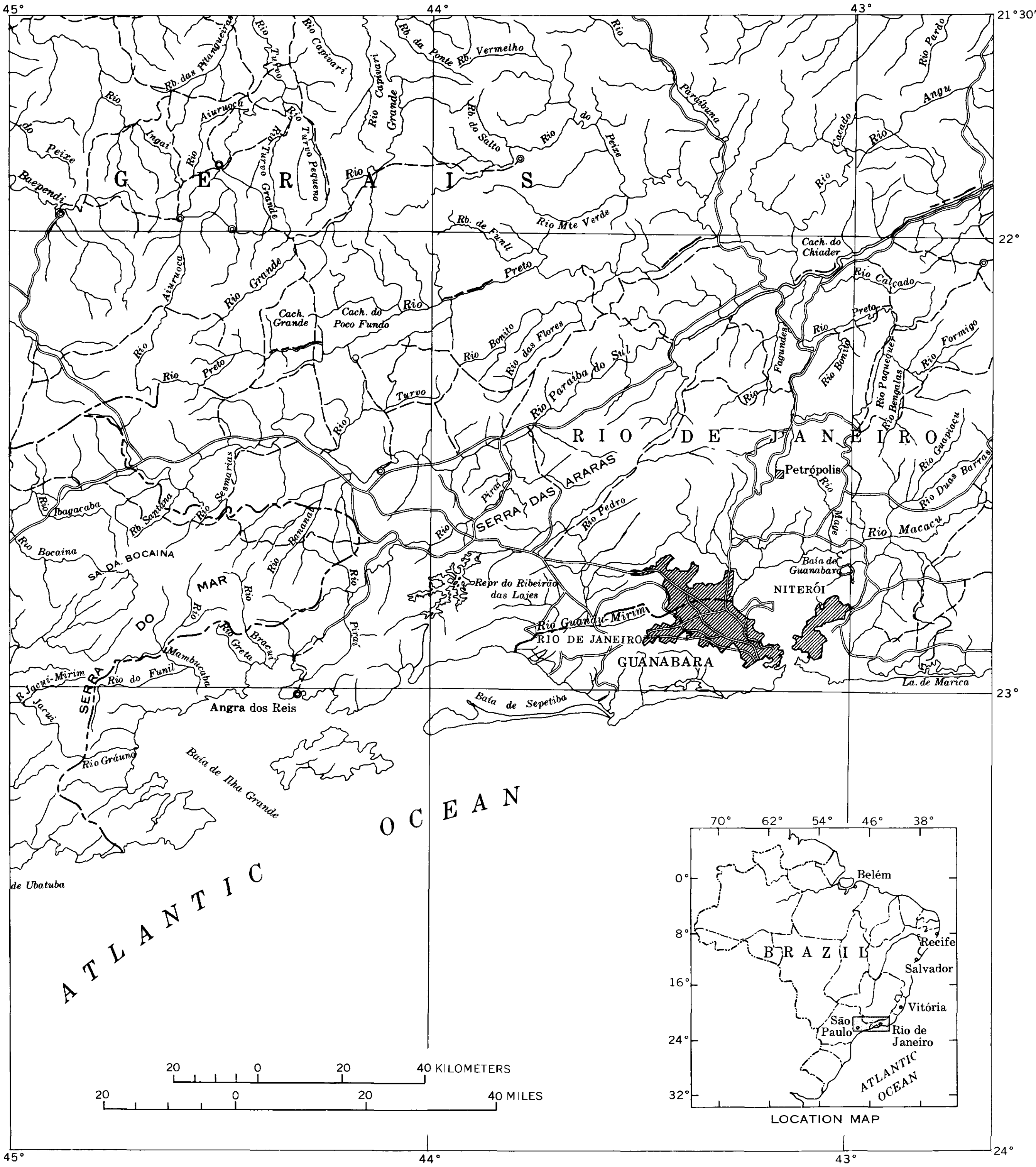


FIGURE 1.—Index map showing the

fall with heavy showers at shorter intervals. The first rains softened the hillsides and made it easier for the next showers to wash the earth away. Mud blocked the drainage system and the rising water turned the streets into rivers. It was estimated that the amount of rubble cleared away was approximately 300,000 cu m, more than seven times that recorded for the 1942 rains.



area from São Paulo to Niterói, Brazil.

During the 1966 season, two exceptionally heavy rains fell; they were the storms of January 10, 11, and 12, and March 26 and 27. On January 10, 1966, a cold front moved into the city of Rio de Janeiro area and remained stationary there for 3 days. At the meteorological observatory in the center of Rio, the oldest station in the city, which has about 80 years of recorded observations, the depth of rainfall in the 3 days reached a total of 484 mm (millimeters) (19.05 in.). The normal rainfall for January is 171 mm (6.73 in.), and the previous maximum rainfall recorded for any 1 month was 473 mm (18.62 in.) in January 1962. During the 3-day January 1966 storm, the Alta da Boa Vista station recorded 675 mm (26.57 in.) of precipitation.

The storm of March 26 and 27 began about 3 p.m. Precipitation was most intense during the early part of the storm when 240 mm (8.45 in.) of rain fell in 6 hours. The intensity reached 100 mm (3.94 in.) per hour. During the 18 hours of total duration there was 320 mm (12.6 in.) of precipitation. Two characteristics set this storm apart from the January storm—there was a greater amount of rainfall in a shorter period of time and a greater amount for a single day.

After the Serra das Araras landslide and flood disaster of January 22 and 23, 1967, conditions in Rio de Janeiro and its environs were chaotic for many weeks. People by the tens of thousands were homeless. Power and water were rationed; this resulted in complete lack of services in various sections of the city and region for many hours at a time. People stood in block-long lines for elevator service, and because of unexpected power interruptions, elevators stopped and trapped passengers between floors. Operation of air conditioners was prohibited; this caused suffering and major personal discomfort in the closely built apartments, offices, and hotels during 90° and 100°F temperatures. Hundreds of passengers, arriving at Rio's Galeão International airport along its dimly lighted runways powered by emergency units, found themselves plunged into jet black pandemonium without water, telephones, food, or coffee. Wading knee deep in water and mud in the streets of Rio during and after cloudbursts was a commonplace experience. Inoperative signal lights caused horrendous tieups in traffic. Stalled cars and electrically powered buses compounded the traffic problems. Extensive street construction was in progress and the avoidance of the street excavations where safety barriers had washed away was nearly impossible. Small holes in roads were transformed into yawning craters by the rushing waters. As bridges collapsed and vehicles washed into drainage canals and streams, transportation throughout many areas was brought to a standstill.

The field observations and studies summarized in this report are representative of many thousands of landslides in the Rio de Janeiro region during the summers of 1966 and 1967. Detailed investigations were concentrated in the city of Rio de Janeiro and the Serra das Araras landslide disaster areas.

Investigations were facilitated greatly by the unlimited helicopter support furnished by the Brazilian Government. The helicopter services made it possible to secure aerial-oblique photographs of many significant slides and slope-stability features. Selected photographs have been reproduced in this publication. Although topographic forms vary widely, more than half of Brazil is made up of geologic formations similar to those found in the areas studied. The solutions to slope-stability problems which prove beneficial here should have wide application in other parts of Brazil and perhaps elsewhere in the world.

ACKNOWLEDGMENTS

The association with Engineer Alberto Castello of the Departamento Nacional da Produção Mineral, who served both as geologic engineer assistant and interpreter, was of inestimable value and pleasure. He assisted in the preparation of sections of the report describing topography. Geologist Othon Henry Leonardos, Jr., assisted in the preparation of sections of the report describing bedrock geology.

Many Brazilian officials, engineers, and geologists contributed generously of their time and knowledge to aid in the investigation. I am especially indebted to the following: Dr. Antônio M. Couceiro, Engineer Francisco Moacyr de Vasconcellos, Dr. Adilson C. Seroa da Motta, Engineer Galileo Antenor de Araujo, Dr. Fernando E. Barata, Dr. Ronald Young, Dr. Paulo Erichsen de Oliveira, Dr. Herman Haberlehner, Geologist Urbano Heine, Engineer Willy Lacerda, Engineer Ana Margarida Maria de Couto e Silva, Brigadeiro Hamlet Azambuja Estrela, Engineer Paulo Azevedo Romano, Engineer Ataulfo Coutinho, Engineer Walter Pinto Costa, Geologist Francisco Danziger, Engineer Amarilio de Vasconcelos Pereira de Souza, Engineer Eugenio Silveira de Macedo, Engineer Helio Macedo Franco, Engineer Luiz Cezar V. Pires, Engineer Paulo de Castro Benigno, Engineer Carmen Sylvia de Menezes Ferreira, Engineer Antonio Jose da Costa Nunes, Engineer Evaristo Penna Scorza, Dr. Friedrich Wilhelm Sommer, Dr. Antonio Gallotti, Dr. Adolpho Santos, Mr. John D. Fitch, Engineer H. P. Duston, Engineer Walter Stuckenbruck, Dr. José Rubem Fonseca, Consultant Basil Simmonds, Engineer Fernando Mello, Dr. Paulo Albuquerque, and Mr. Edson da Silva.

I am also grateful for the wholehearted interest and support this investigation received from Max G.

White, U.S. Geological Survey, who had general supervision of the fieldwork and the preparation of the report. The arrangements Mr. White made prior to my arrival for a comprehensive review of landslide areas in the company of Brazilian engineers and geologists gave the investigation an accelerated momentum that extended throughout the field assignment.

LANDSLIDE TYPES

Landslides having a great variety of physical characteristics are found in the surficial deposits and rocks of the Brazilian Precambrian Complex (fig. 2). For purposes of this report, they are divided generally into four groups—slump earthflow slides, debris slides and avalanches, debris flows or mudflows, and rockfalls and rockslides.

SLUMP EARTHFLOW LANDSLIDES

Slump earthflow landslides combine the processes of sliding and flow. The upper part slides downward in one or more blocks that commonly rotate slightly about axes that are horizontal and parallel to the slope in which the landslide forms; the lower part flows as viscous liquid. The surface of rupture is commonly concave toward the slip block in horizontal section. In vertical cross section, the surface of rupture takes the shape of a circle, an arc of an ellipse, or a logarithmic spiral. Examples of this type are the Urubus Hill and the Comendador Martinelli Street slide in Rio de Janeiro (fig. 14 and pl. 2).

DEBRIS SLIDES AND AVALANCHES

The debris slides are formed in loose material resulting from the decay and disintegration of rocks. They are relatively shallow in vertical cross section. The surface of rupture is nearly parallel to the slope or bedrock surface, except at the top of the main scarp where it steepens to intersect the surface.

The gradations between debris slide and debris flow reflect very largely the differences in water content, although material of a given water content may slide on a gentle slope but flow on a steeper slope. Debris slides and, less commonly, debris avalanches may have slump blocks at their heads. In debris slides, the moving mass breaks up into smaller and smaller parts as it advances toward the foot, and the movement is usually slow. In debris avalanches, progressive failure is more rapid and the whole mass, either because it is quite wet or is on a steep slope, flows and tumbles downward and advances well beyond the foot of the slope. Debris avalanches are generally long and narrow and many leave a serrate or V-shaped scar tapering uphill at the head, in contrast to the characteristic horseshoe-shaped scarp of a slump earthflow slide (Diamond and Kinter, 1965).

Examples of these types of landslides abound in the city of Rio de Janeiro and the Serra das Araras region. Examples from the city of Rio are shown in figures 7, 10, 12, and 13. Examples from the Serra das Araras area are shown in figures 18, 21, 22, 24, 25, 34, 37, 38, and 42.

DEBRIS FLOWS AND MUDFLOWS

Debris flows and mudflows form in the surficial deposits of slopes. If more than half of the material making up the flow is the size of sand, silt, and clay, it is classified as a mudflow; if more than half is made up of coarser rock fragments, it is classified as a debris flow.

Debris flows almost invariably result from unusually heavy precipitation during torrential runoff after cloudbursts. They are most prevalent in deep soil on mountain slopes from which the vegetative cover has been removed, but the absence of vegetation is not a necessary prerequisite. Once in motion, a small stream of water heavily laden with soil has transporting power out of all proportion to its size, and as more material is added to the stream by sloughing, its size and power increase. These flows comonly follow preexisting drainage ways, incorporating trees and bushes, and removing everything in their paths. Such flows are of high density, perhaps 60 to 70 percent solids by weight, so boulders as big as an automobile may be rolled along. If such a flow starts on an unbroken hillside, it will quickly cut a V-shaped channel. Flows may extend many miles until they drop their loads in a valley of lower gradient or at the base of a mountain front. Some debris flows and mudflows have been reported to proceed by a series of pulses in their lower parts; these pulses presumably are caused, in part, by periodic damming and release of debris (Diamond and Kinter, 1965).

