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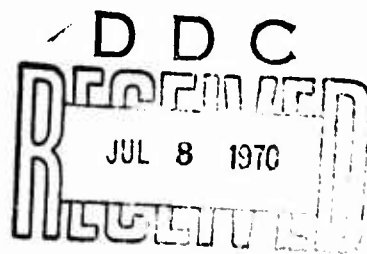
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**CHEMICAL PROPERTIES OF SOILS  
AT MINE-TUNNEL  
DETECTION RESEARCH SITES,  
PUERTO RICO**

**Timothy J. Simpson  
and  
Richard P. Murrmann**

**June 1970**

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DA PROJECT 1J662708A462

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## **PREFACE**

This report was prepared by CPT. T.J. Simpson, Ph.D. (Soil Scientist) and Dr. R.P. Murrmann (Research Chemist). The authors are members of the Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL).

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## CHEMICAL PROPERTIES OF SOILS AT MINE-TUNNEL DETECTION RESEARCH SITES, PUERTO RICO

by

T.J. Simpson and R.P. Murrmann

The need to consider the influence of environmental parameters on the response of detection devices to objects of military significance has become generally accepted. In addressing this requirement, Puerto Rico was selected as an area where, due to a wide variety in environmental conditions, a facility could be developed for mine-tunnel detection research with emphasis on subtropical and tropical conditions.

The U.S. Army Engineer Waterways Experiment Station, which maintains an environmental study group in Puerto Rico, has recommended about twenty sites for future development. In this site selection, the requirements associated with both long-term environmental effects research programs and performance appraisal of current and future generations of detection devices were considered. A general description has been given of the soil at each of the mine-tunnel detection sites.<sup>8</sup> A detailed analysis of the physical properties of the soils has been made by Waterways Experiment Station.\* The results of the chemical analysis of the soils are given in this report. Knowledge of the chemical properties is expected to be useful in interpretation of the response of various detection devices to the soil at each site.

Soil samples were collected at each of the proposed mine-tunnel sites in May 1969 using a 3-in.-diameter auger. At the Laguna Joyuda tunnel site, samples were obtained at 1-ft intervals to a depth of 8 ft at 3 locations to characterize chemical variability. The remaining sites to be used primarily for mine detection research were sampled only at one location to a 3-ft depth. The field-moist samples were stored in plastic bags until chemical analysis at which time sub-samples were dried and ground to pass through a 2-mm sieve. The analyses performed and references to the corresponding procedures are as follows: cation exchange capacity,<sup>5</sup> exchangeable sodium ions,<sup>2</sup> exchangeable potassium ions,<sup>2</sup> exchangeable calcium ions,<sup>2</sup> exchangeable magnesium ions,<sup>2</sup> exchange acidity,<sup>2</sup> soluble salt conductivity,<sup>2</sup> pH,<sup>2</sup> carbonates,<sup>1</sup> organic matter,<sup>1</sup> organic carbon,<sup>1</sup> total nitrogen,<sup>2</sup> iron oxides.<sup>1</sup>

Before discussing the results of the chemical analyses, it seems worthwhile to review how soils develop so that differences in chemical properties can be better understood. The genesis of a soil depends upon the interrelationship between climate, vegetation, parent material, topography, and time. In a subtropical and tropical region such as Puerto Rico, most soils are formed by laterization which can be visualized as two separate processes, primary laterization and resili-cation.<sup>3</sup> Primary laterization is chemical weathering during which  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and silica are depleted with a concurrent enrichment of the oxides of aluminum and iron in the soil.

Primary laterization occurs under conditions of high temperature and unusually high rainfall on extremely well drained soils. The clay mineral content of these soils is very low. They may be composed of up to 90% free  $\text{Fe}_2\text{O}_3$  plus  $\text{Al}_2\text{O}_3$ . Under moderate rainfall and drainage conditions,

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\* Private communication, Mr. Warren Grabau, U.S. Army Engineer Waterways Experiment Station

the process of silication to be described below may occur simultaneously with the result that some soils contain the clay mineral kaolinite which has a low  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of one, and up to 10%  $\text{Fe}_2\text{O}_3$ . Other chemical properties which typify the situations described above are a low cation exchange capacity, low percent base saturation, and a low pH.

Silication is a chemical synthesis process by which silica resulting from primary laterization combines with iron and aluminum oxides in areas where silica accumulates as a result of imperfect drainage. This situation may occur near the water table level in soil below a zone of primary laterization, or near the surface in low-lying areas where drainage is impaired. Silication can also occur when conditions of low pH and moderate rainfall exist but the total water supply is too low to allow the transport of soluble silica. In any event, the products of silication are clay minerals. Depending on the amount of silica available, the minerals formed may be either of the kaolinite type with a low  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of one, or the montmorillonite type with a relatively high  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of two. In the latter case, soils are characterized by a high cation exchange capacity, high percent base saturation, and a high pH, with a relatively low  $\text{Fe}_2\text{O}_3$  content of less than 3%.

