Geotechnics of Mining, Lexington, KY, Oct. 1979, pp. 37-43.
32. P.P. Hudec. Development of Durability Tests for Shales in Embankment and Swamp Backfills. Ontario Ministry of Transportation and Communications, Downsview, April 1978.

Publication of this paper sponsored by Committee on Engineering Geology.

Swelling Shale and Collapsing Soil

A.C. RUCKMAN AND R.K. BARRETT

Geotechnical engineering parameters of both rock and soil can be significantly influenced by regional environmental factors. Climatic factors such as rainfall and temperature, coupled with geologic and geomorphic factors such as bedrock type and landform configuration, combine to present very different kinds of problems for highway pavements in the several physiographic provinces of the world. Two causes for pavement deformation that are physiographically bounded are swelling shale and collapsing soil. Swelling soil is not a significant problem for highway builders in the semiarid climates of the western United States. Swelling bedded shale, however, can completely disrupt the traveled way. Soil surveys, laboratory testing, and corrective and/or preventive measures designed for swelling soils are frequently not appropriate for effectively dealing with swelling shales. Low-level blasting is presented as one method of preventing or correcting swelling-shale problems under roadway pavements. This technique cost-effectively approximates subexcavation. Proper selection and placement of the explosive are important to the success of the technique. Soils that have a measurable swell potential can collapse on wetting in a semiarid climate because of a combination of environmental factors. Pavement distortions over collapsible soils are often misidentified as resulting only from swelling soil or internal fill deterioration. Prewetting of collapse-susceptible soils alleviates long-term settlement problems.

Two major causes of distortion in highway pavements have been identified in Colorado: swelling shale and collapsing soil. Both are products of local geologic, geomorphic, and climatic factors. Neither swelling nor collapse is significant in many parts of the United States. But in physiographic regions where either of these problems exists, substantial disruption of the traveled way can occur.

Problems with swelling soil and/or shale have been recognized and treated in Colorado for several years. Collapsing soils have only recently been identified as a cause for gradual deterioration in rideability on roadways over outwash-mudflow soil sequences. Previously, undulating pavement surfaces over collapsible soils were attributed to swell, especially in areas where swelling shales were used in fill construction. Although either phenomenon can occur independently, this paper reports on both because of their interrelationship with environmental factors and their similar effect on the riding surface.

Literature searches have failed to turn up definitive mapping for areas where either problem may exist. Independently variable environmental factors, including climate, rainfall, slope, bedrock, exposure, and vegetative cover, must be collated onto a single map in order to delineate physiographic regions that may be susceptible to either phenomenon. This, to our knowledge, has yet to be accomplished.

SWELLING SHALE

Swelling bedded shale is a common cause of pavement distortion in arid and semiarid climates. Swelling soils are much less likely to cause significant deformation of the riding surface in these climates. This is an important distinction for both the design and the maintenance of roadways in areas where swelling is known to occur.

Swell Potential

Snethen and others at the U.S. Army Engineer Waterways Experiment Station (WES) at Vicksburg, Mississippi, have performed extensive compilations of the existing literature as well as independent research on the swelling phenomenon under a Federal Highway Administration (FHWA) research grant. The several reports that have resulted from these studies represent the most comprehensive literature available on swelling soils.

Very briefly, significant swell potential in shale is attributable to the presence of montmorillinitic clay minerals (1,2). Most clay minerals will expand on wetting, but significant volume changes are related to montmorillonite clay content and distribution.

Occurrence

Shales in the United States that exhibit significant swell potential are typically Mesozoic and Tertiary in age and are abundant in the semiarid climates of the West.

Sampling and Testing

Sampling and testing requirements for determining the presence of swelling clay minerals in bedded shale for highway-design purposes are much less stringent than, for example, those for building-construction purposes. In fact, no testing is required where a knowledge of local geology and performance of existing pavements can provide qualitative data.