Flows of this type occurred by the hundreds in the Serra das Araras region during the 1967 rains. An example in the city of Rio is the Santo Amaro Street (Rua Santo Amaro) flow (pl. 2) which formed at the head of a large alcove and partly inundated an apartment house approximately 200 m (meters) down the valley. Examples from the Serra das Araras are shown in figures 23, 27, 28, 33, and 34.

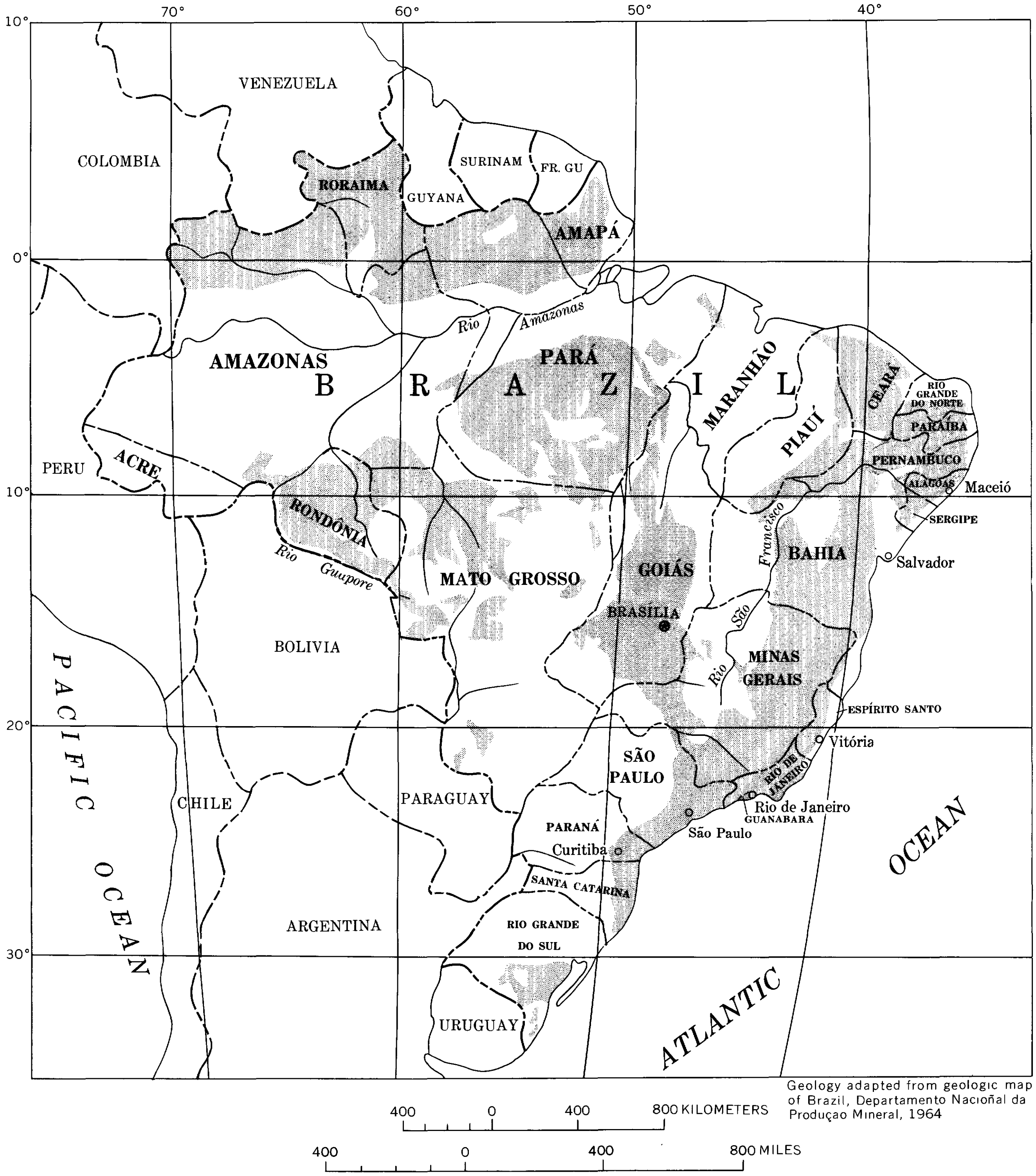


FIGURE 2.—Areas of Brazil underlain by Precambrian Complex (shaded).

ROCKFALLS AND ROCKSLIDES

True rockfalls, in which a mass of rock travels mostly through the air, are rare. Rockslides in which exfoliation slabs and weathered-out blocks are loosened and slide or roll down the slopes are common. Examples within the city of Rio de Janeiro are shown in figures 3 and 4.

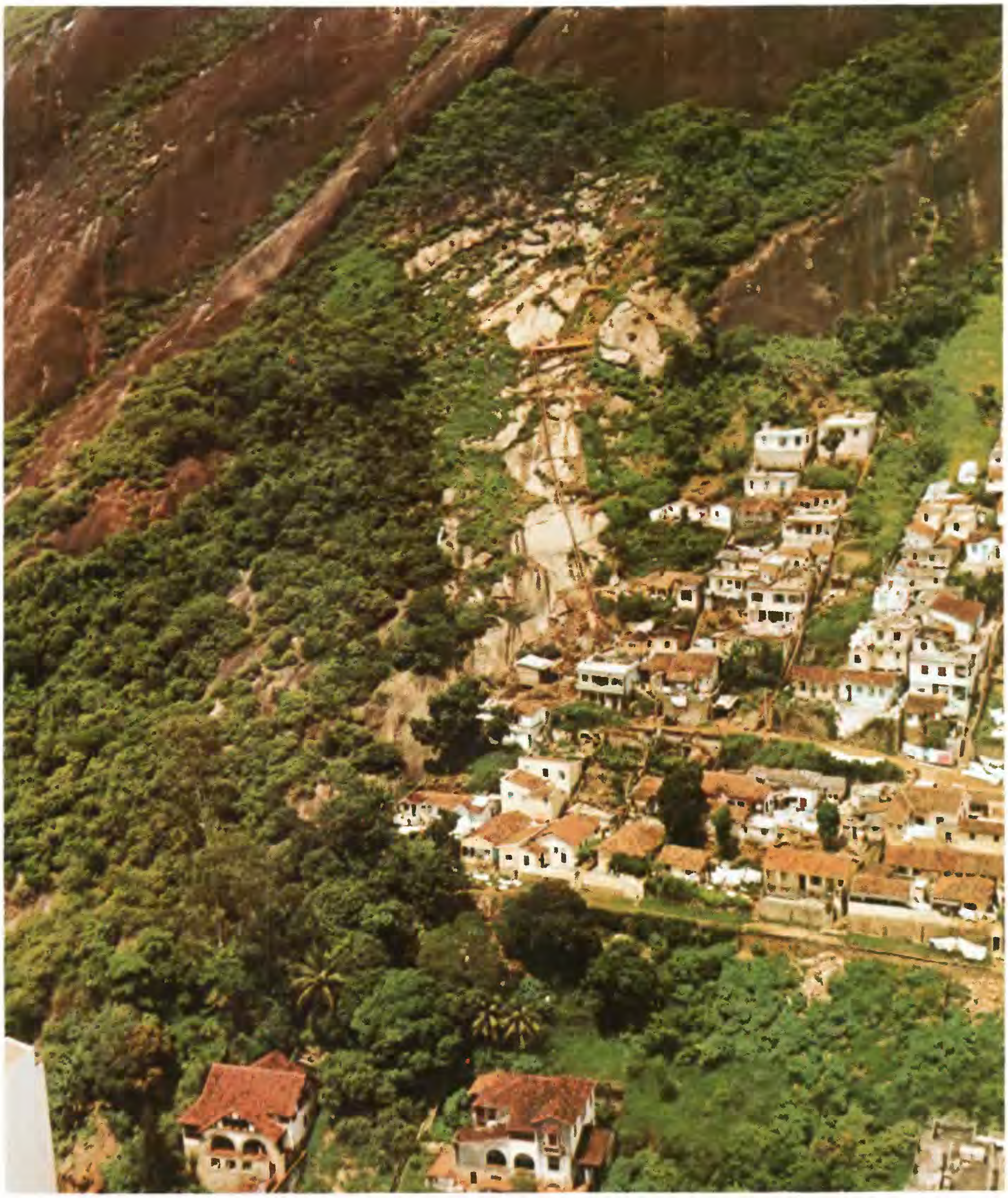


FIGURE 3.—Rockslide on the slope of Cabritos Hill (Morro dos Cabritos) in 1966 which took many lives and destroyed several homes. Ladders lead to platforms where stabilization work was in progress. The heavy vegetation line outside the fresh rock area suggests that a much larger rockslide took place at this location in the not too distant past.

FIGURE 4.—Vitor Meireles Street (Rua Vitor Meireles) landslide in the Riachuelo district. The slide occurred during the rains of February 18 and 19, 1967. This slide of large blocks in thin soil illustrates the dangerous condition of hillsides such as that shown in figure 5.

LANDSLIDE PROCESSES

An examination of the processes leading to the slides suggests that the physical agents at work to produce slides are principally water, the weight of the slope-forming material, and gravity stresses. (Landslides are discussed in reports by Terzaghi (1950), Eckel (1958), and Jones and others (1961).) The events or processes that bring the agents into action are rains and construction operations. The modes of action of the rain are raising the piezometric surface in the slope-forming material, seepage toward the slope, removal of soluble binders in joints, subsurface erosion, rearrangement of grains, chemical weathering, and displacement of air in voids and joints. The modes of action of construction operations are high-frequency vibrations and an acceleration of creep by undermining and locally overloading the slope. The modes of action combine to produce changes in the stress of the slope-forming material, thus causing damage to intergranular bonds, rearrangement of grains, opening of new joints and closing of old ones, an increase in pore water pressure, and elimination of surface tension. When some of the various elements of the processes combine to increase shearing stresses and to decrease cohesion and frictional resistance to a sufficient degree, a slide is activated.

LANDSLIDE AND SLOPE STABILITY PROBLEMS OF RIO DE JANEIRO

TOPOGRAPHIC SETTING

The city of Rio de Janeiro occupies the eastern half of the State of Guanabara. It is bordered on the south by the Atlantic Ocean and on the east by Guanabara Bay. Along the northern edge, the State of Guanabara borders the State of Rio de Janeiro into which the city extends for many kilometers. West of the city proper are smaller cities and an agricultural area (fig. 1 and pl. 1).

The State of Guanabara can be divided into two topographic units: the mountain ranges and the coastal plains. Three ranges are alined in a northeast-southwest direction—the Pedra Branca, the Mendanha, and the Tijuca Ranges. The Pedra Branca Range in the central part of the state branches to the southwest and separates the Jacarepaguá Plain from the Sepetiba Plain (west of area shown on pl. 2). Within the range are the Cabaçu, Viegas, and Lameirão Ridges. The highest peak in the range is Pedra Branca at 1,025 m above sea level. The Mendanha Range in the northern part of the state has a maximum altitude of 887 m. The Tijuca Range in the eastern part of the state has a maximum altitude of 1,023 m above sea level. It is divided into the Carioca Ridge (Serra de Carioca) and the Tijuca Ridge (Serra da Tijuca) (pl. 2). The most famous peaks of Brazil are in this range—Corcovado (Morro do Corcovado), Sugar Loaf (Pão de Açúcar), Tijuca (Pico da Tijuca), and Gávea Rock (Pedra da Gávea) (pl. 2).

The three major coastal plains are the Guanabara Plain in the northeastern part of the state, the Jacarepaguá Plain in the southern part, and the Sepetiba Plain in the western part. Jutting westward in the shape of a giant swordfish from the Sepetiba Plain is the Marambáia sand bar (Restinga da Marambáia) which extends over a distance of 45 km.

The slopes of the mountain ranges are steep. For the most part they are mantled with superficial deposits except where they have been swept clean by erosion and landslides. It is with the stability of the near-surface materials on the slopes that we are here concerned.

GEOLOGY OF THE SLOPES

Underlying varying thicknesses of soil and rock fragments, the hillslopes of the city are composed of gneissic bedrock formations (pl. 2). An older series of gneiss is derived mostly from granitic and mafic rocks; a younger series is derived mostly from sedimentary rocks. The latter series includes beds of quartzite and calc-silicate rocks derived from sandstone and limestone, respectively. It includes some intrusive bodies that were metamorphosed together with the metasedimentary series. The textural varieties of the gneiss reflect the varying composition and nature of the original rocks and the processes of formation.

The gneiss belongs to the Precambrian Era of geological time some 600 million years ago. About 450 million years ago in the Ordovician Period, great masses of granitic rocks were forced into the gneissic rocks in an irregular pattern. As the processes of rock formation proceeded at depth in the earth and as the land mass was elevated and eroded to its present form, faults, fractures, and fissures formed in the rocks. The most prominent faults in the State of Guanabara lie in a subparallel system in a northeast-southwest direction. In Cretaceous time, mafic rocks contemporary to the Paraná basalt lava flows were intruded along some faults and formed diabase dikes. Later, some 70 million years ago, in the Tertiary Period, alkaline rocks such as phonolites, trachytes, and lamprophyres were emplaced in the same sort of fractures.