Although the rainfall and temperature regimes fit the requirements for laterization throughout most tropical and subtropical regions, soils other than laterite soils are common. For example, soils classified as podzolic owe their development to the fact that they have been steadily supplied with weatherable mineral matter by rapid geologic erosion. The base and primary mineral silica content of these soils exceeds that of lateritic soils even though the environmental conditions favor laterization processes. Any major deviation from the required interrelationship between climate, vegetation, parent material, topography and time can produce conditions favoring other soil types. In Puerto Rico, due to the wide diversity in environmental conditions, many of the 22 great soil groups found on a world wide basis are present. As illustrated in Table I,<sup>8</sup> 13 of these great soil groups are represented by the mine-tunnel detection sites.

The results of this investigation are compiled in Table II. The chemical properties of the soils, although not as obvious in the field as the physical properties, nevertheless vary over a wide range. This is illustrated in Table III where the extreme values for each chemical property of the surface soil at the sites are listed. Despite the wide range in values obtained for a given type of determination, the variability can be explained in terms of the processes of primary laterization and silication described earlier.

The cation exchange capacity (CEC) of a soil arises primarily from two sources. The crystal lattice of most types of clay minerals is negatively charged, mainly due to substitution of divalent cations such as  $\text{Mg}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Zn}^{2+}$ , and  $\text{Co}^{2+}$  for  $\text{Al}^{3+}$  which is the primary constituent of the inner layer of 2:1-type layer silicates such as montmorillonite, and substitution of  $\text{Al}^{3+}$  or  $\text{Fe}^{3+}$  for  $\text{Si}^{4+}$  in the outer layer of both 2:1 and 1:1 layer clay minerals such as kaolinite. The negatively charged lattice which results is neutralized by exchangeable ions that are capable of undergoing exchange reactions with both inorganic and organic cations from the solution phase. The negative charge is expressed quantitatively as the number of milliequivalents of negative charge per 100 grams of material. Most clay minerals have a CEC of 5 to 200 meq/100 g. The second source of exchange capacity is decomposed organic matter (humus) which has a CEC of 50 to 150 meq/100 g.

The degree to which the CEC of a soil is neutralized by basic exchangeable cations such as  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  other than  $\text{H}^+$  and cationic forms of Fe and Al is termed percent base saturation. At low base saturation, acidic conditions (low pH) prevail, whereas basic conditions (high pH) are present at high percent base saturation. Other ionic constituents in soil solution include salts which arise from numerous sources including dissolution of soil constituents, fertilizer additions, and seawater. The variation in these chemical properties with climatic and soil conditions

Table I. Description of mine detection research sites.