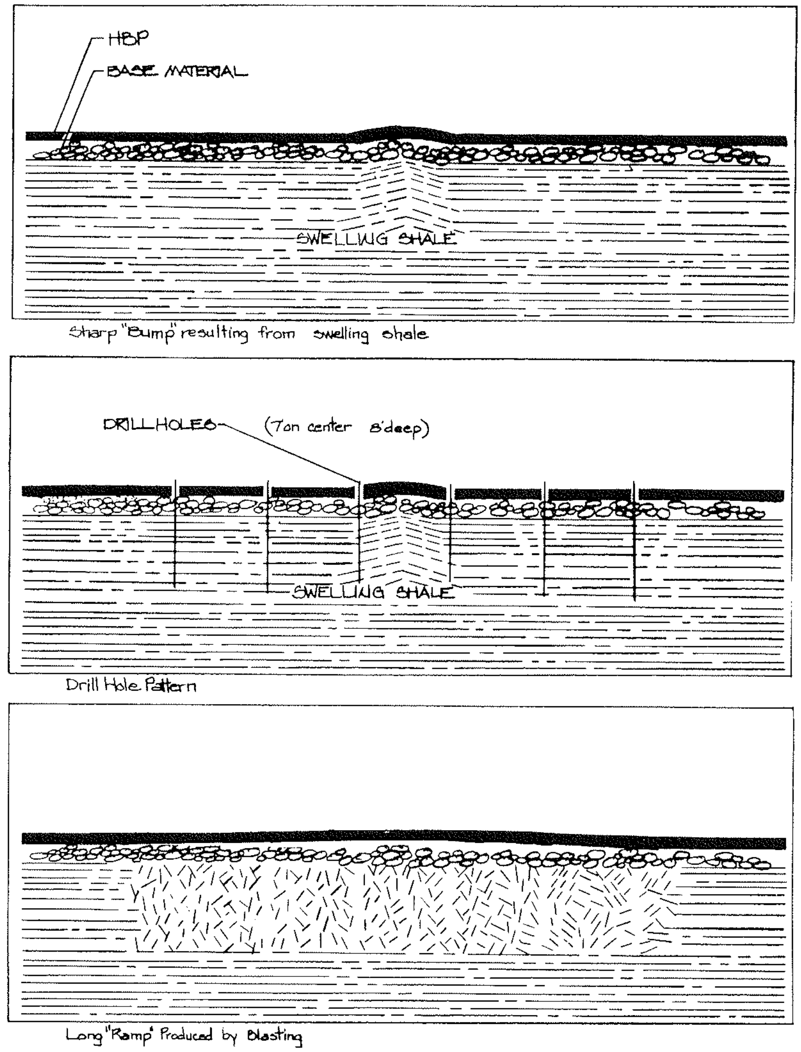
Where sampling and testing programs are contemplated, it is important to obtain samples from bedded materials rather than from alluvial and residual soils. Tests performed on samples from unbedded soil deposits are not reliable indicators of the swelling problems that may be experienced over bedded shales after the roadway is completed.

The shales can be sampled in test pits or by using coring equipment. Testing has traditionally been performed on material crushed to soil gradations (3).

Correction and Prevention

Subexcavation and recompaction of bedded shale below the profile grade line to a depth of 2-3 m (6-10 ft) have consistently proved to be the most cost-effective solution to swelling-shale problems in semiarid climates; however, the costs of this procedure are relatively high in comparison with

Figure 1. Use of blasting technique to repair pavement distortion caused by swelling shale.



costs for similar roadway templates over nonswelling bedrock.

The results of experimental work in District 3 of the Colorado Department of Highways (northwest Colorado) indicate that the use of low-level blasting to disrupt the bedded shale has been highly successful. Although blasting to accomplish reduced density and disruption in shale bedrock produces a more variable result than subexcavation and recompaction, swelling has ceased to be a problem at almost all locations where the blasting technique has been attempted. Thus, we have concluded that blasting is a cost-effective solution for swelling-shale problems.

When blasting is performed on new construction or on pavement recycling projects where the pavement is completely removed, holes are drilled 2.4-3.3 m (8-10 ft) deep, approximately 8 cm (3 in) in diameter, on about 2-m (6- to 7-ft) centers. These holes are loaded with 0.1 kg (0.25 lb) of dynamite and ±0.9 kg (±2 lb) of factory-mixed fuel oil and ammonium nitrate (ANFO). The charges are detonated with Primacord, or its equivalent, and fused caps. Loading and spacing can be varied to achieve optimum results at a given location. On new construction, it is also acceptable to carry production blasts 3 m (10 ft) below the planned grade in order to disrupt the swelling bedrock.

