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Heaving–Bedrock Hazards, Mitigation, and Land–Use Policy: Front Range Piedmont, Colorado

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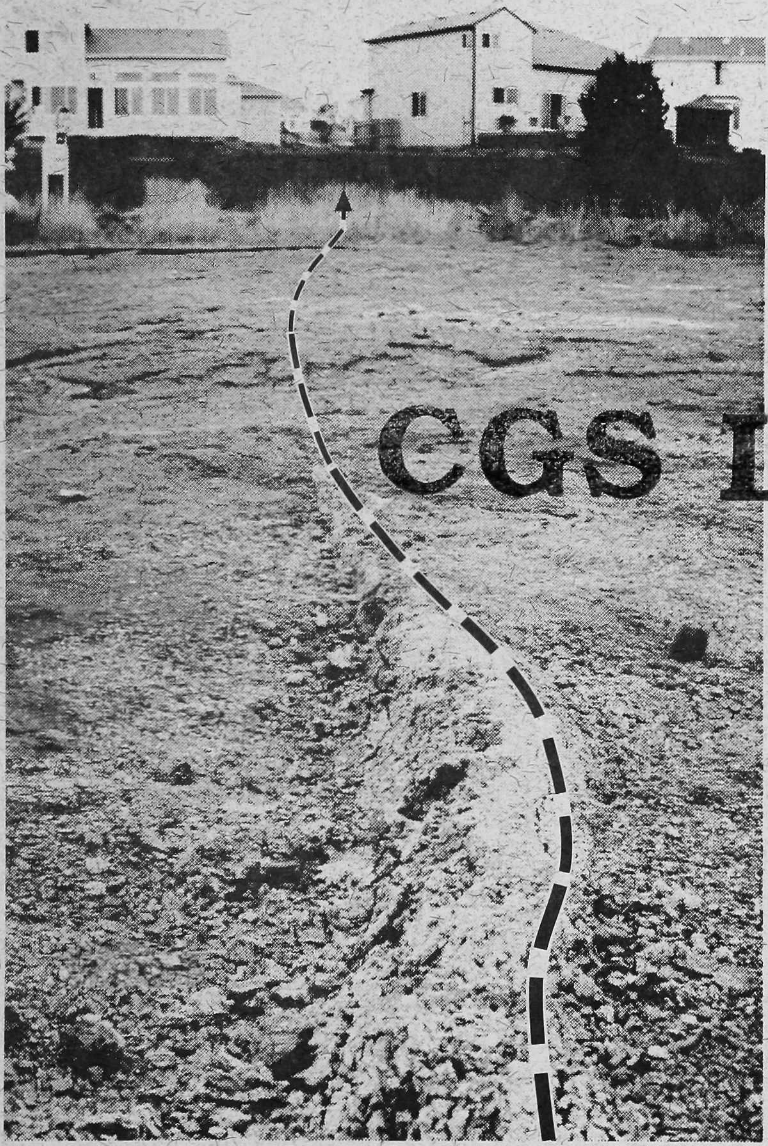

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Heaving-Bedrock Hazards, Mitigation, and Land-Use Policy: Front Range Piedmont, Colorado

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ABSTRACT

Heaving bedrock is a geological hazard that is related to expansive soils, but it is more complex in terms of its uplift morphologies, deformation mechanisms, and regional distribution. It is common along Colorado's Front Range piedmont where steeply dipping sedimentary bedrock containing zones of expansive claystone is encountered near to the ground surface. It occurs in the Pierre Shale and other Upper Cretaceous formations. The heave features associated with heaving bedrock are distinctly linear and are caused by differential swelling and/or rebound movements within the bedrock. Heaving bedrock has caused exceptional damage to houses, roads, and utilities along the Front Range piedmont since suburban-type development began in the early 1970s. Much of this damage may be attributed to the longstanding tendency to assume that the bedrock may be treated, for site-exploration and design purposes, as an expansive soil having essentially uniform properties. This approach ignores the strong heterogeneity that is often present in the bedrock. In particular, drill-hole exploration surveys and drilled pier foundations, which are generally appropriate for expansive soil hazards, have proven to be inappropriate for recognizing and mitigating heaving-bedrock hazards.