| Devel.<br>priority                          | Site name         | Group<br>classification | Physiographic<br>classification              | Surface<br>texture | Parent<br>material                    | Vegetation           |
|---------------------------------------------|-------------------|-------------------------|----------------------------------------------|--------------------|---------------------------------------|----------------------|
| <b>Primary Sites (USA CRREL Research)</b>   |                   |                         |                                              |                    |                                       |                      |
| 1a                                          | Laguna Joyuda     | Laterite                | Upland, deep                                 | Clay loam          | Serpentine rock                       | Sugar cane           |
| 1b                                          | Lajas             | Alluvial                | River floodplain,<br>poorly drained          | Clay               | Alluvium                              | Grass                |
| 1c                                          | Isabela           | Sand                    | Coastal lowlands,<br>well drained            | Sand               | Coral, shells                         | Grass, palm          |
| 1d                                          | El Yunque         | Yellow podzol           | Upland, medium deep                          | Silt loam          | Cretaceous, tuff-<br>aceous sediments | Tropical forest      |
| 2a                                          | Florida           | Yellow-brown laterite   | Coastal plain,<br>compact                    | Sandy clay         | Limestone                             | Grass                |
| 2b                                          | Salinas           | Red prairie             | Terrace and alluvial<br>fans, compact        | Clay loam          | Cretaceous, tuff-<br>aceous sediments | Sugar cane           |
| 2c                                          | Manati            | Alluvial                | River floodplain,<br>well drained            | Silt loam          | Alluvium                              | Sugar cane           |
| 3a                                          | Sierra Bermeja    | Rendzina                | Upland, shallow                              | Clay loam          | Limestone                             | Grass, shrub, cactus |
| 3b                                          | Pargue            | Half-bog                | Coastal lowland,<br>poorly drained           | Loam               | Coral, shells                         | Mangrove             |
| 4                                           | Yauco             | Chernozem               | Terrace and alluvial<br>fans, medium friable | Clay               | Limestone                             | Sugar cane           |
| 5                                           | Laguna Tortuguero | Yellow-brown laterite   | Coastal plain, very<br>friable               | Sandy loam         | ?                                     | Grass, palm          |
| <b>Secondary Sites (USA CRREL Research)</b> |                   |                         |                                              |                    |                                       |                      |
| 6                                           | Rio Guayanes      | Red prairie             | River flood plain,<br>well drained           | Sandy loam         | Granodiorite and<br>quartz diorite    | Grass                |
| 7                                           | Rio Abajo         | Lithosol                | Upland, medium deep                          | Clay               | Cretaceous, tuff-<br>aceous sediments | Forest               |
| 8                                           | Yaubaucó          | Wiesenboden             | River floodplain,<br>poorly drained          | Sandy loam         | Alluvium                              | Sugar cane           |
| 9                                           | Sabana Hoyos      | Brown laterite          | Coastal plains,<br>compact                   | Sandy clay         | Alluvium                              | Sugar cane           |
| 10                                          | Toro Negro        | Red-brown laterite      | Upland, deep                                 | Clay loam          | Cretaceous, tuff-<br>aceous sediments | Forest               |
| 11                                          | Llanos            | Planosol                | Coastal plain,<br>compact                    | Loam               | Cretaceous, tuff-<br>aceous sediments | Grass, palm          |
| 12                                          | Moca              | Alluvial                | River floodplain,<br>poorly drained          | Clay               | Alluvium                              | Sugar cane           |
| -                                           | Rio San Patricio  | Red-brown laterite      | Upland, deep                                 | Clay loam          | Cretaceous, tuff-<br>aceous sediments | Forest               |
| -                                           | Dorado            | Alluvial                | River floodplain,<br>well drained            | Silt loam          | Alluvium                              | Sugar cane           |
| -                                           | Loiza             | Alluvial                | River floodplain,<br>well drained            | Silt loam          | Alluvium                              | Sugar cane           |

corresponding to the processes of primary laterization and silication is given in Table IV. As expected on the basis of earlier discussion, conditions of upland topography, good drainage, high rainfall, and old landform lead to lower CEC, low percent base saturation, and low pH. Due to leaching conditions, the soluble salt content is low. The iron oxide content is enriched as a result of primary laterization. However, silication must also occur in these upland soils since kaolinite is present<sup>1</sup> and the iron oxide content is relatively low. The fact that montmorillonite is present<sup>4</sup> in the young, imperfectly drained soils supports the view that silication is the dominant process under these environmental conditions.

Table II. Chemical properties of soils at mine-tunnel detection research sites, Puerto Rico