A very irregular and picturesque pattern of topography has developed in the city of Rio de Janeiro area. This pattern has resulted from subsidence and differences in resistance to erosion of the various rock types. It has been strongly influenced by the fault system and related joints, and to a lesser extent by the position of dikes. Where the faults are associated with soft and fractured rock, erosion has followed these lines of weakness and cut valleys. To a lesser extent, valleys have been cut along soft dikes. Where the dikes are harder than the surrounding rock, they weather to form steep ridges.

Exposures in the numerous quarries in the city and in tunnels show that at depth almost all the rock formations are very hard and relatively stable. Above firm rock is an irregular zone of softened decomposed rock in some places extending to a depth of many meters. Test drilling and excavations show that firm rock may be 2 m below the surface of one location while only 10 m away firm rock may lie at a depth of 6 m. Within the decomposed rock zone and in the upper 5 m of firm rock are seams and joints parallel to the slopes. In the bare bedrock slopes these are referred to as exfoliation joints. The surface of the rock scales off in concentric shells as a result of temperature changes, chemical

FIGURE 5 (above).—Loose rocks in thin soil mantle on the slope of Tijuca Range. Grajaú-Jacarepaguá highway in foreground. Many thousands of square kilometers of the slopes of Brazil that are underlain by the Precambrian Complex have huge rocks such as these imbedded in the residual soil.

weathering, and the relief of the pressure caused by removal of the overlying rock. These processes produced the exfoliation domes, of which Sugar Loaf is the classic example. On covered slopes, similar joints are sometimes referred to as lift seams, even though the processes which developed them are nearly identical to the exfoliation joint processes.

Overlying the irregularly weathered and jointed bedrock on most of the slopes are surficial deposits of soils and loose rocks. The soil is chiefly the product of residual weathering and varies from clay to sand. Loose rocks within the soil range from small fragments to huge blocks (figs. 4 and 5). They have resulted from weathering and ancient rockfalls. Creep, ancient landslides, and erosion have modified the distribution of the soil on the slopes so that at higher altitudes the soil is relatively thin and at lower altitudes it is relatively thick. Thicknesses as great as 100 m have been reported.

FIGURE 6 (left).—Slope of Cabritos Hill (Morro dos Cabritos) exfoliation dome in Copacabana district showing apartment houses at base of bare-rock slope and adjacent to steeply sloping deposits in tree and brush-covered area. Hazards to people and property include rockslides, mixed rock and soil slides, surficial deposits sliding down onto the city, and deeper failures that cause uplift of the ground near the base of the slope.

SLOPE STABILITY

The slope-stability problems of Rio de Janeiro are probably greater than those of any city of its size in the world. The surficial deposits on the slopes have been increasingly disturbed for centuries. In early times, the slopes of Guanabara were denuded to obtain trees for lumber and fuel and to clear space for agriculture. Historical accounts are limited, but it seems that slope failures were associated with rains and early building on the hills. A number of hills in the city were removed, and a program of reforestation was undertaken in the 1800's. More recently as the city has continued to expand up the slopes for lack of room on the plains, the vegetative cover has been removed and roads and excavations for building have been placed at successively higher levels. The cuts caused by building at the toes of the slopes have severed the surface soil mantle at its most critical point (figs. 6, 7, 8, 9, and 10). This undercutting of the toe has served to accelerate the process of creep in the soil mantle on the slopes and to set the stage for slope failures all the way from the bottom to the top. It has made the slope areas just above the toe excavations particularly vulnerable. Cuts higher in the slopes for streets, trails, highways, and buildings have opened the way for slides from above the cuts (figs. 11 and 12). The placing of steep fills below the cuts has increased the load on the already potentially unstable surficial deposits and endangered the safety of the fills themselves and the underlying soil strata (fig. 12). With the unusually heavy rains of 1966 in Rio, reported to be the greatest in the memory of men now living, it is not surprising that a great many slope failures took place. It is awesome to contemplate what would have happened had the 1967 deluge of the Serra das Araras fallen on the slopes of the city of Rio de Janeiro.

Westward in the state, just outside of the city, the slopes were little affected by the 1966 rains, even though they are equally as steep as those in the city. These slopes are covered by fields of bananas, oranges, and other agricultural shrubs. The only differences are that the toes of the slopes have not been undercut by roads and that the slopes above the toes have not been notched by cuts and fills.

The stabilization of some of the slopes that have already failed in the city is completely impractical. One example of this is on the south spur of Cabritos Hill (Morro dos Cabritos) (fig. 8) where the toe support for the surficial deposits has been completely cut away on three sides of the hill by excavations for buildings and streets. Another example is the slide above the quarry behind the Benjamin Constant Institute where the quarry face has cut the sloping surficial deposits (fig. 13). In these areas the removal and use of the soilmass for fill would appear to be the most appropriate solution to the problem. There no doubt are other examples of slope failures in the city that fall into this category.

LIME AS AN AID IN SOIL STABILIZATION

According to Ho and Handy (1964), since ancient times lime has been used to stabilize soil and is now used in road building throughout the world. The plasticity of clay is rapidly reduced by the addition of lime, $Ca(OH)_2$. Montmorillonitic clay soils are most improved by lime treatment, even though in the natural state they are usually already calcium saturated. Ho and Handy (p. 279) concluded:

1. Small amounts of $Ca(OH)_2$ added to bentonite increase negative charges on the clay particles, probably by dissociation of clay OH groups. The action is complicated in Na-bentonite by accompanying partial ion exchange.

2. Further additions of $Ca(OH)_2$ allow Ca^{++} adsorption to compensate the increased negative charge gradually and cause floc formation. Both a high pH and presence of polyvalent cations are required for this type of flocculation.

3. Complete Ca^{++} saturation is not necessary for this flocculation; flocculation and partial exchange occur rapidly, but complete interlayer cation exchange is comparatively slow and probably continues by diffusion.

4. Dissociation of clay OH groups, and accompanying adsorption of Ca^{++} ions to change viscosity and plasticity, reaches a maximum at the "lime retention point"—about 6 percent $Ca(OH)_2$ for Na-bentonite, and about 2 percent $Ca(OH)_2$ for Ca-bentonite. Lime added in excess of these amounts remains undissolved until needed to replenish the system as the dissolved lime is used up in slow pozzolanic reactions.

APPLICATIONS IN OTHER AREAS

Reaction products in lime-treated soils are probably similar to those in concrete. In California the addition of lime to unmanageable soils in a highway fill changed the character to that of soft rock or concrete (Rock Products, 1966). Lime stabilization was introduced in highway work in Oklahoma during 1960 and 1961 (Rural and Urban Roads, 1963). The method consisted of boring holes 9 inches in diameter and 30 inches deep and spaced on 5-foot centers. A half bag of lime (25 lb) was used in each hole and water and backfill were added.

It has been found that, in soils containing montmorillonite, the movement of some slides can be halted by installing horizontal drains below the surface of rupture, by carefully channeling all surface runoff into concrete drains, and by treating the surface with hydrated lime. This has been successful

FIGURE 7 (above).—Cantagalo Rock (Morro do Cantagalo) and the surficial deposits around its base constitute one of the most active and potentially dangerous landslide areas in the city of Rio de Janeiro. The surficial deposits have been disturbed by cuts and fills for buildings and roads. Sliding along the left side of the rock in 1966 and again in 1967 caused heavy damage and led to the condemnation of some large buildings. Each new cloudburst endangers more structures. Tunnels and water-supply chambers within the rock intersect numerous faults.

FIGURE 8 (below).—Landslide area covering south spur of Cabritos Hill (Morro dos Cabritos). The toe of the slope around three sides of the spur has been excavated for building and street construction. The surficial deposits on the spur are all unstable and new sliding occurs annually. Quarry in gneiss on left.

FIGURE 9 (above).—Heavily jointed exfoliation dome in Copacabana district. The dome is surrounded by steeply dipping surficial deposits which have been excavated at the toe for building and street construction.

FIGURE 10 (right).—Belisário Távora Street (Rua Belisário Távora) landslide in the Laranjeiras district. This catastrophic landslide, during the night of February 18, 1967, completely demolished several houses and two apartment buildings. More than 132 people lost their lives. Investigations indicated that a small slide above a highway cut near the top of the slide overloaded the slope area and caused the main failure. The failure took place parallel to a dike in the bedrock where the residual slope deposits were thicker than on either side of the slide.

FIGURE 11 (above).—Favela on Dona Marta Hill in the Botafogo district. Sliding in the surficial deposits along the right side of the favela and in localized areas within it have caused extensive damage. Rockfalls from above have caused damage at the base of the rock areas. Sliding will continue during cloudbursts unless something is done to stabilize the soil and rocks.

where all other methods of stabilization have failed. Several slides treated in this manner were observed in the residual soils of Panama in December 1966 by the writer during the course of a field examination with R. H. Stewart, Chief Geologist of the Panama Canal Company. The lime reacts with the montmorillonite and causes the soil to stiffen and release groundwater downward to the subdrain system. The result is a lowering of the piezometric surface in the slide-forming materials. On the Panama slides, the lime has been spread on the surface of the slide and on an area 25 to 50 feet outside the crown and flanks. Particularly heavy applications of dry lime or slurry are made in the main scarp crack and open cracks within the slide. Applications have varied from 3 to 5 tons per acre. Lime deposits form coatings on the drain pipes. Stalactites are formed at the outlets of the drain pipes and lime deposits build up like pavement below the outlets of the pipes. Vegetation is equally as lush on the slides as on adjacent areas.

FIGURE 12 (left).—Slope failures in a favela of the Tijuca district. All the slope failures appear to be related to man-made cuts and fills.

A simple test was developed by the geologists of the Panama Canal Company to determine whether a soil is susceptible to lime treatment. The test consists of placing approximately equal amounts of soil in two test tubes. To one a small amount of lime is added. To both test tubes equal amounts of water are added. Both are agitated simultaneously until the soil is broken up and the solutions reach a similar cloudiness. The test tubes are then allowed to stand for observation. If a significantly more rapid flocculation is observed in the tube containing lime than in the one without lime, the reaction indicates that the soil probably contains montmorillonite clay and that lime would serve as a beneficial additive to stabilization of the soil. The rapid flocculation is believed to be either an electrokinetic (Ho and Handy, 1964) or a pozzolanic reaction (Diamond and Kinter, 1965) or a combination of both.

In 1957, several homes in the $25,000 to $35,000 price range were constructed on filled land bordering a ravine in Des Moines, Iowa (Handy and Williams, 1967). The fill was poorly compacted silty clay borrowed from loess and glacial till. It was placed on a relatively impermeable shale having a surface slope of 15 to 20 percent. In 1959 the area became known as the Aurora Avenue landslide or, informally, as skid row. Numerous attempts were made to stop the slide, including use of all the conventional methods of draining the slope, unloading the toe, and the placing of concrete piles and wooden bulkheads.

In 1963, two of the lots were treated with lime. The treatment consisted of drilling 6-foot auger holes in a 5-foot grid down to the shale and through a perched aquifer above the shale. Approximately 50 pounds of quick lime were placed in the bottoms of the drillholes: it filled about the lower 3 feet of the holes. Holes adjacent to the houses on the lots were completely filled with lime in the hope that this would stabilize the soil immediately under the footings. More than 500 holes were drilled over an area 200 by 125 feet, consuming 20 tons of lime. Movement of the two houses ceased immediately after the treatment. The results were attributed to an increase in soil strength caused by the drying action of the quick lime on the soil. Meanwhile, sliding in adjacent untreated areas continued. X-ray diffraction showed the most abundant clay minerals in the sliding materials to be calcium montmorillonite. Montmorillonite, even when calcium saturated, is peculiarly susceptible to modification by lime (Handy and Williams, 1967). The lime causes rapid flocculation and an increase in the plastic limit, accompanied by a slower pozzolanic cementation reaction that forms new hydrated calcium silicates and aluminates similar to those in Portland cement concrete (Ho and Handy, 1964; Diamond and Kinter, 1965). Physical and chemical tests on the soils for a period of 2 years and 8 months following treatment showed progressively increasing strength in the soil (Handy and Williams, 1967). X-ray diffraction tests showed that little of the lime in the bore holes had reacted, and it is assumed that the pozzolanic reaction will continue for many years. Two drill holes put down to the shale 2 years and 8 months after treatment showed no water table within the fill. The lime treatment did not appear to have been deleterious to lawns, trees, or weeds.

CITY OF RIO DE JANEIRO AREA

A reconnaissance survey of the city of Rio de Janeiro was made to study the possibility of increasing the stability of the soil on the slopes with the aid of lime. One hundred eighty-three soil samples were collected and tested. They were taken from geographic areas of diverse bedrock formations (table 1, pl. 2).

