HOW TO CALCULATE A CALCULATED RISK

An Engineering Appraisal of Limestone Landforms

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Construction jobs are not often considered in terms of areas and the particular problems related to them. When a construction project, such as a highway or airport or a dam and reservoir, extends for some distance, an area concept is particularly valuable as a money and time-saving factor. Beyond the consideration of turning in a good job, the understanding of what a landform is, what it means, and how it affects a job goes a long way in saving unnecessary expense.

How does it do this? Simply by directing your efforts in an intelligent way. If you know the characteristics of a landform, then you know when to be careful and when the risks are small. In other words, it is easier to judge the type and degree of risk, or even better, how to calculate a calculated risk. This is especially true in subsurface exploration and in job estimations for excavation.

Landforms are land units in which the geology, soils, and topography are generally the same. Some are simple, others are complex; some are large and some small. In many places, a highway will cross one or more landforms in the course of a mile. Landforms are not only topographic units, but they are units containing definite soil associations (several soils that are distinctly associated and somewhat similar in some respects). This does not say that the topography within a land form is identical, nor is the soil exactly the same at each point within these unit areas. See "The Engineering Significance of Landforms," Highway Research Board Bulletin No. 13, 1948. With these oft-repeated conditions within the landform of topography, soil material, and drainage come the repetition of conditions that affect design, construction, and maintenance of structures and pavements. Much of this influence is felt in surface and near-surface construction and deals mainly with soil problems. But in rock problems, the landforms are equally useful as units in which problems will be repeated or uncertainties acknowledged. In this respect, it is as important to know what you do not know as to be sure of your knowledge.

The limestone landform is a potent illustration of one of these rock landforms. Because it is so full of uncertainties, many expensive errors have been made and a review is in order.

Because topography is an important factor in the description of landforms, they are classified into two divisions, Level Terrain and Hilly Terrain.

Limestone is a common rock. It is formed in deep and extensive deposits, and as a result, large areas are scattered throughout the United States and elsewhere. Limestones are also formed in thin layers along with shales and sandstone, but under these circumstances the effect of the limestone is diluted by the presence of strata of other rocks.

The most important distinguishing characteristic of this rock is that of solubility. The fact that it dissolves quite readily in rainwater is the predominant force in creating both the topography of the limestone landform and the engineering problems.

Terrain - The surface of the limestone landform differs from all others. Usually, it is gently rolling and dotted with sinkholes or depressions as illustrated in Figure 1. The topography is seldom cut up by streams, since most of the water falling on the surface drains downward through the rock. This unusual factor makes each depression more or less independent of others nearby, so there is little gullying or

LEVEL TERRAIN

Landform	What	Where
1. Alluvium	Flood plains of streams and rivers rivers (Sands, silts and clays)	Everywhere.
2. Terraces	Elevated benches above floor stage (coarse texture)	Near mountains and all northern states.
a. River		
b. Lake or Ocean		
3. Filled Valley (Coarse alluvium)	Waterlaid by perennial streams and sheet flow	Western states.
4. Coastal Plain	Marine sediments near coast. (Sands and clays)	Especially Atlantic and Gulf Coast areas.
5. Continental Alluvium	Outwash from remote mountain areas.	Colorado to Texas.
6. Glacial Outwash	Gravelly plains in glaciated regions.	North of the Ohio and Missouri Rivers.
7. Tidal Flats	Clays to sands in pockets along the coast, exposed by tidal changes.	All coastal areas.
8. Beach Lines	Very low sand ridges along some coastlines.	Intermittently along coastlines.
9. Alluvial Fans	Fan-shaped deposits of coarse material.	Transition between steep and flat slopes
10. Deltas	Level lowlands	River mouths.
11. Lakebeds	Fine soils deposited in lake bottoms.	In glaciated areas and in mountain basins.
12. Till Plains	Undulating clay mantle over drift	Midwestern states.
13. Marsh and Swamp	Lowlands at or near ground water table.	Everywhere
14. Basalt	Lava	Colorado, Washington and Oregon.
15. Sandstone	Flat-lying beds.	Eastcentral and south-western states.