| Site name     | Depth, feet | CEC, meq/100g | Exchangeable cations, meq/100g |                |                  |                  | pH                     |     | Salt conductivity, $\mu\text{mho} \times 10^5$ | Carbonates, percent | Organic matter, percent | Organic carbon, percent | Nitrogen, percent | Iron oxides, percent |
|---------------|-------------|---------------|--------------------------------|----------------|------------------|------------------|------------------------|-----|------------------------------------------------|---------------------|-------------------------|-------------------------|-------------------|----------------------|
|               |             |               | Na <sup>+</sup>                | K <sup>+</sup> | Ca <sup>2+</sup> | Mg <sup>2+</sup> | H <sup>+</sup> (equiv) |     |                                                |                     |                         |                         |                   |                      |
| Laguna Joyuda | 0-1         | 17.2          | .05                            | .13            | 6.01             | .43              | 17                     | 5.0 | 22                                             | .051                | 4.4                     | 2.30                    | .172              | 5.81                 |
|               | 0-1         | 17.2          | .05                            | .12            | 5.58             | .40              | 14                     | 5.0 | 22                                             | .060                | 5.0                     | 2.90                    | .164              | 5.62                 |
|               | 1-2         | 15.8          | .05                            | .05            | 1.76             | .51              | 15                     | 4.6 | 12                                             | .042                | 2.2                     | 1.44                    | .108              | 8.55                 |
|               | 2-3         | 16.9          | .04                            | .03            | 1.49             | .65              | 12                     | 4.7 | 12                                             | .069                | 1.2                     | .67                     | .061              | 9.28                 |
|               | 3-4         | 15.8          | .09                            | .03            | .88              | 1.19             | 9                      | 4.7 | 12                                             | .066                | .5                      | .37                     | .040              | 9.59                 |
|               | 4-5         | 13.5          | .10                            | .03            | .35              | .91              | 9                      | 5.0 | <5                                             | .039                | .3                      | .27                     | .036              | 9.40                 |
|               | 5-6         | 17.8          | .15                            | .03            | .26              | .65              | 11                     | 5.1 | <5                                             | .060                | .4                      | .30                     | .038              | 9.32                 |
|               | 6-7         | 15.2          | .14                            | .03            | .26              | .43              | 11                     | 5.0 | <5                                             | .039                | .4                      | .26                     | .035              | 9.32                 |
|               | 7-8         | 14.7          | .13                            | .03            | .24              | .40              | 10                     | 5.0 | <5                                             | .054                | .4                      | .25                     | .032              | 9.62                 |
|               | 0-1         | 25.1          | .05                            | .16            | 3.95             | .80              | 21                     | 4.7 | 26                                             | .033                | 5.2                     | 2.90                    | .204              | 7.68                 |
|               | 0-1         | 24.4          | .04                            | .20            | 4.30             | .80              | 21                     | 4.7 | 26                                             | .051                | 5.3                     | 2.92                    | .208              | 7.51                 |
|               | 1-2         | 18.0          | .04                            | .10            | 2.85             | .76              | 13                     | 5.0 | 14                                             | .048                | 2.8                     | 1.54                    | .080              | 8.26                 |
|               | 2-3         | 14.4          | .03                            | .05            | 2.85             | .72              | 11                     | 5.3 | 11                                             | .054                | 1.7                     | 1.05                    | .084              | 9.84                 |
|               | 3-4         | 14.4          | .03                            | .04            | 2.72             | .80              | 9                      | 5.6 | 10                                             | .066                | .8                      | .63                     | .076              | 9.98                 |
|               | 4-5         | 12.1          | .03                            | .03            | 2.10             | .91              | 9                      | 5.2 | 15                                             | .072                | 1.1                     | .58                     | .064              | 10.32                |
|               | 5-6         | 13.7          | .02                            | .03            | 1.19             | .83              | 10                     | 4.9 | 12                                             | .045                | .8                      | .55                     | .060              | 10.58                |
|               | 6-7         | 12.7          | .02                            | .04            | .92              | 1.05             | 8                      | 5.0 | 10                                             | .054                | .9                      | .54                     | .056              | 10.38                |
|               | 7-8         | 11.8          | .02                            | .02            | .69              | 1.01             | 6                      | 4.9 | 9                                              | .063                | .3                      | .54                     | .060              | 11.06                |
|               | 0-1         | 17.8          | .04                            | .25            | 3.69             | 1.01             | 14                     | 4.7 | 36                                             | .021                | 4.8                     | 2.52                    | .216              | 6.56                 |
|               | 0-1         | 18.6          | .05                            | .28            | 3.95             | 1.05             | 15                     | 4.6 | 40                                             | .039                | 5.0                     | 2.62                    | .216              | 6.31                 |
|               | 1-2         | 16.7          | .04                            | .05            | 3.07             | .87              | 10                     | 5.3 | 11                                             | .054                | 2.3                     | 1.21                    | .114              | 8.50                 |