This article presents a summary of heaving bedrock as a distinct geological hazard and describes the technological and policy advances that have been made in recent years to promote understanding and effectively mitigate the problem. The Colorado Geological Survey has played a key role in these advances by introducing the term "heaving bedrock" to differentiate the problem from expansive soils; leading stakeholder field trips and conferences; investigating the physical characteristics, mechanics, causes, and distribution of heaving bedrock; publishing the investigation results; assisting county governments in creating new land-use regulations; and reviewing site investigation reports for actual subdivision projects. From this experience, we conclude that a state geological survey must be active in numerous arenas—scientific, practical, and political—to assist effectively in addressing potential hazards that impact the general public.

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Key Words: Heaving bedrock; expansive soils; geological hazard; differential heaving; steeply dipping bedrock; bentonite; Pierre Shale; damage; site exploration; mitigative designs; policy; Colorado Geological Survey; land-use regulations; Front Range; Colorado.

INTRODUCTION

A high incidence of damage to roads, utilities, lightly loaded residences, schools, and commercial buildings has occurred where steeply dipping beds of expansive claystone bedrock are encountered at shallow depth along Colorado's Front Range piedmont (Figures 1 and 2). The total cost of this damage amounts to tens of millions of dollars and includes maintenance and repair costs incurred by homeowners, warranty insurers, water and sanitation districts, school districts, county public works departments, and taxpayers; litigation costs; and damage that has not been repaired. Damage typically begins within 10 years after construction. Some suburban areas have experienced recurring ground deformations and damage for nearly 20 years. Site exploration and mitigation practices based on widely used expansive soils models have proven to be unsuccessful in this particular region.

The damage described above is associated with distinctive, highly differential ground deformations that form elongate heave features. Called "speed bumps" by area residents, these heave features may attain sizes as large as 0.65 m high, several tens of meters wide, and several hundreds of meters long (Figure 3). The heave features exhibit a variety of cross-sectional shapes, ranging from symmetrical to strongly asymmetrical. This type of heaving is common within 1.6 to 4.8 km (1 to 3 miles) of the mountain front along the piedmont but is atypical of other areas of Colorado that are underlain by relatively flat-lying expansive soils and bedrock. A majority of the heave features are associated with the Upper Cretaceous Pierre Shale, but heaving is observed in other Upper Cretaceous formations as well (Figure 4).

The Colorado Geological Survey (CGS) has introduced the term "heaving bedrock" to describe the geological hazard responsible for this style of ground heaving. This paper