Thorough wetting of the blasted zone is recommended after blasting is completed. This measure accelerates the achievement of moisture equilibrium within the blasted zone.

Blasting as a maintenance technique requires careful drill-pattern control and precise charges. Holes on 2-m (6- or 7-ft) centers, 7.62 cm (3 in) in diameter, and 2.4 m (8 ft) deep have proved to be the optimum combination in western Colorado. Holes are drilled on either side of a sharp upheaval, loaded, and detonated simultaneously. When the proper charge is used, the pavement is lifted but not broken and a long "ramp" is produced in the roadway as opposed to a sharp bump. Experience in Colorado indicates that this explosive treatment produces a more permanent solution than does ramping with cold mix and at a significantly lower cost.

Figure 1 shows the roadway improvement that results from the maintenance blasting technique.

Use of Blasting Technique in Colorado

Experimental blasting of swelling shale under roadways was begun in Colorado in 1976. The first series of hole spacing and loading trials was conducted at the Mesa County landfill in freshly exposed Mancos shale bedrock. Of the several experimental combinations, it was found that the use of 7.62-cm holes 2.4 m deep and on 2-m centers, with specific explosive loading and carefully compacted stemming material, yielded predictable results.

Holes 3.3-4 m (10-12 ft) deep would either produce a large cavity around the bottom-hole loads or produce airborne fragments and severe surface disruption. Holes 2 m deep occasionally produced excessive surface disruption as well as airborne fragments, even with relatively light loads.

The first roadway blasting experiment took place in a Mancos shale cut on US-50 between Whitewater and Grand Junction, Colorado. That section of roadway was scheduled for a leveling and overlay project. The first series of holes consisted of a square grid of 20 holes on 2-m centers. At first, middle holes were loaded as heavily as outside holes, and the pavement rose about 2 m in the center. Thereafter, center holes were loaded lighter, and fewer holes were detonated with each shot.

A total of three areas were blasted in the Whitewater area of US-50. After four years, these areas continue to perform satisfactorily whereas control sections in that area have exhibited severe surface distortions.

The next experimental blasts were conducted on US-40 west of Craig, Colorado, in an area that was exhibiting extreme distortions. One bump had caused several accidents, including one involving a semitrailer loaded with shotgun ammunition that broke in half as it landed on the down side of the bump. The blasting performed on this section accomplished the necessary ramping of five of the seven sites blasted so that no further work was required by maintenance forces. After four years, the blasted areas have shown no movement.

An asphalt-recycling research project at Grand Junction included 606 lane-m (2000 lane feet) of blasting to monitor the long-term effects of this technique. This area traversed a shale ridge that had been repeatedly leveled by maintenance forces. Blasting was performed in 1979, and the performance of the riding surface continues to equal that of adjacent areas.

The most recent use of blasting on a Colorado Division of Highways project was west of the town of Rifle on a deep cut through Wasatch sequences of shale and siltstone. Older roadway cuts in the area exhibited either swelling or rebound (or both), which created severe bumps in those roadways. Production blasts were carried 3 m (10 ft) below grade. The performance of the pavement at these locations is equal to that in adjacent areas.

COLLAPSING SOILS

A factor that often goes unrecognized for its potential to severely reduce the rideability and service life of roadway surfaces is collapsing soils. Western Colorado abounds in deep soil deposits that will collapse as much as 25 percent in volume on thorough wetting. In the early 1960s, the U.S. Bureau of Reclamation (now the Water and Power Resources Administration) identified several major areas of California as susceptible to collapse (4-6). Similar areas must exist in semiarid climates of the western states; however, this has not been the subject of comprehensive geologic mapping.

Collapse Potential

Bureau of Reclamation studies in the San Joaquin Valley of California identified geomorphic and climatic factors that contribute to the deposition of collapse-susceptible soils. Briefly, these soils are alluvial outwash and mudflow deposits. Mudflows are typically quite viscous, containing between 16 and 20 percent free water. As the flow dries, the frothy texture or fabric is retained, forming what has been described as a "honeycomb texture". After drying to a moisture content of about 6 percent, the flow is structurally sound. Subsequent flows can be deposited without wetting the underlying flows because of the low moisture content of these flows. The added weight of subsequent deposition creates a potential for collapse.