In the lime tests summarized in tables 1 and 3, most of the samples were judged to have a reaction classified as excellent, good, fair, or negative. A few of the samples were simply classified as negative or positive. In an excellent reaction, flocculation of the lime-treated sample began momentarily after agitation ceased, and the water cleared completely within 5 to 10 minutes. Many of the untreated sample solutions remained cloudy for longer than 24 hours. In a good reaction, the flocculation of the lime-treated sample was slightly less rapid and the clearing of the water was not so complete. In a fair reaction, some of the flocculation of the lime-treated sample could be detected, but it did not appear to be significant as compared to the excellent and good reactions. In the negative reaction, no more rapid flocculation of the lime-treated sample could be observed than in the untreated sample. In some samples, the untreated sample solution cleared more rapidly than the lime-treated sample solution. When samples giving an excellent or good reaction were allowed to stand overnight, the sediment in the bottom of the test tubes became hard and was much more difficult to remove than the sediment that had not been treated with lime. Tests were made for various periods of time, many for as long as 24 hours. From the various tests, it was determined that a 30-minute period of observation after agitation was sufficient to make the classification.

TABLE 1.—*Results of lime tests of soil samples, city of Rio de Janeiro*

[Sample locations shown on pl. 2]

Sample	Positive			Negative
No.	Fair	Good	Excellent	
1		×		
2			×	
3		×		
4				×
5			×	
6		×		
7		×		
8				×
9				×
10		×		
11	×			
12		×		
13		×		
14				×
15				×
16				×
17			×	
18				×
19				×
20	×			
21		×		
22				×
23				×
24		×		
25			×	
26			×	
27			×	
28			×	
29	×			
30		×		
31		×		
32		×		
33	×			
34		×		
35		×		
36		×		
37		×		
38			×	
39			×	
40	×			
41			×	
42			×	
43				×
44	×			
45				×
46			×	
47				×
48				×
49	×			
50				×
51	×			
52	×			
53				×
54			×	
55			×	
56	×			
57		×		
58		×		
59		×		
60			×	
61		×		
62			×	
63	×			
64			×	
65		×		
66		×		
67			×	
68	×			
69			×	
70		×		
71	×			
72				×
73	×			
74		×		
75	×			
76	×			
77		×		
78				×
79		×		
80	×			
81			×	
82	×			
83		×		
84			×	
85		×		
86		×		
87	×			
88		×		
89			×	
90			×	
91			×	
92			×	
93		×		
94				×
95	×			
96			×	
97				×
98			×	
99		×		
100				×
101			×	
102	×			
103			×	
104		×		
105		×		
106			×	
107			×	
108		×		
109		×		
110			×	
111			×	
112			×	
113		×		
114		×		
115			×	
116		×		
117			×	
118			×	
119			×	
120			×	
121			×	

TABLE 1.—*Results of lime tests of soil samples, city of Rio de Janeiro*—Continued

Sample No.	Positive: Fair	Positive: Good	Positive: Excellent	Negative
122			×	
123	×			
124			×	
125			×	
126			×	
127			×	
128			×	
129			×	
130			×	
131			×	
132			×	
133			×	
134		×		
135			×	
136			×	
137		×		
138			×	
139			×	
140			×	
141			×	
142		×		
143		×		
144			×	
145			×	
146			×	
147			×	
148	×			
149		×		
150			×	
151			×	
152		×		
153	×			
154			×	
155	×			
156		×		
157		×		
158			×	
159			×	
160			×	
161			×	
162		×		
163			×	
164			×	
165			×	
166			×	
167 [1]				
168			×	
169		×		
170		×		
171			×	
172	×			
173		×		
174				×
175	×			
176		×		
177				×
178		×		
179				×
180			×	
181			×	
182	×			
183	×			
184	×			
Total	30	53	76	24

[1] Sample not tested.

Of the 183 samples, 13 percent resulted in a negative test and 87 percent tested positive. The 87 percent that tested positive were divided into three groups—16.5 percent that showed only fair reaction, 29.0 percent that showed a good reaction, and 41.5 percent that showed an excellent reaction. No significant relationship is apparent between localities of positive or negative tests and the various types of gneiss plotted on the geologic map of the city. More detailed testing and geologic mapping may reveal a significant correlation between areas of positive tests and montmorillonite content of clay in the soils.

The key to slope stabilization is surface and subsurface drainage of water off and out of the slopes. Preliminary tests indicate that many of the soils of Rio de Janeiro can be induced to drain and stiffen by the application of lime to the surface. The possible effect of applying lime to unstable or potentially unstable slopes without providing subsurface drainage is unknown. Study of the soil profiles and the upper rock profiles in the city of Rio de Janeiro indicates that in general the soils are most impermeable at the surface and that permeability increases downward through the soil and decomposed bedrock. The lift seams and related joints in the upper part of bedrock are more permeable than the overlying formation and the underlying firm rock. This sequence in the soil-rock profiles may provide a natural drainage system that could provide escape for ground water from the soil. In most areas relatively short horizontal drainholes could serve as outlets for the water introduced into the open seams and joints in the bedrock. Unless a system of ground-water escape is provided, stability conditions within the slopes could conceivably become more hazardous with the lime treatment than without it.

COMENDADOR MARTINELLI STREET SLIDE AREA

A detailed study has been made of the Comendador Martinelli Street slide. Ten samples were collected for lime tests of the soil. The test results for all samples are positive (excellent and good) and indicate that the slide is amenable to lime treatment.

The Comendador Martinelli Street is in the Grajaú district of the city of Rio de Janeiro. Plate 2 and figure 14 show the general geographic and geologic setting of the slide. Towering above the area is a tremendous exfoliation dome. The landslide area extends from the base of the sheer bare gneissic dome to the city on the plain. Along the streets are many fine homes and apartment buildings, and several new apartment buildings were under construction at the time of the field studies. The slide mass consists of colluvial soil and boulders, and in some places huge blocks 20 to 30 m across have weathered out of the dome and have fallen from its steep slope. The soil mass in which the boulders are imbedded was derived by residual weathering and it accumulated at the foot of the dome by slope wash, creep, and ancient landsliding.

Landsliding activity of the mass of soil and boulders is probably very ancient. The heavy rains of 1966 removed parts of the slide and caused extensive damage to several buildings in the lower regions of the slide. R. P. Chaves and Ulysses Helmeister (unpub. data, January 24, 1956) refer to studies of movements of the slide dating back to 1941. They pointedly outlined the danger of further building in the area.

The Comendador Martinelli Street slide is a classic example of the slump-earthflow type limited by bedrock. The upper part of the surface of rupture follows the bedrock slope of the gneissic dome. The slide is more than 300 m wide at street level and extends up slope about 340 m nearly to the contact of the surficial deposits with the rock. The approximate outline of the slide is shown in figure 14. It has a vertical component of 120 m between altitudes of about 60 m and 180 m.

About halfway up the slope, a basin holds a small pond fed by a spring and surface runoff. A small stream follows the north side of the slide. The upper part acts as a driving force which activates removements during periods of excessive rain and an increase in ground-water pressures within the slide.

The alternative solutions to the problems are either to cease all land utilization of the area and remove the buildings and inhabitants that might be endangered from future movements or to stabilize the slide. It is believed that the slide can be stabilized because tests have shown that the slide mass can be induced to stiffen and release water to a subdrainage system by the application of lime to the surface.

The chemical and physical changes produced in the montmorillonite soils by treating them with lime are not considered permanent. Under conditions of heavy rainfall, the artificially created hydrated calcium silicates and aluminates may in time dissolve and revert to their original form. In any lime applications to landslides, natural slopes, or fills, continuing physical and chemical tests should be made to determine the necessity for repeated treatment. Discovery of the fact that lime will react favorably with so many of the soils of Brazil is perhaps a clue to a solution of some of the problems presented by the surficial deposits.

In soils containing other types of clays, other chemicals may produce favorable stabilization results. Moum, Sopp, and Løken (1968) found in laboratory tests that the stabilization of quick clays of illitic-chloritic composition was markedly improved by the addition of potassium chloride.

EXFOLIATION DOMES

Much has been done in the past to stabilize decomposed bedrock, dangerous-appearing slabs on exfoliation domes, and weathered out blocks; much work is in progress in the city at present. The identification of potentially unstable rock is essential to the safety of the people and the many fine buildings in the city.

At many unstable-appearing rock slabs, the exfoliation joints can be traced along the surface above the slabs. Some of the joints are narrow and tight; some are more open. Others are obscured by soil and vegetation. The water entering these joints from above and the prying action of roots of trees and other vegetation tend to reduce stability of the rock.

Plans are being formulated for a large-diameter interceptor, or sewer, which would carry floodwaters and sewage from a major part of Rio de Janeiro to a pumping plant at the ocean edge. It would lie below sea level and would run in a north to south direction. The southern section would pass through the mountains which separate the Lagoa and the Ipanema districts from the Copacabana district (fig. 7).

One of the problems that arises with plans for the tunnel through Cantagalo Rock (Morro do Can-

FIGURE 13 (above).—Landslide above a rock quarry on the north slope of Babilônia Hill (Morro da Babilônia). Benjamin Constant Institute is in upper left of photograph. The principal sliding took place in 1966. Further movement in 1967 was accompanied by caving action along the crown and flanks of the slide. Heavy rains washed the slide material into the streets for a block or more from the toe of the slide and temporarily closed the streets.

FIGURE 14 (below).—Comendador Martinelli Street landslide. Central foreground area covered by large blocks periodically moves down onto apartment houses.

tagalo) and for a large pumping plant inside the rock is whether the huge slab along the north side of the mountain and other rock units will remain stable or collapse (fig. 7). The collapse of any major unit would be catastrophic because the city is built up to and into the toe of the mountain. Aerial studies suggest that a very steep, north-dipping fault or contact passes through the mountain between the slab in question and the main mountain mass. A number of exfoliation joints are also present, and the trends of some appear to interlock with the fault. The tunnel would cross the fault at nearly a right angle.

Although detailed surface mapping of the joints and fissures has been undertaken (L. B. G. Lemos, unpub. data) it is not possible to establish visually the existence or relative movement of adjacent blocks of rock.

Much of the fault and joint system on Cantagalo Rock is exposed to the surface where removing vegetation and sealing the joints against infiltrating water would tend to add to the stability of the slab.

At many construction sites, problems similar to those in the rocks of the exfoliation domes of Brazil are analysed by means of data from drilling, rock tests, and the use of monitoring systems placed in drillholes. From the resulting data the degree to which the processes of weathering have taken place is determined. Quantitative and qualitative data on the rock structure indicate the rate at which gradual failure or relaxation of the rock mass is taking place.

THE SERRA DAS ARARAS ESCARPMENT LANDSLIDE DISASTER

On the night of January 22 and 23, 1967, a landslide disaster of unbelievable magnitude struck the Serra das Araras region of Brazil. Beginning at about 11:00 p.m., an electrical storm and cloudburst of 3½ hours duration laid waste by landslide and fierce erosion a greater land mass than any ever recorded in geological literature. The area laid waste was shaped like a banana, 26 km in length and 8.6 km in maximum width (figs. 1 and 15, and pl. 1). A large part of the area of heavy destruction was on the steep slopes of the Serra das Araras escarpment. In the northern part of the region, the boundary of the heaviest landsliding generally followed the edge of the escarpment (figs. 16, 17, and 18). Rain, flooding, and sliding of less intensity extended outside the perimeter described. Thunderbolts from the lightning and the collapse of the hills shook the region like an earthquake. Landslides numbering in the tens of thousands turned the green vegetation-covered hills into wastelands and the valleys became seas of mud.

Within the area of most intensive sliding are the Rio Light generating complex (figs. 15 and 17), the principal power supply for the Rio de Janeiro region, and the Presidente Dutra Highway, the main arterial between Rio de Janeiro and São Paulo (figs. 15, 19, and 20). In the area of the generating complex, there were three rain gages. During the storm, the rainfall recorded at these gages was as follows: Fazenda da Rosa, 275 mm (10.83 in.); Ipe Acampamento, 225 mm (8.85 in.); and the Lajes Creek dam, 218 mm (8.58 in.) (fig. 15). Between 30 and 50 minutes after the beginning of the storm, the Lajes Creek dam station recorded intensities varying from 100 to 114 mm per hour.

The area most heavily affected by sliding lies along the southeast-facing escarpment of the Serra das Araras. The escarpment has developed by uplift and erosion since late Tertiary time.[1] Erosion has been very rapid east and southeast of the escarpment since uplift occurred and quite slow on the top of the plateau above the escarpment where at many places there is more than 50 m of residual soil and decomposed rock. The foothills area southeast of the escarpment is highly dissected. The plateau topography has only moderate relief and is known as the Meia Laranja Hills topography because of their rounded, half-orange shape (figs. 16 and 17).