HILLY TERRAIN

Landform	What	Where
1. Dunes	Sand (wind-blown)	Widely distributed.
2. Loess	Silt (wind-blown)	Central states; Idaho and Washington.
3. Eskers	Glacial gravels and sands in ridges.	Northern states.
4. Kames	Glacial gravels and sands in ridges.	Northern states.
5. Drumlins	Glacial drift; cigar-shaped ridges.	Northern States.
6. Moraines	Glacial drift, jumbled hills.	Northern states.
7. Lava	Porous lava with flow marks.	Western states.
8. Basalt	Viscous lava, forms tableland and mesas.	Western states.
9. Dikes	Dense lava ridges.	Western states.
10. Cones	Largely cinders and lava.	Western states.
11. Tuff	Volcanic ash.	
12. Limestone	Pitted terrain.	Kentucky, Missouri, Pennsylvania
a. Horizontal	Stratified sedimentary rock	
b. Tilted	Ridges	
13. Sandstone	Massive hills	Pennsylvania and western states.

HILLY TERRAIN (continued)

Landform	What	Where
14. Shale	Low rounded hills.	Pennsylvania and western states.
15. Mixed Sedimentaries		
a. Horizontal	Contour outlines as hillsides	
b. Tilted	Ridges.	
16. Gneiss	Metamorphic hills.	Southeastern and western states.
17. Schist	Metamorphic hills.	Southeastern and western states.
18. Slate	Metamorphic hills.	Southeastern and western states
19. Serpentine	Small areas of soft rock.	Southeastern and western states.

stream action as in other rock landforms.

The variation in limestone landforms are related to topographic position, (thickness sequence of the various rock strata), to type of climate, and to stage of development in the erosion cycle. The effect of these factors must be considered in the study of airphoto soil patterns for the identification of limestone landforms.

When limestone and associated rocks occur in relatively horizontal bedding and occur at or near the surface, a limestone plain with little or no surface drainage is likely to develop. The stage of sinkhole development will depend upon the climate, thickness of rock strata, and length of exposure of the limestone to weathering. Figure 1 illustrates a limestone plain in a humid-temperate climate. Figure 2 illustrates the effect of a shale strata overlying the limestone bed on the development of the landform. Where the erosion has removed the protecting shale layer, the sinkhole and associated underground drainage has developed; where the shale layer has not been removed, the underground drainage has not developed; and the airphoto soil pattern reflects the characteristics of the shale. Figure 3 shows the contrast in topography of the limestone and shale landforms.

Sinkholes are an outstanding feature of limestone landforms. They may vary in size, depth, spacing, and elevation, as shown in Figure 4. When sinkholes are widely spaced the sinkholes are deep and the limestone thick. Figure 1 illustrates the pock-marked appearance of limestone terrain as seen from the air. The sinkholes will vary from a few feet up to several hundred yards in diameter. A study of them in any limestone region will show a few to contain water. Those holes containing water are the result of the washing of reddish clay soil into the sinkholes and the occasional plugging of local subterranian channels. In the airphoto, those containing water can be distinguished from the dry ones by the distinct regular line developed where the water makes a contour in the depression. Depending upon the angle of the sun, and its reflection into the aerial camera, some may appear as dark spots and others as light areas.

When the limestone occurs in a tilted position the development of the surface and underground drainage usually will reflect the geologic structure. The typical sinkhole pattern of the limestone plain usually will be modified to the extent that elongated sinks and solution valleys occur over the limestone outcrop, as illustrated in Figure 5. The development of surface drainage will be associated with the non-calcareous rocks.