Mudflow deposits are extremely nonuniform in many important geotechnical parameters. Density and grain shape and size vary markedly, both horizontally and vertically, over short distances. Susceptibility to collapse increases as the silt and clay fraction increases. Moisture content, however, typically exhibits relatively uniform gradients with depth. Hydrocompaction is initiated by wetting the dried mudflow deposits.

Adding a pavement over these soils is one way to gradually increase the moisture profile (as a result of the hydrogenesis, or "desert still", phenomenon). Typically, pavement deformation progresses at a relatively slow rate as the moisture profile gradually increases. Thorough wetting, however, results in immediate and complete collapse.

Occurrence

Collapse-susceptible soils are the product of a dry climate and steep slopes formed on soft, fine-grained bedrock. A tie-in with swelling shales is that these shales are frequently slope-forming members that weather rapidly and provide the fine-grained-soil portion of the mudflows. It is frequently possible to obtain test results that show significant swell potential from a soil deposit that will, in fact, collapse with time and wetting.

In western Colorado, the mudflows begin on steep, south-facing valley walls that are composed of sparsely vegetated Mancos, Mesa Verde, Wasatch, Green River, and Maroon formations. These sedimentary bedrock formations contain sequences that weather rapidly on a fresh exposure. The rate of weathering decreases as soil cover is developed. High-intensity, short-duration rainfall washes away the newly developed soil cover every few years and produces mudflows. The freshly washed and exposed bedrock then begins rapid weathering and soil production, continuing the cycle.

Sampling and Testing

Sampling in Colorado is done by using thin-walled seamless tubes with a 6.3-cm (2.5-in) inside diameter that are pushed into the soil with a drilling rig. Frequency is determined on a project-by-project basis but typically averages 24 samples/lane kilometer (40 samples/mile). About half of these samples are not acceptable for testing because of sampling-tube damage by rocks and because of a failure to retain samples in the tube. The most collapse-prone soils are dry and friable and are difficult to successfully extrude and end trim. Some samples are damaged during the extrusion and end-trimming steps.

Testing is performed in a consolidometer device (7). The sample diameter and the oedometer-ring diameter are approximately equal to avoid the necessity of side trimming for fit. Where gross indicators of collapse susceptiblity are acceptable, testing can be appreciably shortened. The Colorado procedure includes loading to in situ values and then saturating the sample. This procedure cuts testing time to three days from the approximate two weeks required for standard consolidation testing procedures.

Data interpretation is very important to the overall analysis and must include an overall evaluation of site geology, sampling frequency, and sampling success. Where it is assumed that the final group of samples is reasonably representative of an area, remedial measures are recommended when more than 25 percent of the total soil volume represented exhibits significant collapse potential. On Colorado highway projects, collapse of greater than 10 percent in laboratory samples loaded to in situ loading is deemed significant. These values should be established for each project based on the consequence of soil collapse. Obviously, hydrocompaction would be of greater negative consequence to a nuclear reactor than it would be to a sheep corral.

Correction and Prevention

Problems with hydrocompaction of collapse-susceptible soils can be avoided by thorough wetting of all dry layers under the pavement. Research performed by the Colorado Division of Highways indicates that all collapse occurs on initial saturation and that only normal consolidation occurs with subsequent loading (8).

Wetting of problem soils can be accomplished by ponding or by using sprinklers (9,10). Ponding is generally more thorough. Sprinkling costs less but has failed to penetrate to full depth in about 20 percent of the areas wetted along I-70 in western Colorado. Backfilling drill holes with gravel can speed up the wetting process but is so expensive that its cost-effectiveness on highway projects is questionable.

Under existing pavements, deep wetting is difficult to accomplish. No projects of this type have been attempted to date, but a project is planned near Grand Junction for 1981 or 1982.

Experience in Colorado

Active investigations into the causes of gradual deformation in several highways in the valleys of western Colorado began in 1975. Hydrocompaction was suspected as the cause. A literature search yielded little information to link collapsing soils and pavement deformation; however, several Bureau of Reclamation reports on sampling and testing procedures for collapsing soils were found.