The rock formations of the escarpment, according to Fox,[1] consist largely of a great thickness of well-banded biotitic, feldspathic, and garnetiferous gneisses. They belong to the Paraíba Series of the Brazilian Precambrian Complex. All the gneisses are cut by aplitic veins and diabase dikes, probably of Cretaceous Age. The general trend of the gneiss foliation is about 60° E. but may be east-west. The difference in hardness or resistance to weathering has produced numerous northeast-southwest parallel ridges. The gneisses are cut by two sets of major joints; one set is nearly parallel to the strike of the gneiss and one set is roughly perpendicular to it. A third set is rare but may be locally important. These joints are responsible for the so-called half-orange hills and are directly responsible for the drainage pattern. Differential erosion of the diabase dikes in some valleys influences the drainage pattern also.

[1] Unpublished report by P. P. Fox, 1949, Preliminary geologic report—Lajes Forcacava project: Companhia Brasileira Administradora de Serviços Técnicos, 3 p.

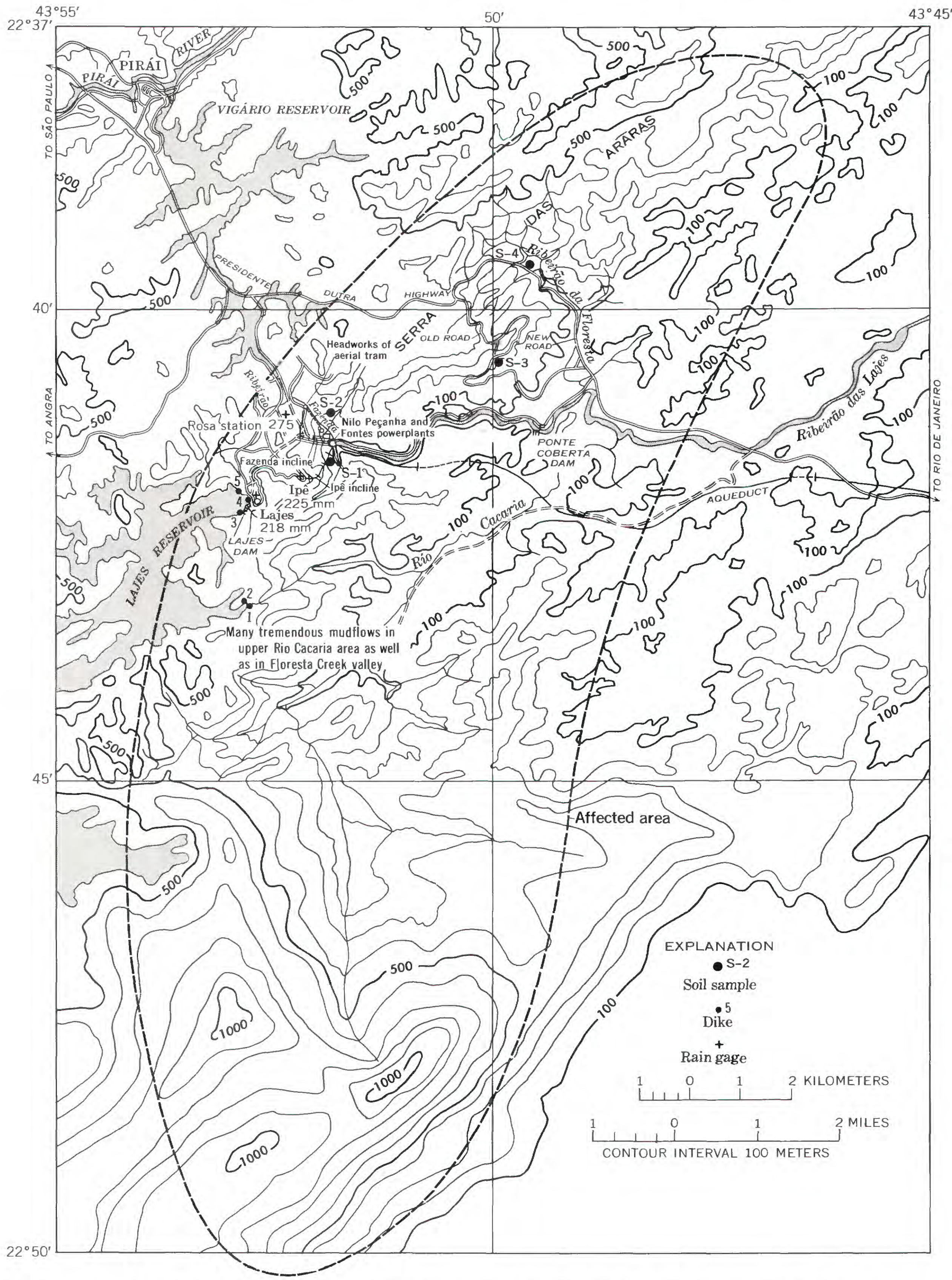


FIGURE 15.—Map of Serra das Araras landslide disaster area showing areas of destruction after the rainstorm of January 22 and 23, 1967. Rainfall recorded at selected points is shown in millimeters.

FIGURE 16 (above).—High level view of São Paulo-Rio de Janeiro highways across the Serra das Araras escarpment. Plateau of the Meia Laranja Hills above escarpment. Confluence of Rio Cacaria and Ribeirão das Lajes in lower foreground. The Rio Cacaria drains a large part of the area of heavy landslide destruction. Ponte Coberta powerplant on Ribeirão das Lajes in lower left.

FIGURE 17 (below).—Rio Light S.A. generating complex.

FIGURE 18 (above).—Ponte Coberta Reservoir and the Serra das Araras escarpment. All the water from the Ponte Coberta Reservoir and a major part of the drainage from the landslide disaster area flows into the drainage where the city of Rio de Janeiro secures about two-thirds of its water supply. The road on the opposite side of the reservoir provides the only truck and car access to the Rio Light generating complex. It was closed by landslides at many places.

FIGURE 19 (below).—Upper part of new road. Slides cut and covered the road at numerous locations. As the toes of the slides on the highway across the Serra das Araras escarpment were removed, the landslides became larger and larger. The photograph was taken 2 days after the disaster. Within a month the slides at points A and B had enlarged to the area shown.

FIGURE 20.—Landslides in the area of the upper part of the old road across the Serra das Araras escarpment. Ponte Coberta Reservoir is at left.

The slopes in the region are characterized by a thin veneer of less than a meter to several meters of residual soil overlying bedrock. The zone of decomposed bedrock just above sound rock, which is so prominent in the city of Rio de Janeiro and plateau areas, is not so prominent on the slopes of the escarpment. As a consequence, contacts of relatively easy parting exist locally between the soil and the rock. The landslides were virtually all of the debris avalanche, debris flow (fig. 21), and mudflow types. Not a single new slump-earthflow-type slide was observed that was caused by the storm. Several older slides of this type showed re-movement.

More avalanches cut areas of heavy vegetation than cut grass-covered slopes. Many avalanches cut areas of forest that are known to have been untouched by man for many years (figs. 22 and 23). The material and the overlying vegetation fell forward or downslope with little or no backward rotation of slide blocks (fig. 24).

FIGURE 21 (left).—Unusual elongated alcove caused by erosion and landsliding in foothills area of the escarpment near the old road. All the material flowed out through a narrow channel about 2 m deep.

High-frequency vibrations of the electric storm and the pressure of water falling on the vegetation and over the slopes are thought to have been unusually important modes of action that led to the avalanches. This does not mean, however, that other modes of action, such as raising the piezometric surface in the slope-forming materials, movement of ground water, subsurface erosion, rearrangement

FIGURE 22 (below).—Fazenda Creek (Ribeirão Fazenda) flows from upper left to the lower right in the central foreground. The cloudburst and avalanches in the northeast tributary of Fazenda Creek in the center and right background produced the mudflow which buried the Nilo Peçanha powerplant. Most avalanches in this area cut into forest-covered slopes known to have been undisturbed for many years.

FIGURE 23.—Fazenda Creek valley mudflow. Boulders in the mudflow were as large as 6 m across. Note head and tail towers of aerial tram and access tunnel to Nilo Peçanha powerplant behind switchyard. Black area above switchyard has bituminous covering for slope stabilization.

FIGURE 24 (left).—Typical Serra das Araras avalanche-type landslide in thin residual soils. Slide is located near highway just above escarpment.

of soil particles, and the action of air in interstices of the soils and in the joints of the rocks, were not operative.

Landsliding is one of the major geologic processes at work in shaping and tearing down the sloping land of the earth. As far as the writer knows, the occurrence of thousands of slides in so short a period from a rainstorm makes the Serra das Araras disaster unique in recorded history. However, storms accompanied by sliding of such magnitude have probably been of frequent occurrence along the midsouthern coast of Brazil during the geologic past.

RIO DE JANEIRO-SÃO PAULO HIGHWAYS

Between the edge of the plain of Lajes Creek (Ribeirão das Lajes) and the summit of Serra das Araras there are two highways—one, the old highway that normally carries traffic down the escarpment, and another, a new highway that normally carries traffic up the escarpment (figs. 15, 16, 19, and 20). The topography is very rugged and both highways wind along steep canyons and slopes. Debris avalanches, debris flows, mudflows, and the failures of fill areas cut both of them in many places (figs. 25 and 26). The new highway was sev-

FIGURE 25 (below).—Landslides near the top of the Serra das Araras escarpment along the new road.

FIGURE 26 (above).—Failure of new road in Floresta Creek valley.

FIGURE 27 (below).—Floresta Creek valley mudflow at the base of the Serra das Araras escarpment. Prior to the disaster, the valley bottom contained a village and a highway construction camp. Several hundred people lost their lives. The mudflow reached a depth of about 12 feet.

ered in substantially more places than the old during the rains of January 22 and 23, 1967.

The floods and landslide debris from many tributaries converged in the Floresta Creek (Ribeirão da Floresta) valley at the toe of the escarpment to form a mudflow which completely engulfed a highway construction camp and virtually an entire village (figs. 27 and 28). The area was 0.8 to 1.3 km above the confluence of Floresta Creek and Lajes Creek. Two buses became stalled at the bridge during the early stage of the flood and about 20 cars lined up behind them. The cars and occupants all were carried away and most of the people in the buses lost their lives. The construction camp included many houses, an office, store, service station, and many pieces of heavy construction equipment. Some of the heavy equipment was salvaged. Brush on the equipment indicated that surges of the mudflow reached a depth of 12 feet. One house containing 23 people exploded from the pressure of the mudflow around it. One man in the house caught a log and managed to hang onto it until he reached safety 1½ km below the camp. In total, several hundred people perished. Survivors reported that the main destructive part of the mudflow came in a wave or surge as if a dam above had suddenly burst. Residents adjacent to the disaster reported that by 1:00 a.m. the mudflow was past and that by

FIGURE 28.—Section of Floresta Creek mudflow at a location just downstream from the area shown in figure 27. The gray material below the point of the geologist's pick is the old alluvium of carbonaceous silty, clayey sand. The mudflow material above the pick is silt and sand containing angular rock fragments. The interior of the mudflow contained surprisingly few pieces of wood. Most of the trash apparently was washed downstream. The little that was left was either on top of the mudflow or within a few inches of the top.

2:00 a.m. only soft yellow mud remained on the valley bottom. This timing suggests that precipitation intensity during the early part of the storm may have been much greater in places than that recorded by the rain gages at the Rio Light generating complex.