|               | 2-3         | 16.9          | .05                            | .03            | 2.63             | 1.05             | 6                      | 5.8 | <5                                             | .042                | .8                      | .46                     | .048              | 8.95                 |
|               | 3-4         | 12.1          | .05                            | .03            | 1.93             | 1.09             | 5                      | 5.1 | <5                                             | .048                | .5                      | .27                     | .036              | 9.71                 |
|               | 4-5         | 15.2          | .07                            | .03            | 2.41             | .83              | 5                      | 5.4 | <5                                             | .081                | .4                      | .27                     | .032              | 12.76                |
|               | 5-6         | 15.2          | .08                            | .04            | 3.07             | .83              | 5                      | 5.6 | <5                                             | .084                | .2                      | .18                     | .030              | 9.14                 |
|               | 6-7         | 17.4          | .07                            | .03            | 3.07             | .76              | 3                      | 5.6 | <5                                             | .090                | .4                      | .15                     | .029              | 10.70                |
|               | 7-8         | 10.5          | .07                            | .03            | 3.16             | .60              | 3                      | 5.7 | <5                                             | .108                | .4                      | .09                     | .024              | 8.86                 |
| Lajas         | 0-1         | 51.6          | 5.2                            | .68            | 36.2             | 16.2             | 9                      | 6.3 | 400                                            | .315                | 2.1                     | 1.27                    | .104              | 2.63                 |
|               | 1-2         | 51.1          | 8.7                            | .57            | 33.8             | 18.8             | 7                      | 6.7 | 600                                            | .348                | 2.0                     | 1.05                    | .076              | 2.38                 |
|               | 2-3         | 48.8          | 9.7                            | .50            | 30.0             | 18.2             | 4                      | 7.2 | 675                                            | .384                | 1.3                     | 0.65                    | .052              | 2.38                 |
| Isabela       | 0-1         | 1.2           | .11                            | .03            | 11.1             | 1.3              | 0                      | 8.8 | 17                                             | 1.49                | 0.2                     | .86                     | .016              | .17                  |
|               | 1-2         | 1.0           | .10                            | .02            | 11.7             | 1.4              | 0                      | 8.7 | 10                                             | 1.47                | 0.2                     | .41                     | .016              | .35                  |
|               | 2-3         | .9            | .08                            | .02            | 11.2             | 1.3              | 0                      | 8.7 | 9                                              | 1.47                | 0.2                     | .54                     | .016              | .35                  |
| El Yunque     | 0-1         | 33.3          | .23                            | .14            | 4.17             | 1.45             | 23                     | 4.8 | 21                                             | .045                | 10.8                    | 4.54                    | .272              | 4.21                 |
|               | 1-2         | 30.5          | .08                            | .08            | .40              | .43              | 14                     | 4.8 | <5                                             | .039                | 11.6                    | 5.50                    | .275              | 4.25                 |
|               | 2-3         | 25.4          | .10                            | .05            | .41              | .51              | 20                     | 4.6 | <5                                             | .030                | 5.7                     | 2.88                    | .152              | 7.95                 |
| Florida       | 0-1         | 15.2          | .23                            | .25            | .59              | .14              | 16                     | 4.8 | <5                                             | trace               | .8                      | 1.53                    | .168              | 3.31                 |
|               | 1-2         | 18.1          | .08                            | .08            | .73              | .12              | 16                     | 4.5 | <5                                             | "                   | 2.5                     | 1.38                    | .112              | 5.49                 |
|               | 2-3         | 20.0          | .10                            | .11            | .21              | .09              | 15                     | 4.4 | 9                                              | "                   | 5.0                     | 1.05                    | .088              | 6.55                 |
| Salinas       | 0-1         | 37.3          | .47                            | .73            | 25.6             | 5.97             | 3                      | 7.8 | 22                                             | .417                | 2.5                     | 1.15                    | .114              | 3.45                 |
|               | 1-2         | 35.1          | .55                            | .68            | 25.6             | 6.85             | 4                      | 7.6 | 13                                             | .402                | 0.8                     | .38                     | .056              | 3.51                 |
|               | 2-3         | 30.5          | .53                            | .62            | 27.5             | 5.97             | 2                      | 7.7 | 25                                             | .474                | 0.5                     | .21                     | .032              | 3.45                 |
| Manati        | 0-1         | 29.1          | .19                            | .18            | 19.3             | 5.41             | 8                      | 6.9 | 11                                             | .33                 | 1.5                     | .82                     | .076              | 4.26                 |
|               | 1-2         | 30.3          | .16                            | .15            | 18.4             | 5.09             | 6                      | 7.1 | <5                                             | .40                 | 0.8                     | .41                     | .052              | 3.95                 |
|               | 2-3         | 27.0          | .17                            | .15            | 18.4             | 5.09             | 6                      | 7.2 | <5                                             | .40                 | 0.8                     | .31                     | .036              | 3.80                 |