The type of climate past and present, the time the geologic and soil forming processes have acted, and the age of the parent material are important factors to be considered in the identification and comparison of limestone landforms on a regional basis. In semi-arid climate the solution action is not as great as is found in the humid-temperate climate for the same degree

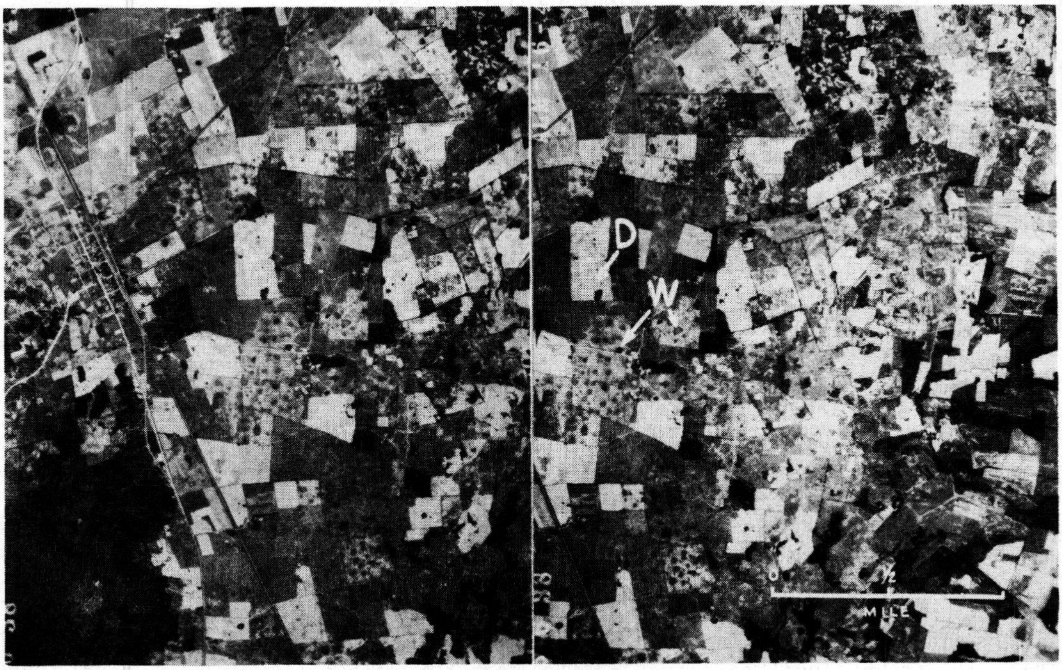

Figure 1. This limestone plain is dotted with many sinkholes. The terrain is gently rolling to rough, depending on the number and depth of the sinks. The sinkhole (D) is dry and is connected to the subterranean channels below. Those marked (W) are filled with water to form temporary ponds.

of exposure to the climatic factor. Figure 6 illustrates the airphoto soil pattern developed on tilted limestone in semi-arid climate. Figure 7 illustrates the rugged topography developed under tropical climate where more intense weathering has resulted in a rather complete collapse of the subterranian caverns in an advanced stage of the limestone-erosion cycle. Thus, in making appraisals of limestone areas it is important to consider the influence of many factors; however, the development and type of drainage is one of the most important factors for the identification of limestone landforms.

Drainage - Drainage is primarily underground. The absence of any surface drainage, except large streams or rivers, is another unusual feature common in the limestone landform. For this reason, highways and railroads are committed to tunnels and deep cuts rather than "climbing" by following stream valleys. When the underground-drainage system is inadequate, surface flow occurs during brief periods. This inverted drainage may come as a flushing of sinkholes, as at Belleville, Ohio, or as in some sections, "lost rivers" again flow until the subsurface capacity is again adequate.

The few valleys that do exist are like trenches in cross-section (Fig. 8). The shear rock walls that form the valley sides are typical of portions of the Mississippi, Tennessee, and Kentucky rivers where they flow through limestone landforms. These vertical-sided valleys are explained as being remnants of underground rivers exposed by the collapse of the cavern roof. Since this is the process that produces the sinkholes, it is reasonable to assume it to be accurate. In this way the entire limestone landform decays or is dissolved.