The old highway (figs. 16 and 20) was constructed on slopes having a more shallow soil cover over firm but decomposed bedrock formations. Slide damage along the road was intense, but it was possible to open the road to emergency traffic within a few days after the storm. The new road (figs. 16

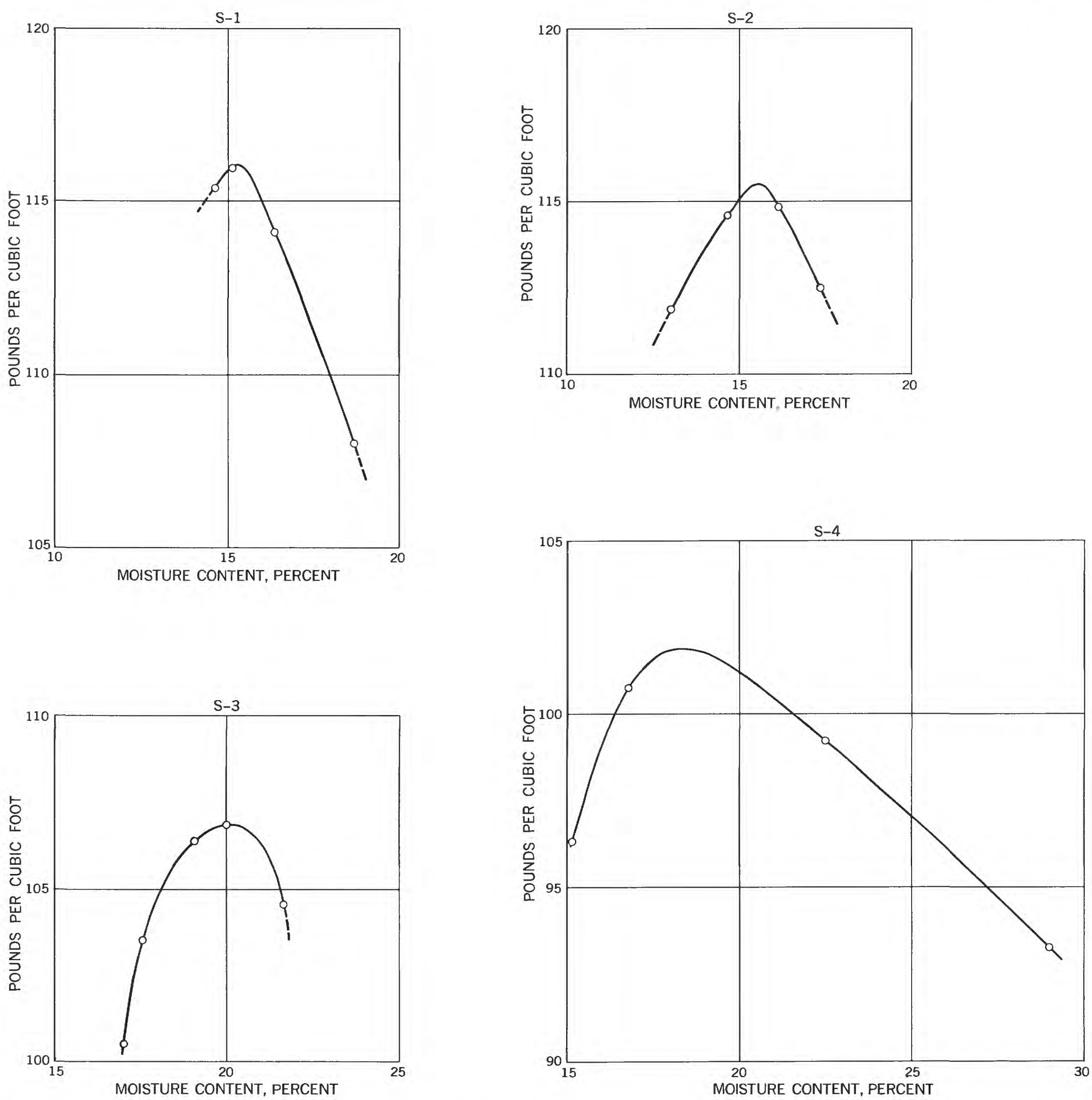


FIGURE 29.—Moisture-density curves for soil samples S–1 to S–4 using the Harvard compaction apparatus. Natural-state moisture content could not be determined on the samples as they were received in a dry condition with a moisture content of only a few percent. It was assumed that the natural-state moisture content was much greater. Compactive effort: five layers, fifteen 40-pound tamps per layer. Analyses by E. E. McGregor, U.S. Geological Survey.

and 19) which was located on slopes of thicker soil deposits was not opened to traffic for many weeks. Whether the highways can be restored to normal year-round heavy traffic is questionable. The exposure of such large areas of fresh soil and rock above the highways to erosion and future slope failures presents stabilization problems of staggering proportions. Two typical soil samples (Nos. 3 and 4), one taken from the old road and one from the new, were tested in the U.S. Geological Survey laboratory in Denver, Colo., by E. E. McGregor. Results of the tests are given in table 2 and in figures 29 and 30. The locations at which the soil samples were taken are shown in figure 15. A small

TABLE 2.—*Results of laboratory tests of four soil samples from landslides in the Serra das Araras disaster area*

[Analyses by E. E. McGregor, U.S. Geological Survey. Sample locations shown in fig. 15]

Sample	S–1	S–2	S–3	S–4
Unified Soil Classification	SM–ML	SM–ML	ML	ML
Size distribution: [1]				
Gravel ..... percent	5	7	1	5
Sand ..... do	59	62	47	43
Silt ..... do	19	16	14	13
Clay ..... do	17	15	38	39
Sieve analysis (particles passing indicated sieve number): [1]				
10 ..... percent	95	93	99	95
40 ..... do	65	63	78	72
60 ..... do	56	52	68	65
200 ..... do	38	33	52	53
Atterberg limits:				
Liquid limit	34	33	40	47
Plasticity index	8	2	13	16
Proctor density: [2]				
Optimum moisture ..... percent	15.5	15.5	20.3	18
Maximum dry density ..... lb per cu ft	116	115.5	107	102
Potential volume change: [3]				
Swell index ..... psf	2,500	1,800	3,400	3,700
Rating	3.0 (marginal)	1.4 (noncritical)	4.3 (critical)	4.7 (critical)
X-ray mineralogy of the −230 sieve fraction: [4]				
Quartz ..... percent	15	20	15	10
Plagioclase ..... do	10	15	—	—
Potash feldspar ..... do	—	—	—	—
Amorphous iron ..... do	10	20	15	—
Clay ..... do	65	45	60	65
Relative abundance of minerals [5]	K>I>M	I>K	I≥K	K>I

[1] See figure 30.
[2] See figure 29. Derived from the moisture-density curve plotted according to method of American Society for Testing and Materials (1964, p. 160–162).
[3] Lambe (1960).
[4] Schultz (1964). To nearest 5 percent.
[5] K, kaolinite; I, illite; and M, mixed-layer montmorillonite-illite.

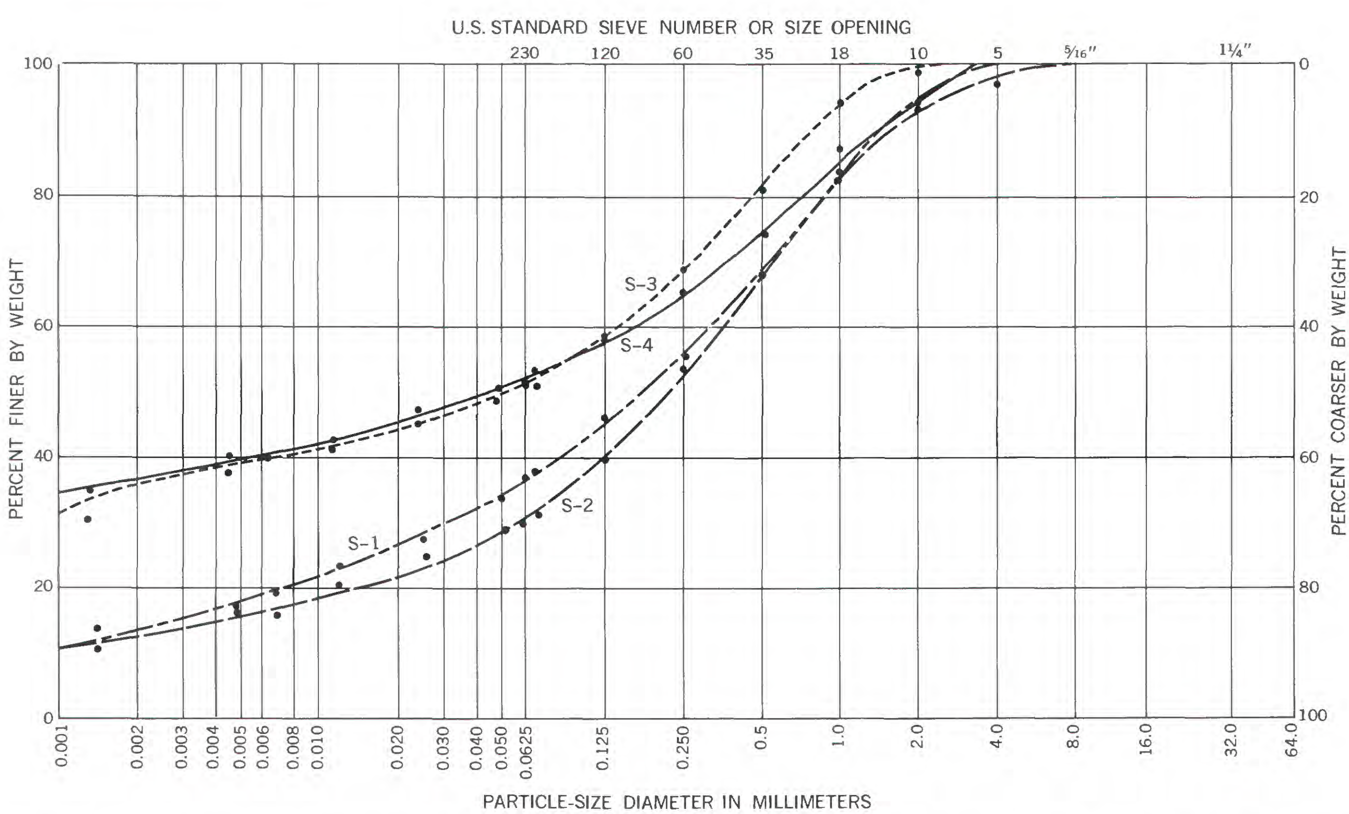


FIGURE 30.—Particle-size distribution of four soil samples, S–1 to S–4. Analyses by E. E. McGregor, U.S. Geological Survey.

FIGURE 31 (above).—Landslide at dike 4, Lajes Reservoir. Lajes Creek dam and reservoir in the background. The slide has been moving periodically for some time. Minor re-movements occurred during the rain of January 22 and 23, 1967.

part of the fines of the soil samples was lost in transit, so the results of the tests must be evaluated with that in mind. The samples contain only kaolinite and illite, not montmorillonite clay. Lime tests were made on soil samples taken at 17 locations on the old and new roads (table 3). These tests do not indicate that lime would be particularly effective as an additive to the soil to aid in stabilization work.

RIO LIGHT S. A. HYDROELECTRIC COMPLEX

The hydroelectric system which supplies most of the power to the city of Rio de Janeiro is about 70 km northwest of the city. It is composed of two distinct developments—the Lajes development and the Paraíba-Piraí diversion (figs. 15, 17, and pl. 1). The following description was prepared with the aid of Engineer Walter Struckenbruck, Assistant Chief of Plant, Rio Light S.A.

TABLE 3.—*Results of lime tests on soil samples from the Serra das Araras landslide disaster area*

[General location of samples shown in fig. 15]

Location	Number of samples	Positive	Negative
Rio de Janeiro-São Paulo highway at escarpment:			
New road	6	2	4
Old road	11	5	6
Rio Light hydroelectric complex:			
Landslide near valve chamber and Fazenda incline	8	8	0
Landslide south of Ipê incline	10	[1] 10	0
Landslide north of Ipê incline	6	6	0
Dike 4 (landslide)	15	[2] 10	5
Dike 2 (dike proper)	8	[3] 8	0
Dike 1 (dike proper)	2	[1] 2	—

[1] Excellent.
[2] Excellent, 7; good, 2; fair, 1.
[3] Excellent, 7; good, 1.

The original Lajes development, completed in 1908, utilized only the water of the Lajes Creek. It consisted of the Lajes Creek dam (fig. 31), a concrete buttressed-arch structure 32 m high and 234 m long, having a 134-m-long spillway at its crest;

FIGURE 32 (below).—Landslides adjacent to valvehouse of Fontes plants and Fazenda incline cable trolley.

the Lajes Reservoir having a useful storage capacity of 182 million cu m of water at its maximum altitude (404 m above sea level); an intake structure, situated about 150 m upstream from the dam and about 55 m from the shore; two 8-foot-diameter steel pipes, about 2 km long, connecting the intake to the valvehouse (alt 347 m, fig. 32); six steel penstocks, 0.8 m in diameter and about 600 m long, starting at the valvehouse and leading to the powerplant; and the old Fontes powerplant itself equipped with six 9,000 hp (horsepower) vertical Pelton-type water wheels working under a head of 310 m and driving six 5,000-kw (kilowatt) generators (figs. 33 and 35).

In 1913, additional water was brought into the Lajes Reservoir from the Piraí River (Rio Paraí) by means of a tunnel 8 km long. Two more units of 12,500 kw each were added to the old Fontes powerplant. This was the first diversion of a river over the Serra do Mar toward the sea.

In 1939, the new Fontes powerplant upstream adjacent to the old began operation with a 40,000-hp Francis turbine driving a 35,000-kw generator (figs. 17 and 33). This brought the total capacity of the plant to 90,000 kw.

Between 1940 and 1950, the height of the Lajes Creek dam was raised 28 m; this increased the useful storage capacity of the Lajes Reservoir from 182 million cu m to 1,025 million cu m at its maximum water level of 430 m above sea level. Two additional power units installed were of the same size and type as those installed in 1939. To take care of the increased discharge required by the plant, a new intake structure was built right at the dam, and a concrete-lined tunnel 6.15 m in diameter and 2,100 m long was driven between the new intake and the valvehouse, and the two 8-foot pipes and the old intake structure were abandoned.

By the end of 1950, the generating capacity of the Lajes development was 160,000 kw, 55,00 kw supplied by the eight units of the old Fontes plant, and 105,000 kw by the three units of the new Fontes plant.