CHEMICAL PROPERTIES OF SOILS, PUERTO RICO

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| Site name         | Depth,<br>feet | CEC,<br>meq/100g | Exchangeable cations, meq/100g |                |                  |                  | pH | Salt con-<br>ductivity,<br>mho x 10 <sup>3</sup> | Carbonates, percent | Organic<br>matter,<br>percent | Organic<br>carbon,<br>percent | Nitrogen,<br>percent | Iron<br>oxides,<br>percent |
|-------------------|----------------|------------------|--------------------------------|----------------|------------------|------------------|----|--------------------------------------------------|---------------------|-------------------------------|-------------------------------|----------------------|----------------------------|
|                   |                |                  | Na <sup>+</sup>                | K <sup>+</sup> | Ca <sup>2+</sup> | Mg <sup>2+</sup> |    |                                                  |                     |                               |                               |                      |                            |
| Sierra Bermeja    | 0-1            | 34.6             | .08                            | 1.52           | 37.7             | 3.34             | 2  | 7.7                                              | 4.26                | 4.4                           | 3.83                          | .24                  | 1.16                       |
|                   | 1-2            | 24.8             | .14                            | .55            | 25.6             | 3.18             | 1  | 8.2                                              | 1.49                | 1.2                           | 1.32                          | .06                  | 2.22                       |
|                   | 2-3            | 38.2             | .21                            | .78            | 31.4             | 6.21             | 1  | 7.7                                              | 1.37                | 2.6                           | 1.67                          | .16                  | 2.13                       |
| Parquera          | 0-1            | 20.4             | 42.1                           | 2.0            | 24.1             | 13.9             | 1  | 7.0                                              | 4.41                | 4.6                           | 2.45                          | .044                 | 4.41                       |
|                   | 1-2            | 11.8             | 31.1                           | 1.9            | 14.0             | 10.0             | 0  | 8.2                                              | 6.78                | 2.0                           | 2.70                          | .048                 | 6.78                       |
|                   | 2-3            | 39.5             | 85.7                           | 4.5            | 25.6             | 27.1             | 1  | 7.6                                              | 3.76                | 6.8                           | 3.59                          | .104                 | 3.76                       |
| Yauco             | 0-1            | 51.6             | .60                            | .91            | 43.5             | 7.7              | 3  | 7.3                                              | .894                | 3.2                           | 1.76                          | .18                  | 2.74                       |
|                   | 1-2            | 48.8             | .61                            | .65            | 40.6             | 7.0              | 2  | 7.8                                              | 2.61                | 1.1                           | .67                           | .08                  | 2.78                       |
|                   | 2-3            | 33.3             | .51                            | .47            | 32.4             | 5.1              | 0  | 8.1                                              | 5.31                | 0.9                           | .64                           | .044                 | 1.43                       |
| Laguna Tortuguero | 0-1            | 3.6              | .08                            | .08            | 1.1              | .54              | 2  | 5.9                                              | .13                 | 1.1                           | .61                           | .076                 | .88                        |
|                   | 1-2            | 2.7              | .07                            | .03            | .72              | .43              | 3  | 5.7                                              | .11                 | 0.3                           | .15                           | .074                 | 1.02                       |
|                   | 2-3            | 15.1             | .34                            | .17            | 4.4              | 2.4              | 5  | 6.0                                              | .16                 | 0.4                           | .26                           | .064                 | 2.57                       |
| Rio Guaynabes     | 0-1            | 16.7             | .15                            | .16            | 9.5              | .94              | 12 | 5.0                                              | .20                 | 2.4                           | 1.1                           | .11                  | 1.25                       |
|                   | 1-2            | 5.6              | .15                            | .03            | 2.9              | .25              | 9  | 5.1                                              | .18                 | .5                            | .23                           | .044                 | 1.2                        |
|                   | 2-3            | 3.4              | .17                            | .03            | 1.5              | .40              | 4  | 5.5                                              | .23                 | .3                            | .06                           | .022                 | .89                        |
| Rio Abajo         | 0-1            | 53.9             | .15                            | .23            | 27.5             | 5.1              | 17 | 5.5                                              | .213                | 3.6                           | 2.17                          | .22                  | 5.42                       |
|                   | 1-2            | 47.2             | .16                            | .18            | 18.4             | 4.0              | 20 | 5.1                                              | .138                | 2.5                           | 1.47                          | .17                  | 4.39                       |
|                   | 2-3            | 46.6             | .23                            | .20            | 11.0             | 2.3              | 20 | 5.1                                              | .138                | 1.3                           | .69                           | .08                  | 5.87                       |
| Yabauco           | 0-1            | 16.7             | .15                            | .16            | 9.5              | .94              | 6  | 6.1                                              | .204                | 2.6                           | 1.1                           | .10                  | 1.25                       |
|                   | 1-2            | 5.6              | .15                            | .03            | 2.9              | .25              | 1  | 5.8                                              | .132                | 0.5                           | .23                           | .04                  | 1.20                       |
|                   | 2-3            | 3.4              | .17                            | .03            | 1.5              | .40              | 1  | 5.9                                              | .114                | 0.1                           | .06                           | .03                  | .89                        |
| Sabana Hoyos      | 0-1            | 13.9             | .03                            | .25            | .88              | .10              | 11 | 4.2                                              | .045                | 1.9                           | 1.0                           | .114                 | 5.65                       |
|                   | 1-2            | 13.5             | .04                            | .27            | .74              | .11              | 10 | 4.3                                              | .039                | .9                            | .45                           | .080                 | 5.58                       |
|                   | 2-3            | 14.2             | .03                            | .18            | 2.11             | .25              | 9  | 4.8                                              | .063                | .7                            | .42                           | .080                 | 7.29                       |
| Toro Negro        | 0-1            | 28.9             | .06                            | .06            | .14              | .14              | 14 | 4.8                                              | .036                | 1.0                           | .58                           | .036                 | 8.78                       |
|                   | 1-2            | 33.3             | .07                            | .05            | .09              | .16              | 16 | 4.8                                              | .060                | 1.9                           | 1.0                           | .060                 | 7.85                       |
|                   | 2-3            | 33.3             | .09                            | .09            | .26              | .32              | 19 | 4.6                                              | .078                | 4.7                           | 2.5                           | .148                 | 8.23                       |
| Llanos            | 0-1            | 19.3             | .26                            | 2.54           | 7.6              | 4.3              | 6  | 5.9                                              | .126                | 5.2                           | 2.57                          | .275                 | 2.36                       |
|                   | 1-2            | 12.3             | .26                            | 2.75           | 5.8              | 4.3              | 3  | 6.0                                              | .108                | 2.8                           | 1.36                          | .144                 | 2.33                       |
|                   | 2-3            | 17.5             | .49                            | 3.78           | 2.4              | 2.15             | 5  | 5.7                                              | .042                | 0.5                           | 0.54                          | .068                 | 4.50                       |
| Moca              | 0-1            | 50.0             | .27                            | .36            | 28.0             | 3.82             | 12 | 6.0                                              | .225                | 2.8                           | 1.65                          | .132                 | 2.81                       |
|                   | 1-2            | 49.5             | .51                            | .34            | 30.0             | 4.78             | 9  | 6.3                                              | .231                | 1.9                           | .95                           | .108                 | 2.72                       |
|                   | 2-3            | 41.7             | .72                            | .25            | 21.7             | 4.94             | 8  | 6.5                                              | .208                | 0.9                           | .38                           | .048                 | 3.68                       |
| Rio San Patricio  | 0-1            | 39.3             | .12                            | .20            | .78              | 5.33             | 26 | 4.8                                              | .10                 | 0.5                           | .21                           | .032                 | 4.92                       |
|                   | 1-2            | 44.4             | .10                            | .18            | .51              | 8.84             | 29 | 5.0                                              | .11                 | 0.2                           | .83                           | .020                 | 4.46                       |
|                   | 2-3            | 42.4             | .13                            | .16            | .80              | 11.9             | 23 | 5.3                                              | .15                 | 0.4                           | .56                           | .024                 | 4.25                       |
| Dorado            | 0-1            | 35.3             | .22                            | .20            | 15.9             | 5.17             | 15 | 5.0                                              | .447                | 2.6                           | 1.49                          | .124                 | 3.58                       |
|                   | 1-2            | 32.0             | .23                            | .21            | 21.7             | 6.77             | 8  | 6.1                                              | .471                | 2.3                           | 1.33                          | .204                 | 5.49                       |
|                   | 2-3            | 30.3             | .19                            | .17            | 16.9             | 7.56             | 5  | 6.7                                              | .417                | 1.4                           | .72                           | .060                 | 3.41                       |
| Loiza             | 0-1            | 26.1             | .08                            | .38            | 6.01             | 1.12             | 16 | 4.4                                              | .189                | 3.1                           | 1.69                          | .155                 | 2.51                       |
|                   | 1-2            | 22.6             | .12                            | .07            | 14.0             | 2.79             | 6  | 5.7                                              | .285                | 2.1                           | 1.0                           | .107                 | 2.58                       |
|                   | 2-3            | 22.2             | .17                            | .07            | 14.0             | 3.58             | 5  | 6.3                                              | .306                | 1.6                           | .79                           | .084                 | 2.55                       |