Field sampling was initiated on an I-70 preliminary design project west of Grand Valley (now Parachute) that would have to accommodate a future reservoir. High fills over deep alluvial (mudflow) soils were required, and saturation of the mudflow sequences would certainly result when the lake was filled. Consolidometer tests indicated that a collapse of 25 percent was possible in some soil layers. A literature review indicated that laboratory results could be divided by two to predict field performance and that field tests were more reliable than laboratory tests for determining collapse potential.

Laboratory tests of the soils results certainly warranted field tests. Two ponds were constructed, and a dam retaining each pond approximated the proposed highway fill. Settlement measurement grids were established and monitored throughout the field testing.

No settlement was observed after construction of the simulated I-70 fill, but settlements of more than 1 m (3.5 ft) occurred when the ponds were filled. It was determined that precollapsing of this area would be desirable prior to construction of the fills; otherwise, loss of service of I-70 would be a virtual certainty when the lake was filled.

Sprinkling test sites were subsequently established, and sprinkling was found to be the most cost-effective method for consolidating the low-density soils under highways. Prewetting of several miles of subsoil has now been successfully accomplished prior to I-70 construction in the collapse-prone Grand Valley (Parachute) area.

SUMMARY

The behavior and performance of a variety of geologic materials depend on environmental factors. Shales that are exposed as barren hills in dry climates would long since have weathered into soil-covered plains in wetter climates. Modes of soil deposition in arid climates are quite different from those in wetter climates, yielding very different soil textures and fabrics.

Field exploration and laboratory testing programs must be designed to determine regional and local differences as well as universally similar geotechnical properties. For example, it is possible to obtain laboratory test results that indicate swelling potential from collapsing soil deposits in semiarid and arid environments. In this case, the soil fabric--i.e., grain size, shape, distribution, and orientation--is an independent parameter and, for foundation design, has a significance equal to that of soil mineralogy.

In laboratory test results, bedded shales that have first been reduced to soil-sized particles and then remolded can exhibit very different properties than the in situ shale. Neither particle orientation nor density can be successfully duplicated in remolded bedrock samples. The significance of this inability to duplicate field conditions in the laboratory obviously varies with each engineering project.

Both swelling shale and collapsing soil can be accommodated in engineering projects where they have been identified, and appropriate mitigative measures can be cost-effectively applied. Recognition of these and a host of environmentally related phenomena is the key.

REFERENCES

1. D.R. Snethen and others. A Review of Engineering Experience with Expansive Soils in Highway Subgrades. Federal Highway Administration, U.S. Department of Transportation, Rept. FHWA-RD-75-48, Interim Rept., June 1975.
2. D.R. Snethen. Technical Guidelines for Expansive Soils in Highway Subgrades. Federal Highway Administration, U.S. Department of Transportation, Rept. FHWA-RD-79-51, June 1979.
3. Materials Manual. Colorado Division of Highways, Denver, 1980.
4. W.B. Bull. Alluvial Fans and Near-Surface Subsidence in Western Fresno County, California. U.S. Geological Survey, Professional Paper 437-A, 1964.
5. H.J. Gibbs and J.P. Bara. Stability Problems of Collapsing Soil. Journal of Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM4, 1967, pp. 577-594.
6. N.P. Prokopovich. Detection of Areas Susceptible to Hydrocompaction. Presented at Annual Meeting, Assn. of Engineering Geologists, Los Angeles, 1973.
7. H.J. Gibbs and J.P. Bara. Predicting Surface Subsidence from Basic Soil Tests. Bureau of Reclamation, U.S. Department of Interior, Denver, Soils Engineering Rept. EM658, June 25, 1962.
8. A.C. Ruckman and R.K. Barrett. Final Report: Hydrocompaction Investigations, I-70, DeBeque

to Rifle. Colorado Division of Highways, Denver, Feb. 1977.
9. Specifications for Preconsolidation of Laterals 6R, 8R, 9R, and 10R: Central Valley Project, California. Bureau of Reclamation, U.S. Department of Interior, 1975.
10. J.P. Bara. Precollapsing Foundation Soils by Wetting. Proc., 5th Pan-American Conference on Soil Mechanics and Foundation Engineering, Buenos Aires, 1975.