Because of this unusual type of drainage, culverts, as such, and bridges are less important items than in most other landforms. However, the special treatment of sinkholes, whenever they are crossed, counteracts the saving in surface-water

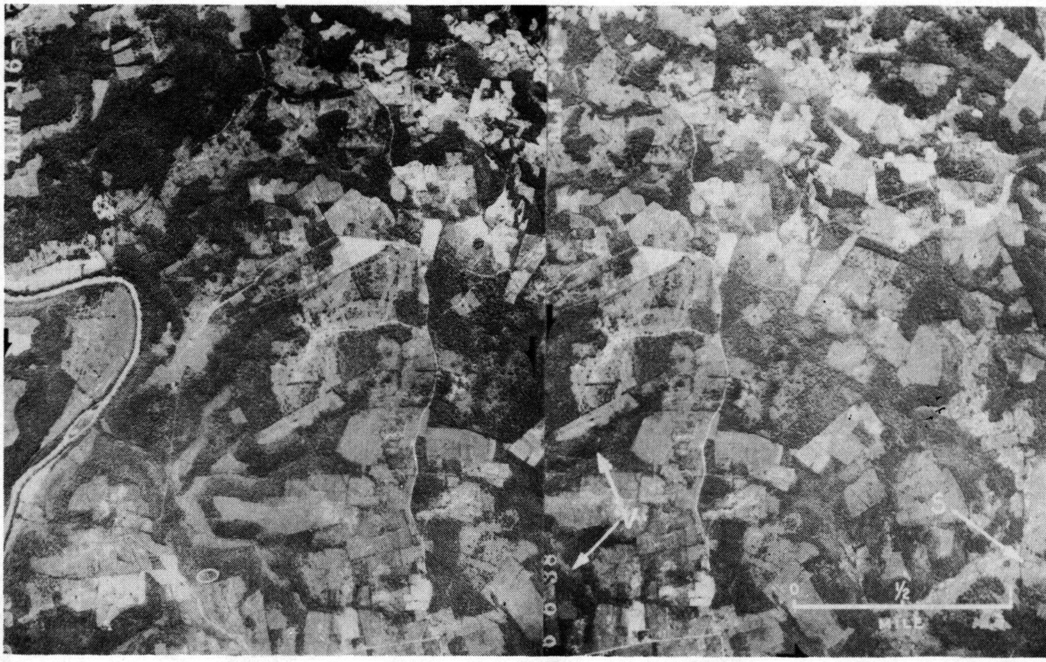

Figure 2. This view shows many features of a typical limestone area. In the upper portion a valley (without stream) has been formed by the complete collapse of a cavern system. It is worth spending extra time on this complex example to follow the process of analysis. The lower portion of the photo shows no sinks and a considerable amount of surface drainage. This indicates an impervious material (shale) rather than limestone at the surface. Since there is no sign of tilting of the rock, the deeply pitted valley at the top implies that the same limestone underlies the entire area. This is confirmed by: 1) steepsided "limestone" valleys (V) cut through the shale and take on the features of the underlying rock; 2) sinks (beyond stereo-coverage) in fields at far right (S) and included in the bend of the river at left. The shale cap will eventually erode away and expose the limestone.

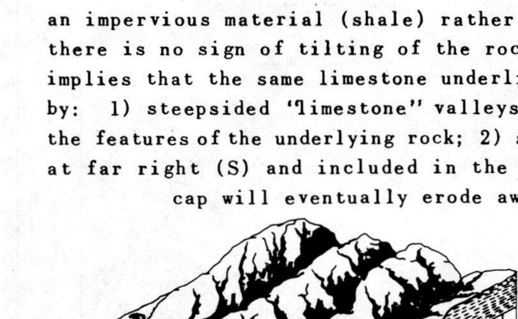

Figure 3. This is a sketch of a transitional zone between limestone (lower) and shale areas. As the limestone area is approached, there are more sinkholes and fewer streams and gullies.

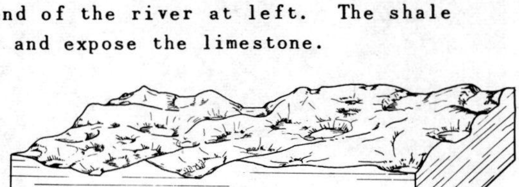

Figure 4. Limestone with sinkhole development. The roughly circular depressions result from the solution of limestone along cracks and fissures which are enlarged by percolating groundwater. They are often drained by subterranean streams but these are sometimes plugged and temporary ponds result. In tilted limestones, these depressions are interconnected and form long, shallow valleys along bedding planes.