In 1954, the Paraíba-Piraí diversion came into operation. Its generating plant, the Nilo Peçanha underground plant, is close to the Fontes plants and has a capacity of 330,000 kw (figs. 17 and 35). The water for this plant is pumped from the Paraíba do Sul River (Rio Paraíba do Sul), which discharges into the Atlantic Ocean about 270 km northeast of Rio de Janeiro. At its closest point to Rio de Janeiro, the Paraíba do Sul River is about 25 km from the edge of the Serra do Mar. At this point is

FIGURE 33.—New and old Fontes powerplants looking down Lajes Creek valley. The photograph was taken after the Lajes Creek valley mudflow had been cleared from the tailrace channel.

located the first of two pumping plants of the diversion, the Santa Cecília pumping plant (pl. 1); it is equipped with four pumps of 40-cu-m-per-sec capacity each.

Water stored in the reservoir at an altitude of 353 m created by the Santa Cecília weir is pumped into a tunnel 3.3 km long and an open canal which carries it to the Santana Reservoir in the Piraí River valley. The reservoir has a useful capacity of 10 million cu m at an altitude of 363 m. It is also fed by the Piraí River.

From the Santana Reservoir the water is lifted an additional 35 m by the Vigário pumping plant to the Vigário Reservoir. The reservoir has a useful capacity of 14 million cu m when filled to an altitude of 398 m. The Vigário pumping plant is equipped with four pumps, each having a capacity of 40 cu m per sec. The units are reversible and have a generating capacity of approximately 13,000 kw each.

Stored water in the Vigário Reservoir is conveyed by the Vigário canal, 1.4 km long, and the Vigário tunnel, 690 m long, to the underground valve chamber above the main generating plants (fig. 34). From there it passes through a steel-lined pressure

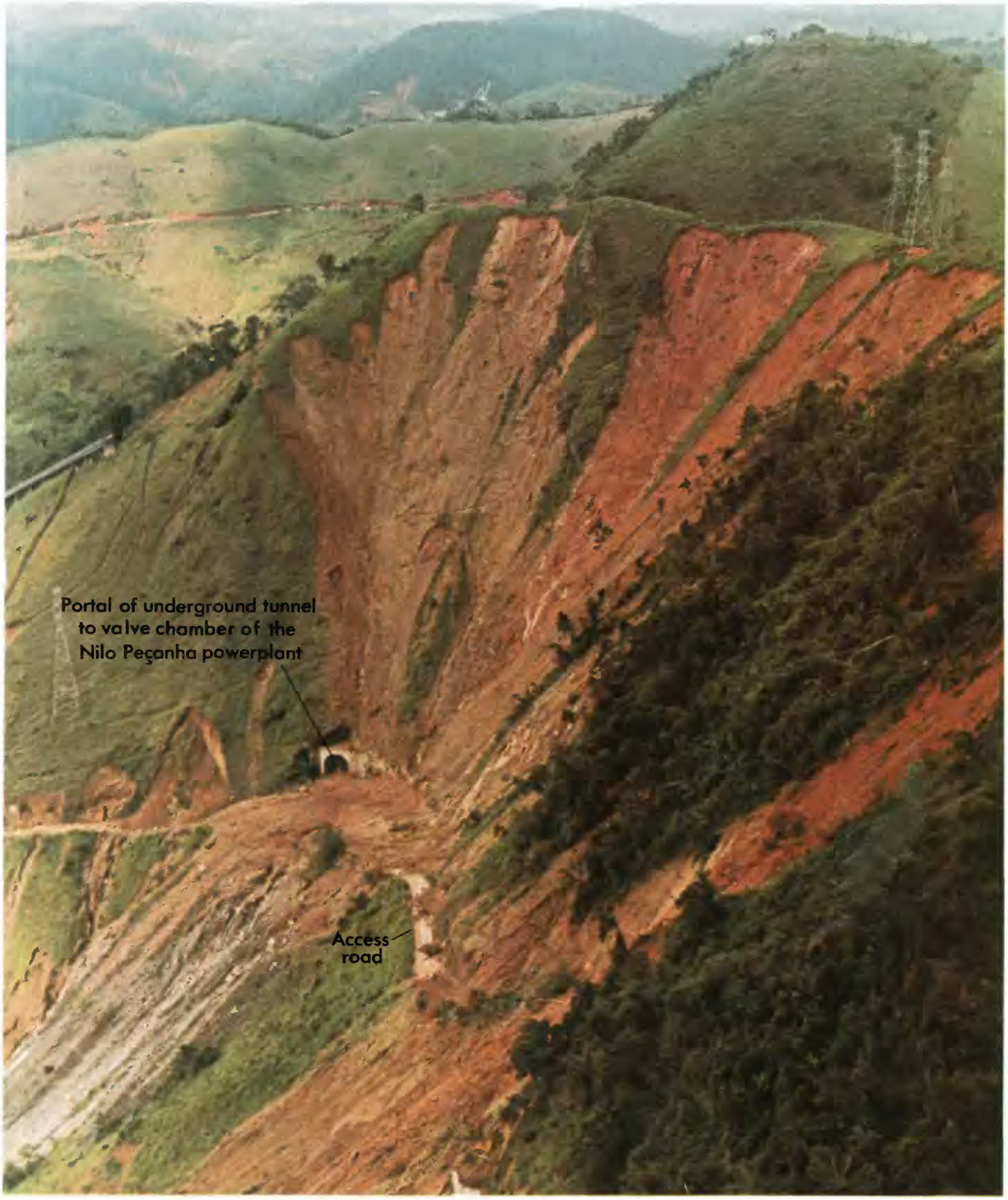


FIGURE 34.—Landslides covering access road to tunnel leading to underground valve chamber of Nilo Peçanha powerplant. A slide cut to within 1 m of the base of one of the transmission tower foundations, upper right.

FIGURE 35.—Fazenda Creek valley mudflow at Nilo Peçanha powerplant. Note how mudflow overflowed switchyard into access tunnel as well as filling tailrace channel and tunnel.

shaft, 6.1 m in diameter and 517 m long, to the Nilo Peçanha underground plant. This plant has four 65,000 kw units and two 35,000 kw units. The water from Nilo Peçanha is discharged through a tunnel 350 m long into Lajes Creek just downstream from the Fontes plants. The underground valve chamber and the valvehouse are interconnected through two tunnels, and thus it is possible to operate the Fontes units with pumped water. This, indeed, is the normal operation during the wet season.

In the first few kilometers downstream from the Fontes and Nilo Peçanha plants, the slope of the river is quite high, and the valley is narrow. These favorable conditions made it economical to build a low-head (37.5 m) plant 5 km downstream from the above-mentioned plants. This plant, the Ponte Coberta (fig. 16), went into operation in 1963 and is equipped with two units capable of generating 50,000 kw each. The dam across the river is an earth dam. The maximum discharge of the plant is 32 cu m per sec.

The main generating complex is in the area of most intensive landslide damage (figs. 17, 18, 22, 23, 32–42). In a small basin and canyon northeast of the plants, 40 to 50 debris avalanches and debris flows joined together in a mudflow in the valley

FIGURE 36 (above).—Outlet of Nilo Peçanha tailrace tunnel after excavation of mudflow.

FIGURE 37 (right).—Landslides in the area of the surge pipes of Fontes powerplants, Fazenda incline trolley, and city of Rio de Janeiro's water-supply line.

FIGURE 38 (below).—Landslides above Rio de Janeiro water conduit and near transmission towers just downstream from powerplants. Ponte Coberta Reservoir in foreground.

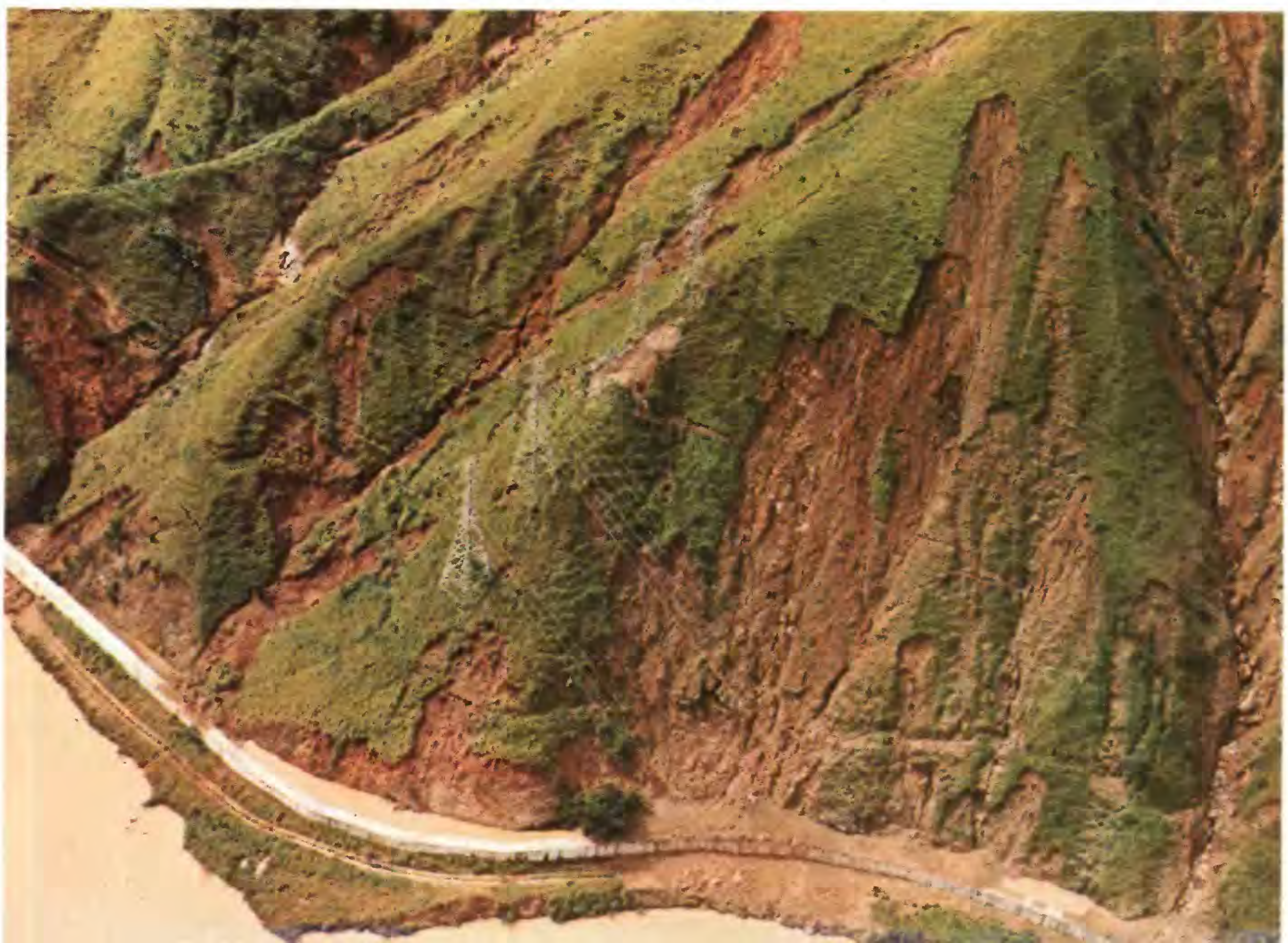


FIGURE 39 (above).—Tailrace channel of new Fontes powerplant choked by Lajes Creek valley mudflow, looking downstream. Men silhouetted in upper left center are walking on city of Rio de Janeiro's water-supply conduit.

FIGURE 40 (below).—Tailrace channel of new Fontes powerplant after mudflow was cleaned out.