**Table III. Range in chemical properties of surface soil (0-1 ft) at mine-tunnel sites.**

| Property                      | Units                     | Range |      |
|-------------------------------|---------------------------|-------|------|
|                               |                           | Min   | Max  |
| CEC                           | meq/100g soil             | 1.2   | 54   |
| Exchangeable Na <sup>+</sup>  | meq/100g soil             | 0.03  | 5.2  |
| Exchangeable K <sup>+</sup>   | meq/100g soil             | 0.03  | 2.5  |
| Exchangeable Ca <sup>2+</sup> | meq/100g soil             | 0.14  | 44   |
| Exchangeable Mg <sup>2+</sup> | meq/100g soil             | 0.10  | 16.2 |
| Exchangeable acidity          | meq/100g soil             | trace | 26   |
| Salt conductivity             | mhos/cm × 10 <sup>5</sup> | <5    | 3000 |
| pH                            |                           | 4.2   | 8.8  |
| Carbonates                    | weight percent            | 0.04  | 4.4  |
| Organic matter                | weight percent            | 0.2   | 10.8 |
| Organic carbon                | weight percent            | 0.2   | 4.5  |
| Nitrogen                      | weight percent            | 0.02  | 0.27 |
| Iron oxides                   | weight percent            | 0.2   | 8.8  |