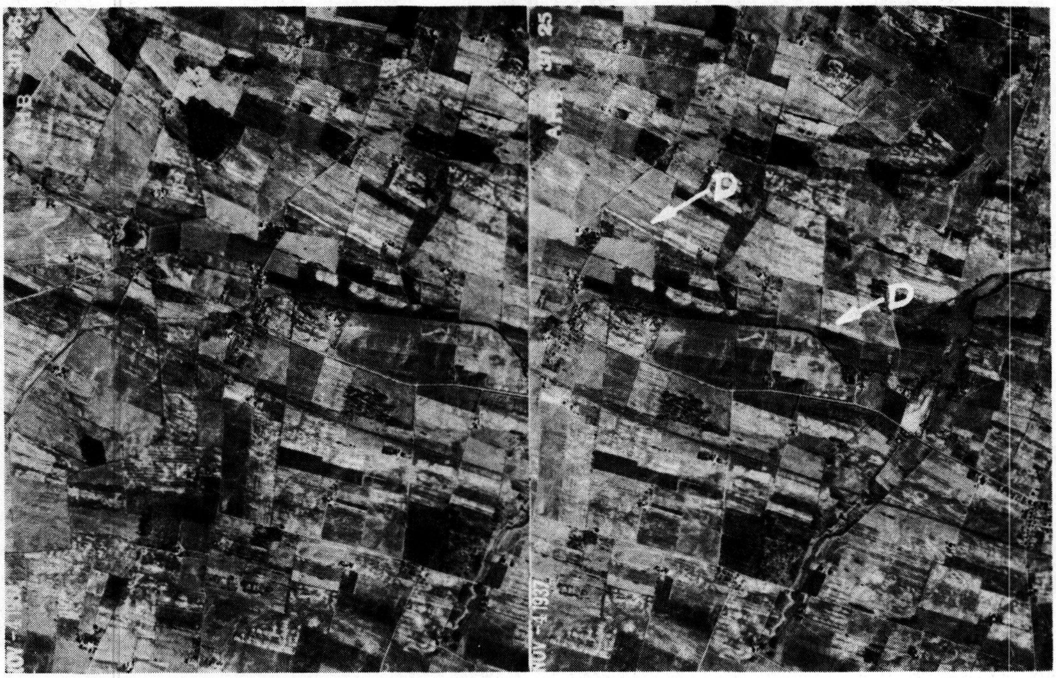

Figure 5. This is an area of tilted limestone. The streaks across the photos (D) are the result of solution along the bedding planes of the tilted limestones. There are no sinkholes here but, instead, these elongated solution valleys and a marked absence of surface drainage indicate a limestone bedrock.