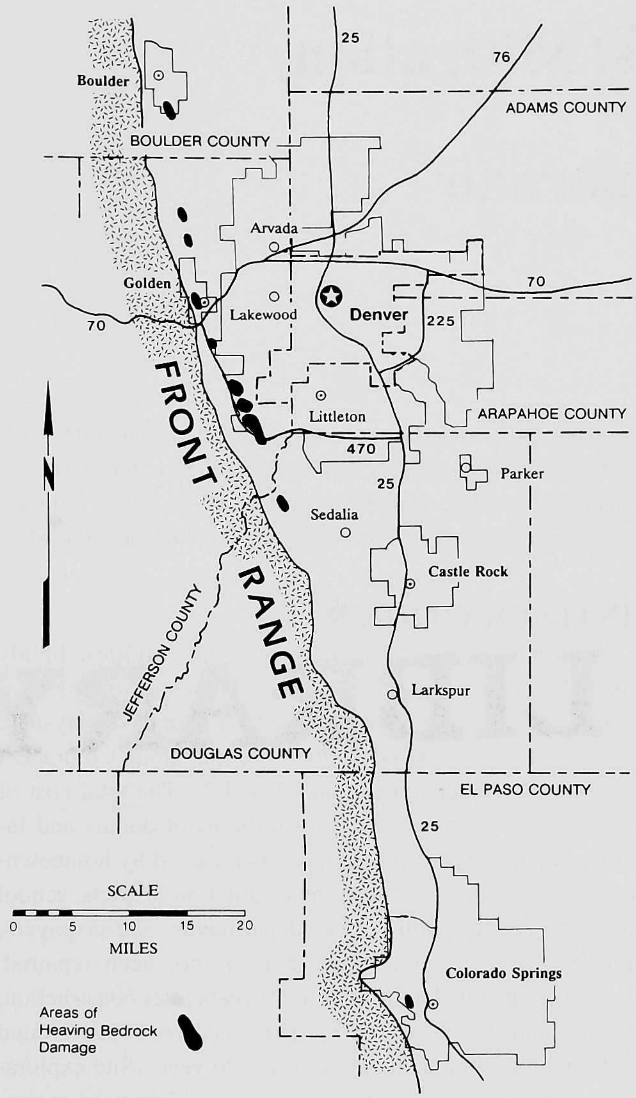

FIGURE 1: Index map of the Front Range piedmont area, Colorado (modified from Noe and Dodson, 1995). Heaving-bedrock damage is most pronounced in Jefferson, Douglas, and El Paso counties within 1.6 to 4.8 km (1 to 3 miles) of the mountain front.

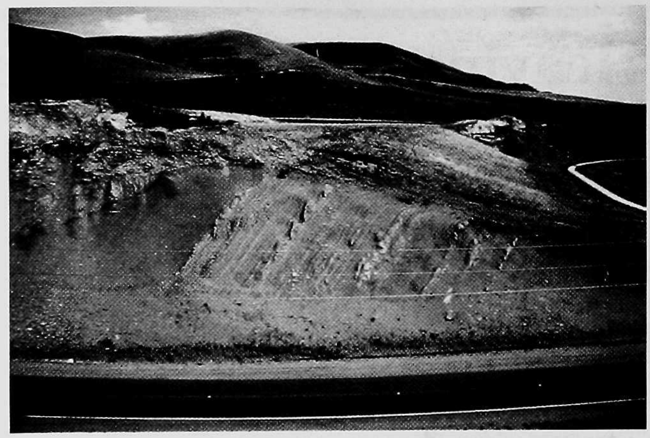

FIGURE 2: Photograph of steeply dipping Pierre Shale in Jefferson County, Colorado. Steeply dipping bedrock is especially prone to differential heaving because of the large number of beds intersecting the ground surface, with each bed having different compositions and engineering properties.

summarizes important distinctions between heaving bedrock and expansive soils, and describes the technological and policy advances that have been made in recent years to promote understanding and effectively mitigate the heaving-bedrock problem in Colorado.

Problem History

Colorado's Front Range urban corridor has experienced significant and costly soil problems since the 1940s, when large-scale suburban development moved out of the central river valleys and onto surrounding low plateaus underlain by expansive soils and bedrock. Much research was conducted in the area (and worldwide) as a result of such problems, and many advances were made with respect to site exploration and structural design in areas underlain by expansive soils (see Chen, 1988; Nelson and Miller, 1992). By the early 1970s, when suburban development first began in the Front Range piedmont southwest of Denver, expansive soils were known as a geological hazard and were addressed with special mitigative designs such as drilled-pier and grade-beam foundations and floating-slab floors. In practice, the relatively soft, expansive bedrock was treated essentially the same as expansive soils. Site exploration consisted of widely spaced drillholes that were sampled and tested for material composition, grain-size distribution, moisture content, dry density, swell potential, and/or Atterberg limits. The subsequent design of houses and other facilities was based on the assumption that the underlying materials would have somewhat uniform properties within the building footprint. This approach achieved relative success when applied to flat-lying soil and bedrock in the Denver area.

FIGURE 3: Photograph of parallel, linear heave features associated with heaving bedrock. Heaving bedrock has caused extensive damage in this neighborhood, which overlies near-surface Pierre Shale.