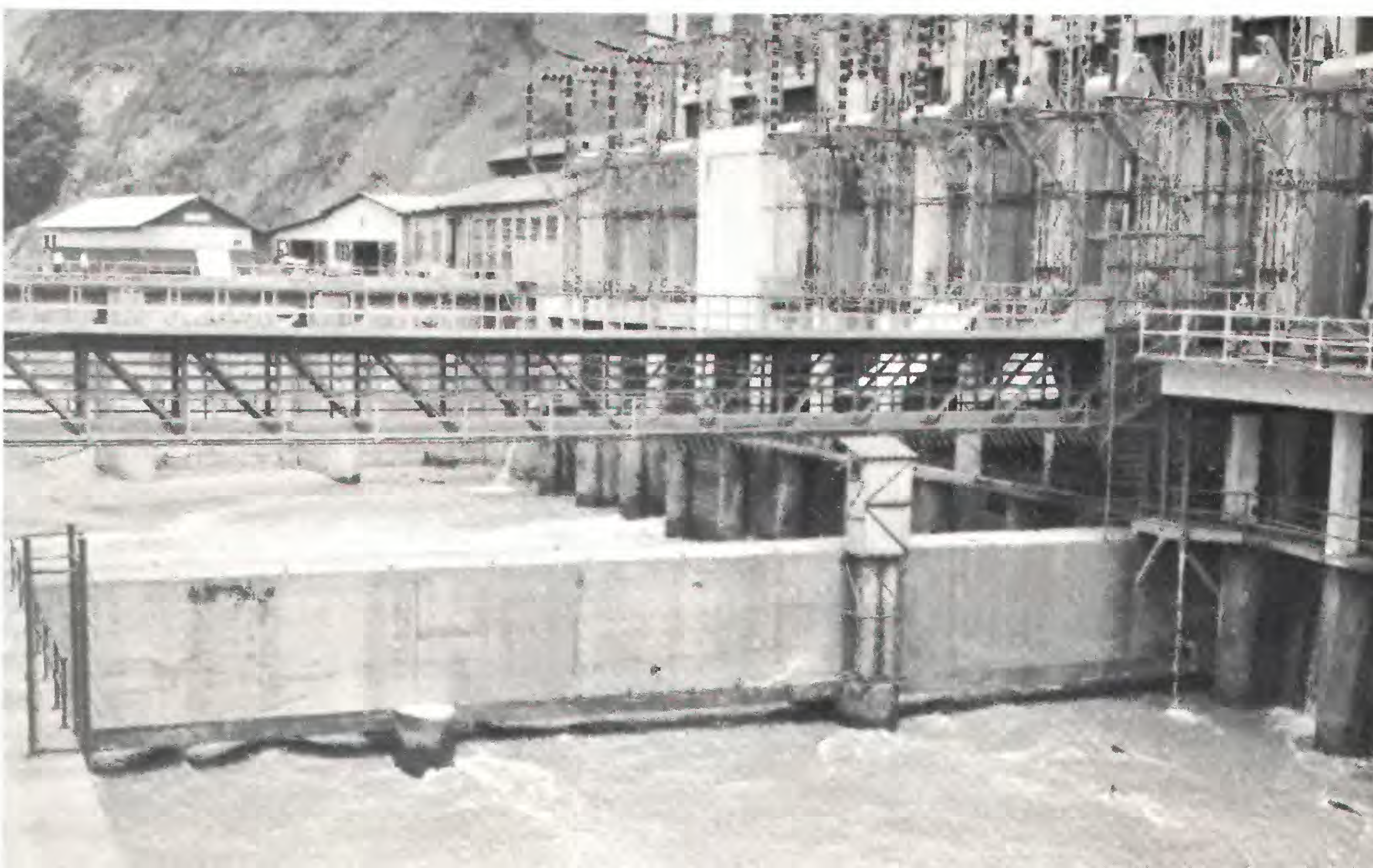


FIGURE 41.—Tailrace channel of new Fontes powerplant choked by Lajes Creek valley mudflow, looking upstream. Water at left is spilling over city of Rio de Janeiro's water-supply conduit. Foreground space below conduit is tailrace channel of old Fontes plant.

bottom (figs. 15, 22, 23, and 35). It carried trees, brush, and boulders as large as 3 m across. This drainage heretofore had been carried by a small rock- and concrete-lined channel. The debris clogged the concrete bridge opposite the plants and formed a dam (figs. 23 and 35). This dam diverted the mudflow out of the channel toward the Nilo Peçanha underground powerplant. Part of the mudflow choked the tailrace tunnel and caused flooding of the plant from below. Another part crossed the switchyard and entered the access tunnel of the plant. The lower three levels of the plant became completely submerged by water containing a great deal of mud. The valve and turbine pits, as well as the turbines, were completely filled. The generating room was filled to within 50 cm (centimeters) of its ceiling. Approximately 40 cm of water, mud, and debris were left on the main floor of the plant. Thus the turbines, generator stations, and all the control equipment of the units were submerged, leaving only the thrust bearings and main exciters of the units above water.

The new Fontes plant is adjacent to and just upstream from the old Fontes plant (fig. 17). Water from Lajes Creek above the plants has no other escape from the valley except through the tailrace channels of both plants (fig. 33). Across the tailrace channel between the two plants is a concrete conduit carrying an auxiliary water supply of about 5 cu m per sec to the city of Rio de Janeiro (figs. 39, 40, and 41). Another 40 to 50 avalanches and flows formed in the old canyon of Lajes Creek between the main dam and the Fontes plants. Similarly, a tremendous mudflow developed as the rocks,

FIGURE 42.—Herringbone-patterned landslide complex adjacent to the Ipê incline. The reason for the development of this slide pattern is unknown, but it probably reflects differential stability of the residual soils due to local variations in their character and thickness.

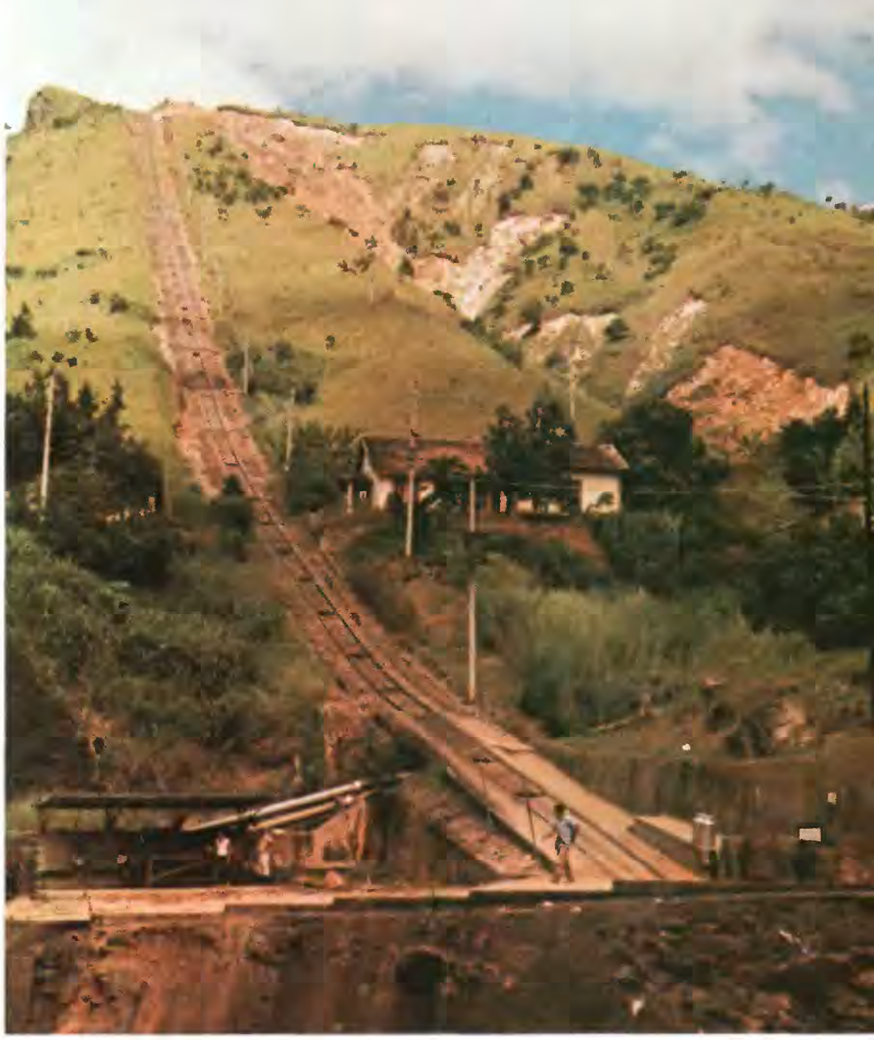


FIGURE 43.—Herringbone-patterned landslide shown in figure 42 one week after the lime treatment. It was not anticipated that the lime treatment alone would stabilize the slide. It was hoped that it would retard enlargement through the 1967 rainy season and keep the slide from severing the incline so that during the dry season the slopes could be shaped and given a bituminous coating to stabilize them from further sliding and erosion.

soil, trees, and water reached the valley bottom. As the mudflow reached the conduit across the tailrace channel with its trees and large rocks, it immediately plugged the channel and the draft tubes of the turbines of the new Fontes plant (figs. 39, 40, and 41). Below this dam formed by the conduit, the tailrace channel of the old Fontes plant remained relatively clear of plugging and could function. Landslides closed the access road along Ponte Coberta Reservoir between the generating complex and the Presidente Dutra Highway (figs. 15 and 18). They came perilously close to about 15 of the transmission towers (figs. 34 and 38). They cut to the very edge of other facilities such as the headworks of the aerial tram (fig. 23), the incline trolleys figs. 32, 37, and 42), the valve chamber structure (fig. 32), and the surge pipes of the Fontes plants (fig. 37). The Lajes Creek Dam and dikes of the reservoir were completely unaffected, except for removement of an earlier slide at dike 4 (figs. 17 and 31).

With such great areas of soil and forest debris laid open, heavy rains again could easily produce mudflows in the same area as before. The steep hillsides will be easy prey to stoping action by caving and washing.

Two typical soil samples (Nos. 1 and 2) were taken in the power complex area. Sample 1 was taken from the Lajes Creek valley, and sample 2 was taken from the east fork of Fazenda Creek valley (fig. 15). The samples were tested in the U.S. Geological Survey laboratory in Denver, Colo. The results of the test are summarized in table 2 and figures 29 and 30. Sample 1 contained montmorillonite clay as well as illite and kaolinite. Sample 2 did not contain montmorillonite clay. The results of lime tests on soil samples taken at selected localities on landslides and other features are summarized in table 3. They indicate that in some areas of the generating complex the addition of lime to the soil will aid in its stabilization.

FIGURE 44.—Landslide at dike 4 immediately after lime treatment.

Because of the critical conditions at a slide near the Ipê incline (fig. 42) and another at dike 4 (fig. 31), the slides were treated with lime as soon as the lime test reaction was known (figs. 43 and 44). It was not expected that the lime alone would halt the sliding, but it was hoped that it would retard movement until the rainy season had ended so that other measures such as drainage and bituminous surfacing could be carried out. Only a few days after the lime application, the surface of the slide material was firm enough to walk on after a rain, whereas before it was so soft that a man would sink into it 10 or 13 cm. Water issuing from the lower part of the slide prior to the lime application was muddy. After the lime application, clear water emerged from the slide area farther down the slopes.

Two years after the application of the lime to the slide at dike 4 no appreciable movement of the slide had been observed and the slide material was drier and firmer than the material in nearby untreated areas (A. Gallotti, President of Rio Light S.A., oral commun., 1967).

Many hydroelectric powerplants are vulnerable to damage from earth and rock movements above them because the plants are most advantageously located at the toes of slopes. Probably no other generating complex ever suffered such intense devastation from a single rainstorm as the Lajes Rio Light installation. The published record of the effect of the Serra das Araras storm on the powerplants and other features may serve engineers in avoiding such damage at plants elsewhere in the world.

REFERENCES

American Society for Testing and Materials, 1964, Procedures for testing soils [4th ed.]: Philadelphia, Pa., Am. Soc. Testing and Materials, 540 p.

Diamond, Sidney, and Kinter, E. B., 1965, Mechanism of soil-lime stabilization—an interpretive review: Natl. Acad. Sci.-Natl. Research Council Highway Research Board, Highway Research Rec. 92, p. 85–102.

Eckel, E. B., ed., 1958, Landslides and engineering practice: Natl. Acad. Sci.-Natl. Research Council Highway Research Board, Spec. Rept. 29, 232 p.; also available as Natl. Research Council Pub. 544.

Handy, R. L., and Williams, W. W., 1967, Chemical stabilization of an active landslide: Civil Engineering-ASCE, v. 37, no. 8, p. 62–65.

Ho, Clara, and Handy, R. L., 1964, Electrokinetic properties of lime-treated bentonites, *in* Clays and Clay Minerals—Proceedings of the Twelfth National Conference on Clays and Clay Minerals, Atlanta, Georgia, September 30–October 2, 1963: New York, Macmillan Company, p. 267–280.

Jones, F. O., Embody, D. R., and Peterson, W. L., 1961, Landslides along the Columbia River valley, northeastern Washington: U.S. Geol. Survey Prof. Paper 367, 98 p.

Lambe, T. W., 1960, The character and identification of expansive soils; a report completed for the technical studies program of the Federal Housing Administration: Washington, D.C., [U.S.] Federal Housing Adm., 46 p. (FHA–701).

Moum, Johan, Sopp, O. I., and Løken, Tor, 1968, Stabilization of undisturbed quick clay by salt wells: Norges Teotek. Inst. Pub. 81, p. 1–6.

Rock Products, 1966, How to spike marginal aggregate: Rock Products, v. 69, no. 7 (special lime issue), p. 82–84.

Rural and Urban Roads, 1963, Subgrade improved with a drill-lime stabilization: Rural and Urban Roads, v. 1, no. 5, p. 24–27.

Schultz, L. G., 1964, Quantitative interpretation of mineralogical composition from X-ray and chemical data for the Pierre Shale: U.S. Geol. Survey Prof. Paper 391–C, 31 p.

Terzaghi, Karl, 1950, Mechanisms of landslides, *in* Paige, Sidney, chm., Application of geology to engineering practice: New York, Geol. Soc. America, Berkey volume, p. 83–123.

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