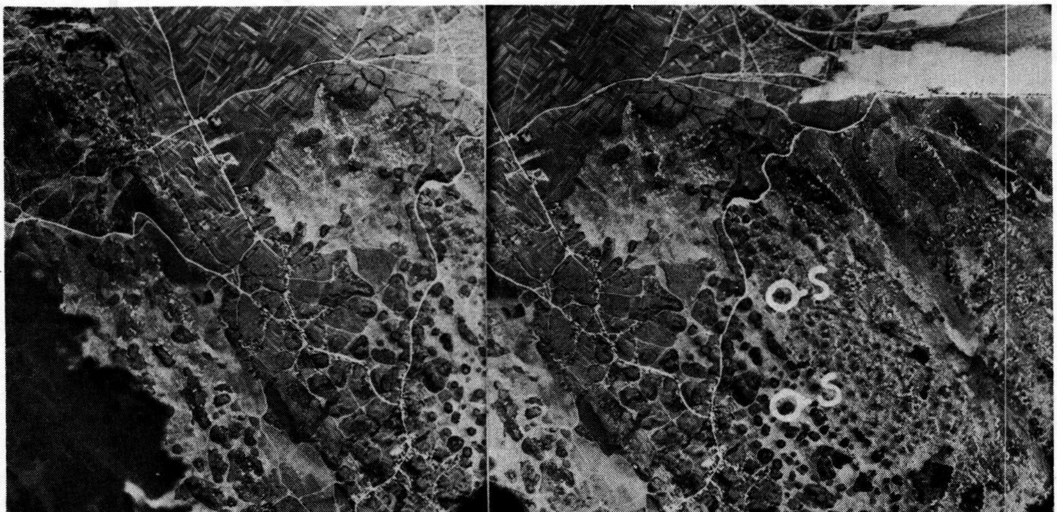

Figure 6. Tilted limestone in a semi-arid region. Here the solution work had not progressed enough to connect the sinkholes - dark circular areas (S) - to form elongated channels. The depressions are aligned along the tilted bedding planes. In this area, the sinkholes are the only productive land, whereas, in humid climates they are usually the only non-productive lands. Cultivation is possible in these sinks because soil and water have accumulated in them.

Figure 7. This area in Puerto Rico is typical of tropical limestone. These photos show the steep-sided hills, the flat-bottomed, vertical-walled valleys, and in particular, several levels of erosion which indicate the variable resistance of limestone beds. The uniform tone throughout the area is the result of vegetative cover. A dense growth of sugar cane covers the level land.

culverts. The small number of bridges required is also offset by the fact that the few bridges needed are large and expensive. For this reason, some sections of Kentucky have remained virtually cut off from modern motor traffic.

The underground, and therefore unseen, drainage system is the basis of most of the engineering problems in these limestone regions. Leakage around and under dams follows these subterranean-stream courses and solution crevices (Fig. 8). The intricacy of these channels and crevices introduces one of the greatest uncertainties in subsurface work. Also, they promote the quick reaction of ground-water flow to rainfall and eliminate the valuable filtering capacity associated with most landforms. Thus, ground-water in these areas is often polluted and the source of pollutionis difficult to detect.

ENGINEERING PROBLEMS IN LIMESTONE LANDFORMS

The Soil - Limestone soils range from silty clays to fat clays and vary in color from yellow to deep red. In a few places they are known to be black, but this is rare in the United States. Although fine textures, the soil is well drained because the porous limestone beneath permits the water to filter through the soil without "backing up" and saturating the clay. For the same reason, the soil is unusually pervious. It is not tight, as most clays are. It absorbs the water quickly with little runoff because of the highly developed soil structure. This structure can be seen by examining cut faces and breaking out the ¼ to ½ in. soil aggregates that form as cubes. The cubes fit loosely together so that between them there is ample space for water to percolate through the soil column. The red color of the soil profile shows that air circulates freely and oxidation has been thoroughly carried out. When engineering projects are carried out using this soil, the working and compacting destroys these natural drainage channels and the reworked soil is converted to a typical impervious plastic clay.

Beneath the soil mantle, which ranges from 2 to 30 ft. in depth, lies the bedrock surface. Ordinarily, there is some correlation between surface and bedrock conformation. But in limestone, as in some

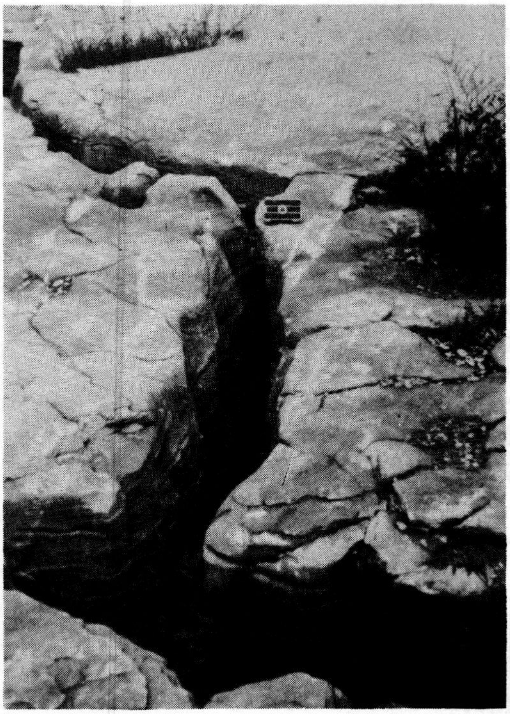

Figure 8. The crevice shown above is typical of the enlargement of joints in limestone. Solution work is active along these joints; they are enlarged and become, in time, the basis for the angular drainage system found in limestone areas. In miniature, the features shown are those of many valleys in limestone.