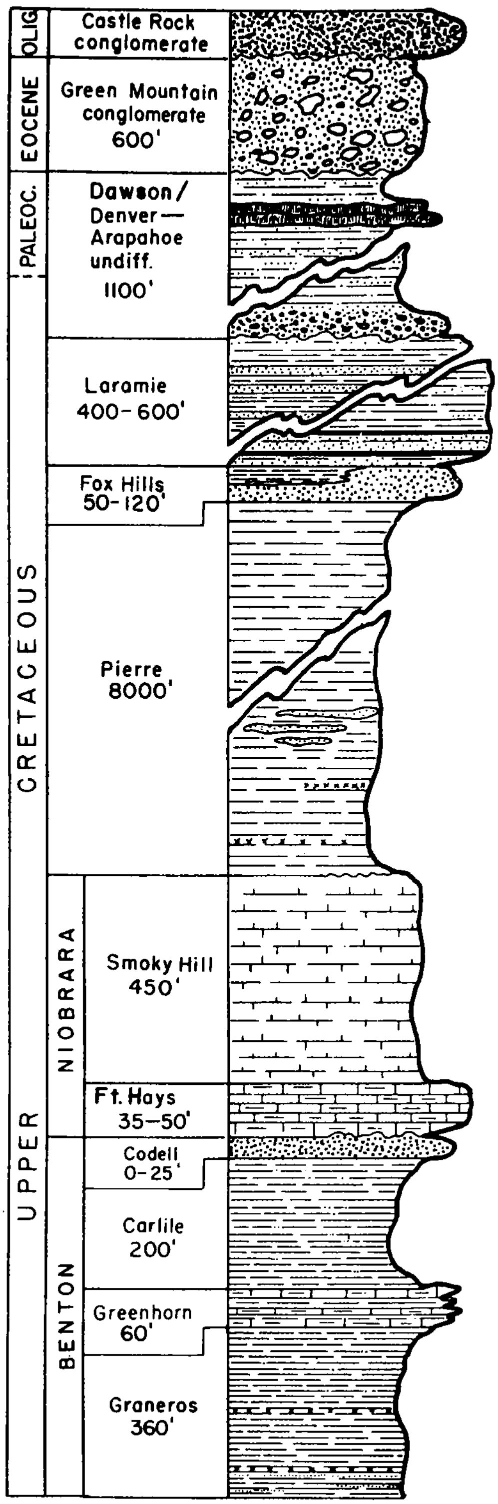

FIGURE 4: Stratigraphic column of Upper Cretaceous and younger rocks in the greater Denver area (modified from LeRoy, 1955). Heaving bedrock occurs in all of the Upper Cretaceous formations where they are steeply dipping, on the flank of the Front Range uplift. The Pierre Shale is the most important formation with respect to heaving bedrock occurrence and damage.

Expansive soils assumptions, and the resulting designs, were largely unsuccessful in the Front Range piedmont area from the very beginning. From the early 1970s to the early 1990s, numerous subdivisions experienced exceptional and recurring damage. Paradoxically, other subdivisions in the area appeared to be relatively unaffected. Although there were advancements in the understanding of expansive soils and the state of engineering practice over this 20-year period, the style and magnitude of damage in this area remained consistently higher than for other expansive soils areas in Colorado. The piedmont area ranked near the top in terms of claims and payouts for several national home warranty corporations. Numerous lawsuits were filed, involving a wide variety of stakeholders on both sides of the disputes. Eventually, however, much of the burden of repairing the long-term, recurrent damage to private property fell upon individual homeowners. Typically, such damage is not covered by homeowners' insurance or federal disaster relief funds.

Previous Work

Published studies addressing this problem are rare, particularly those that link physical geological characteristics to the distinctive type of heaving. The role of the area's bedrock in creating a potentially distinct geological hazard was first mentioned by Gardner (1969), several years before subdivision construction began in the area. Gardner described the occurrence of bentonite beds up to 0.3 m thick in many of the steeply dipping formations and concluded that those areas underlain by near-vertical bentonite beds are unsuitable for building foundations. Hart (1974) mapped several bedrock units along the piedmont that have greatly contrasting swell potentials. Simpson and Hart (1980) warned of a high risk of differential swelling for foundations constructed over steeply dipping bedrock units that contain different compositions within adjoining layers.