Publication of this paper sponsored by Committee on Engineering Geology.

Development of a Laboratory Compaction-Degradation Test for Shales

BARNEY C. HALE, C.W. LOVELL, AND L.E. WOOD

Hard but nondurable shales must frequently be incorporated in embankments in the Midwest. It is essential that these shales be thoroughly degraded and compacted into thin, dense lifts. Yet there is no simple, widely accepted laboratory test for predicting the difficulties of mechanical degradation. The development of a laboratory compaction-degradation test that will make it possible to compare the behavior of shales in the laboratory with their behavior during the construction process is described. After testing three very different Indiana shales over a range of gradation and compaction variables, it was concluded that two types of compaction tests are suitable for this purpose: impact and static. Degradation was evaluated by sieving both before and after compaction and was expressed as the reduction in mean aggregate size caused by compaction (the index of crushing). The static compaction test allows the ready evaluation of compactive work (rather than nominal compactive energy), and the impact test has the advantages of familiarity and acceptance by almost all testing laboratories. It is likely that the impact test will be more widely accepted for the stated purpose. The development of the laboratory test is an important first step, but correlation of the laboratory values with breakdown under field rolling is necessary before the total engineering objective is achieved.

The excessive settlements and failures of many embankments constructed of shale materials have led to major investigations concerning the properties and behavior of shales. It has been found that the deterioration of shale that results from weathering plays a major role in the poor performance record of shale embankments.

Durable shales, which can withstand the weathering process, will perform satisfactorily when placed as rock fill. Nondurable shales, however, must be thoroughly broken down during compaction and placed as soil fill. Shales that are mechanically hard but nondurable present special problems in relation to construction techniques.

The current practice of breaking nondurable shales down into soil fill makes it all the more important to understand shale degradation during compaction. Laboratory tests may be helpful in defining the compaction and degradation functions of shales. These functions may ultimately be related to field conditions.

The work by Bailey (1) established a basis for laboratory degradation tests. The study reported here concentrated on the development of a single standard testing procedure and its application to troublesome Indiana shales.

REVIEW OF LITERATURE AND EXPERIENCE

Shales are the most abundant of the common sedimentary materials. Although shales are generally defined as argillaceous sediments that display fissility, a large number of definitions have been developed (2). The definition presented by Pettijohn (3) and by Underwood (4) and adopted for this study is that shale is the more highly indurated and generally fissile equivalent of claystone and/or siltstone.

Mead (5) proposed a classification system that divided shales into two groups: compaction shales and cemented shales. The compaction shales are consolidated by the weight of overlying sediments and lack significant amounts of intergranular cementation. The cemented shales are strongly bonded by either cementing agents or recrystallization of the clay minerals. The compaction shales are generally softer and more subject to slaking (a rapid disintegration caused by cycles of wetting and drying) than the cemented shales. The cemented shales are harder and more durable and may be successfully used as rocklike materials in embankment construction.

According to Pettijohn (3), the fissility exhibited by shales is the result of both the compaction and concommitant recrystallization during formation as well as the parallel orientation of the micaceous constituents at the time of deposition. Ingram (6) used three dominant types of breaking characteristics to classify the fissility of shale as massive, flaggy, or flaky. Massive shales have no preferred direction of breaking and produce blocky fragments. Flaggy shales break into fragments of varying thickness that have much greater lengths and widths and two approximately parallel, flat sides. Flaky shales split along irregular surfaces parallel to the bedding planes and produce flakes, thin chips, and wedgelike fragments.

Road cuts for highways constructed in the midwestern United States often encounter shale. Economic and environmental considerations generally make the use of the excavated material in nearby compacted embankment sections more desirable. However, the poor strength and durability characteristics of many shales, along with inadequate construction procedures, have resulted in several undesirable experiences with compacted shale embankments.

Excessive settlement and slope failures of large shale embankments have occurred in several states (7). Such embankment failures led to the initiation of research and development programs by the Indiana State Highway Commission (ISHC) through the Joint Highway Research Project at Purdue University (8). Reports from these studies on the following subjects have been completed: the classification of shales (2,9), shale compaction and degradation characteristics (1), the storage and retrieval of existing data on Indiana shales (10), the shear-strength param-