**Table IV. Variation in chemical properties with climate and soil conditions.**

| Climate and soil conditions  | Depth ft | CEC meq/100 g | % B S meq base/CEC | pH   | Conductivity,** $\mu$ mhos/cm | Iron oxides, % |
|------------------------------|----------|---------------|--------------------|------|-------------------------------|----------------|
| Upland, good drainage        | 1        | 21.0          | 28.4               | 4.9  | 10.4(5-22)                    | 4.3            |
| high rainfall, old land-     | 2        | 20.0          | 23                 | 4.85 | 9.0(5-20)                     | 5.0            |
| form (primary lateri-        | 3        | 21.0          | 26                 | 5.0  | 9.0(5-15)                     | 6.0            |
| zation favored).*            |          |               |                    |      |                               |                |
| Imperfect drainage,          | 1        | 35.3          | 73                 | 6.5  | 22.0(8-70)                    | 2.8            |
| low to moderate              | 2        | 30.8          | 76                 | 6.8  | 14.3(5-40)                    | 2.8            |
| rainfall, young land-        | 3        | 32.7          | 75                 | 6.95 | 25.5(5-100)                   | 3.0            |
| form (silication favored). † |          |               |                    |      |                               |                |

\* Average of eight mine-tunnel sites: Toro Negro, Sabana Hoyos, Rio San Patricio, Florida, Laguna Tortuguero, Rio Guayanes, Laguna Joyuda, El Yunque.

† Average of the remaining sites. In some cases drainage was good; however, the landform was very young; i.e. recent alluvium at Dorado, Loiza, and Manati.

\*\* Parguera and Lajas not included because of very high salt content. Parguera conductivity = 3000; Lajas = 600.

A number of soils contained significant amounts of carbonates. This condition, as illustrated in Table II by the Sierra Bermeja, Parguera, and Yauco sites, is typified by a high pH and the presence of relatively large amounts of exchangeable Ca<sup>2+</sup> and Mg<sup>2+</sup>. Since carbonates are water soluble, it is common to find a distinct physical discontinuity in calcareous soils caused by accumulation of carbonates near the permanent water table level.

The total organic matter content of the soils varied from almost zero at the Isabela site to more than 10% at the El Yunque site. At each site the amount of organic matter decreased with depth due to initial accumulation at the surface. Upon the addition of undecomposed organic matter to a soil, soil microorganism populations rise, ingesting the added organic matter to obtain energy.

If the added material has a carbon to nitrogen (C/N) ratio of about 25, both carbon dioxide and soluble nitrogen products are produced from the added organic matter at rates that will ultimately reduce the C/N ratio<sup>7</sup>.

If the C/N ratio is as high as 50, free nitrate compounds originally present in the soil are removed during the decomposition process<sup>7</sup>. Highly decomposed organic matter (humus) is physically amorphous and chemically diverse with a stable C/N ratio of from 8 to 15. The C/N ratios from the mine-tunnel sites are summarized in Table V. A consideration of the carbon and nitrogen content of soil organic matter should be important in attempts to detect underground explosives based upon differences in carbon or nitrogen content. In addition, the types of biological processes occurring may influence the types of volatile compounds of nitrogen present which could interfere with trace gas detection methods.

**Table V. Carbon to nitrogen ratio for surface soils at the mine-tunnel sites.**

| Site              | C/N Ratio | Site             | C/N Ratio |
|-------------------|-----------|------------------|-----------|
| Laguna Joyuda     | 13.5      | Rio Guayanes     | 10        |
| Lajas             | 12.7      | Rio Abajo        | 10        |
| Isabela           | 43        | Yaubaucó         | 11        |
| El Yunque         | 17        | Sabana Hoyos     | 9         |
| Florida           | 9         | Toro Negro       | 14        |
| Salinas           | 10        | Moca             | 12        |
| Manati            | 20        | Rio San Patricio | 7         |
| Sierra Bermeja    | 16        | Dorado           | 12        |
| Parguera          | 60        | Loiza            | 11        |
| Yauco             | 10        | Llanos           | 9.5       |
| Laguna Tortuguero | 8         |                  |           |

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| 13. ABSTRACT<br><br>Soil at each of the proposed mine-tunnel detection research sites in Puerto Rico was analyzed. Samples were obtained at 1-ft intervals to a depth of 8 ft at three locations at the Laguna Joyuda tunnel site to determine chemical variability at the site. At the remaining 20 sites to be used primarily for explosives detection research, samples were obtained at only one location to a 3-ft depth. Analyses performed included cation exchange capacity, exchangeable ions, exchange acidity, pH, salt conductivity, carbonates, organic matter, organic carbon, nitrogen, and free iron oxides. The variation in results observed from one site to another could be explained in terms of primary laterization and silication, two soil formation processes which occur in subtropical and tropical environments. |                             |                                                                                                                                   |
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