The first public-record investigation of damage in the area is a master's thesis by Kline (1983). Kline investigated geologic and nongeologic variables that may have influenced damage in a subdivision. He found that the depth to bedrock was of primary importance, with more damage occurring where the bedrock was shallower. A majority of the damaged buildings were founded on drilled piers. Gipson (1988) described the geologic setting of the Front Range piedmont and described its influence on the damage that had occurred there. He noted two unusual heaving morphologies. The first is the elongate "speed-bump" morphology. The second consists of broad, gently tilting, differentially uplifted surfaces ranging up to a block ($\sim$200 m) long from their lowest to highest edges. Gipson attributed the damage to (1) steeply dipping bentonite layers being flanked on either side by less-expansive bedrock, and (2) weathering of the steeply dipping formations, which appears to be deeper than it is for flat-lying bedrock.

E. C. Weakly (personal communication, 1993) mapped thousands of heave features in the piedmont area for a national warranty company during 1989 and 1990. He noted a strong tendency for the features to be aligned longitudinally along the direction of regional bedrock strike and attributed the distinct style of heaving to the presence of individual bentonite beds. The warranty company used the results to determine areas for which they would not issue warranty insurance for new construction. Unfortunately, because of the private contract, Weakly's mapping and results have not been released for use by the general public.

Major evidence for the differences between damage from steeply dipping bedrock and flat-lying bedrock and soils was presented by Thompson (1992a, 1992b). By comparing the piedmont area with the greater Denver area, Thompson showed that the damage rate in the piedmont area underlain by steeply dipping, expansive bedrock was more than three times greater than the damage rate for flat-lying, expansive bedrock and soils around Denver. He found that the amount of overburden (i.e., the depth to bedrock) was a critical factor governing damage in the piedmont area, with essentially no damage occurring when >3.3 m of overburden soil and/or fill was present. Thompson also showed that subsurface moisture in the piedmont area increased to depths of as much as 10 m after development, much deeper than the 3 m of moisture penetration commonly assumed in engineering practice in the Denver area.

Nichols (1990, 1992) hypothesized that the differential, linear heave features in the Front Range piedmont area were the result of increased rates of rebound (i.e., time-dependent release of stress) from unloading and disturbance of overconsolidated claystones, and not the result of hydration-induced swelling. Nichols et al. (1994) showed an example of ground heaving along a thrust fault surface in near-horizontally bedded Pierre Shale in South Dakota that resulted in an asymmetrical, linear heave feature (similar to those seen in Colorado's piedmont). He attributed this feature to rebound after removal of road-cut overburden.

Setting the Stage for Change

New subdivisions built in the Front Range piedmont during the 1970s, 1980s, and early 1990s continued to experience damage from bedrock heave. Most builders and engineers ignored or were unaware of the relevant technical papers listed above. They continued to use site-exploration and building-design methods based on expansive soils models that assume flat-lying, laterally uniform strata (Figure 5). The use of progressively longer drilled piers (increased from 3 to 5 m in length to 8 to 12 m) and structurally supported floors in place of floating slab floors improved structural performance to some degree. However, these expansive-soil designs were not especially successful in areas experiencing severe differential heaving. A strong prejudice existed to continue to treat the piedmont bedrock as an expansive soil because expansive-soil theories and practices were being applied successfully in expansive soil and bedrock in other parts of the Denver area. Specific designs for expansive soil were accepted as the standard of engineering practice in any expansive substrata. Deviations from the standard of practice were discouraged because of liability issues if subsequent failure occurred.

By the late 1980s, a number of major stakeholders—the engineers, builders, county planners, and especially, the homeowners—had become frustrated by the continued high incidence of damage in the piedmont area. Many of the stakeholders had some experience and knowledge of the problem, but no consensus existed for a solution. When the stakeholders met, it was most often as antagonists in litigation.