granites, the depth to rock is extremely variable. Unlike other residual soils, the transition from the clay soil to rock is abrupt. The most important characteristic of all is the highly irregular rock surface (Figs. 9, 10, 11) which in a few feet horizontally, will vary as much as 25 ft. below the surface. These irregularities make the results of borings highly unreliable and estimates of earth-rock quantities undependable. These are the relatively minor irregularities and do not include the deep fissures and caves that represent another class of problems for engineers.

The Bedrock - Below the irregular surface the bedrock is interlaced with various solution features. These caves, cavities, fissures, and underground channels are constantly enlarged by the action of groundwater. These form along the horizontal bedding planes in the rock and in the vertical cracks that were initially shrinkage and settlement cracks resulting from the drying of the limestone. Figure 8 shows the enlargement of one of these and illustrates the development of small streams on the surface of this landform. As the underground streams enlarge, the roof continues to erode, and when weakened to a point of collapse, sinkholes form on the surface (Fig. 12), giving evidence of underground caves and streams. This erratic perviousness of the rock mass (not individual rock fragment) has an important effect on domestic water-supply problems, sewage disposal, and dam and highway construction. Engineers and contractors building highways, runways, and industrial buildings must use a special set of precautions, because of existing sinks and fissures and impending collapse.

The grouting methods used to seal dam foundations are extensive and costly but necessary to insure against the loss of water. Likewise, the capping of sinkholes with concrete is practiced under roadways to minimize settlement or eventual loss of a section of road. Many contractors, taking a chance on the results of a few test

Figure 9. A ground view of weathered limestone in French Morocco shows the surface character of the rock exposed by erosion of the soil mantle. The white forms in the background are bare outcrops of the rock. In the foreground, the variations in depth of the soil can be seen. The doubtful value of random soil borings and test pits can be visualized.

holes, have found it disasterously expensive but necessary to bring in air hammers to knock off rock pinnacles during the grading operation.

With these hazards associated with limestone in all areas, it is a matter of professional protection to make sure of the landform on which a project is to be constructed. The same features in an advanced

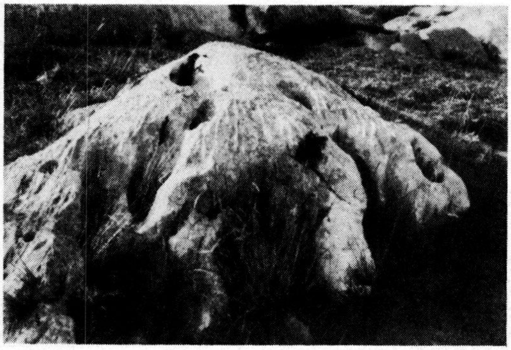

Figure 10. A closeup view of a limestone outcrop in eastern France shows in minute detail the erratic occurrence of solution pits and rivulets on the rock surface. The more or less circular holes are relatively deep. These same features, when expanded several hundred times, are the features that make engineering in limestone land form an interesting experience.

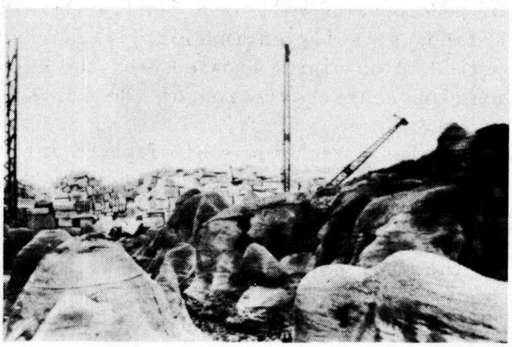

Figure 11. This view of a midwestern limestone quarry shows the same irregular rock surface found elsewhere. These dome-shaped mounds are miniatures of the weathered limestone hills found in tropical countries. At this site the soil depth varied from six to thirty-five feet within short distances. Photo by Professor Fred Serviss

Figure 12. This view of a sinkhole in Kentucky shows that they can be large and deep. Others may appear as small "punctures" in the ground or as shallow depressions containing temporary ponds. The topography is usually pleasantly undulating.

Figure 13. This road cut in the limestone landform (tropical) in Puerto Rico shows by cross section the honeycombed nature of this rock. Opposite the figure a cave entrance can be seen.

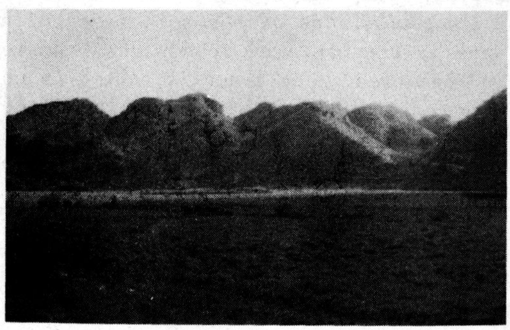

Figure 14. This is a ground view of the rugged limestone hills in tropical Puerto Rico (Plate V). The hills are formed by collapse of the caverns. The low areas between are not actually valleys because they are poorly connected and seldom have the same elevations as adjacent areas.

state occur in most tropical countries. Figures 13 and 14 illustrate these in Puerto Rico. Each landform has its strength and weaknesses, and by identifying the landform and knowing its traits, a better job of engineering can be done. In this way, the risk can be calculated with some reasonable assurance of safety.

On the good side of the record, it is certain that most limestones furnish one of the best and most extensively used aggregates. With the exception of the very cherty limestones, it forms a dependable and high quality material.

ENGINEERING SIGNIFICANCE OF SAND AREAS INTERPRETED FROM AIRPHOTOS

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The investigation summarized here was established as a doctoral thesis in the interpretation of soils by the use of aerial photographs, the interpretation to include both engineering mapping and analysis of highway problems associated with the types of soils classified. It was attempted to interpret the complex patterns of the airphotos of northwest Indiana--patterns which have been made complex by the large variety of glacial and post-glacial deposits which have provided the parent material for the developments of the soils of the region. All or portions of twelve counties were mapped, using airphotos, in the belief that a good knowledge of the soil types of an area is the basis of good highway design in that area. Consequently, the area was studied both from the standpoint of developing techniques of mapping engineering soils from aerial photographs and from the standpoint of determining applications of the knowledge of the mapped soils to problems of highway design and construction. Studies of pavement performance were made during the spring breakup and during the summer season to correlate soil types with the performance of both rigid and flexible pavements.

Before the variable of soil texture can be applied to the performance of a highway, it is necessary to know what the soils involved are--their origin, profile development, drainage characteristics, texture, plasticity, and topography. In the interests of economy it is necessary to develop rapid means of identification of soil types and of characteristics. Until the recent advent of the techniques of airphoto soils interpretation, no rapid method of soils mapping had been developed. To the skilled interpreter, the aerial photograph, combined with a knowledge of the general development of the area being studied and of some of the basic concepts of pedology, as well as a familiarity with methods of soils engineering, is a rapid method of obtaining knowledge of the engineering characteristics of the soils of an area.

The basic techniques of airphoto interpretation of soils have been described in the past (1,2). They include acquaintance with geological developments and processes in the area being studied and with pedological information as to profile development, erosion, and vegetative cover. Study of broad areas is combined with stereoscopic examination of matching prints to determine the details of the surface features. The elements of the airphoto pattern (color tones, drainage, erosion, vegetation, topography, and land use) are used to bound soil areas on the basis of origin, development, texture, topographic position, climate, drainage and plasticity. An im-