DEFINING AND ADDRESSING THE HEAVING-BEDROCK PROBLEM

In 1990, CGS began a small-scale, state-funded scientific investigation into the "expansive soil" problems, in response to the difficulties being experienced in the Front Range piedmont area. Within 5 years, a previously unstudied geological hazard called heaving bedrock was described, a large number of the area stakeholders had reached a consensus on an approach to address the heaving-bedrock problem, and the most-affected counties had taken steps to amend their land-use regulations so that potential heaving-bedrock problems would be taken into account. This section explains how the CGS expanded its role in the areas of technical research, education, technical assistance, consensus building, preconstruction reviews, site assessment, and technical assistance for regulation writing to help achieve these accomplishments.

As the CGS scientific investigation progressed, it became apparent that a purely scientific approach would be of limited success in addressing the overall problem. In particular, no previously published technical papers on the subject had been accepted into practice by the engineering community. Other, nongeological factors forced the CGS to reconsider

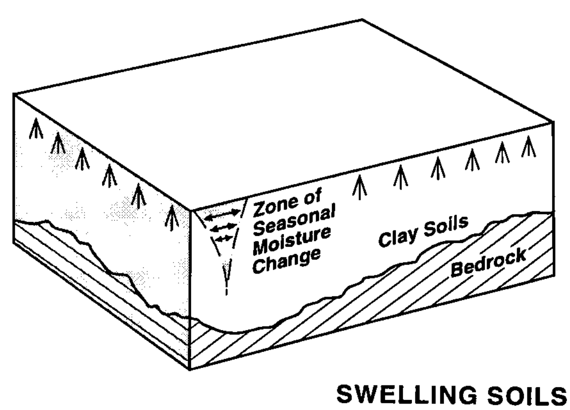

FIGURE 5: Block diagram showing a widely used, general model for expansive soils (modified from Noe and Dodson, 1995). The model assumes that horizontally bedded clay soil or bedrock has uniform composition. Hydration and expansion, resulting in uniform, vertical uplift of the ground surface (vertical arrows), occur within the near-surface zone of moisture change where naturally dry soils are wetted. The soils or bedrock beneath this zone remain at constant moisture and are therefore unaffected by wetting.

its approach. Another building boom had begun in the piedmont area in the 1990s. The rush of new development was outpacing the ability to fully investigate the problem from a purely scientific standpoint. With the boom came an urgency to change the status quo approach of existing mitigation practices and thus prevent future damage.

Three main factors determined the ultimate approach taken by the CGS: (1) the stakeholders, although often antagonistic, all wanted to achieve the same goal of reasonable success in constructing, owning, and maintaining facilities without excessive damage occurring; (2) the different stakeholder groups knew much about certain parts of the problem, but this knowledge was not generally known to all stakeholder groups; and (3) it would take more publishing of the scientific results alone to overcome the status quo resistance imposed by accepted standards of engineering and building practice. Clearly, involvement was needed in a larger, more comprehensive arena, one that involved education and consensus building among the stakeholder groups in addition to scientific research. The CGS modified its approach and based it on involvement with the stakeholders on a number of levels. This approach met with a great deal of success. The different levels of involvement and the major results obtained are summarized below.

Scientific Research

The scope of scientific research was broadened to include observation of actual problems as they occurred. Wherever possible, the link between distinctive heave features and the physical characteristics of the underlying bedrock was defined. The major findings, described in the following paragraphs, are discussed in greater detail by Noe and Dodson (1995, 1997). Other scientific aspects of the problem are under continuing investigation by graduate students at Colorado School of Mines.

Several different types of heave features were documented, each having a distinctive cross-sectional shape and orientation in relation to bedding strike. In several cases, it was possible to compare heave features with the underlying bedrock in trenches. The genetic relationship between heave-feature morphologies and bedrock configuration is summarized in Figure 6. The heave features were found to be associated with several different types of discontinuities. Differential heave occurs along boundaries of individual beds or bedding zones having different compositions and swell potentials (Figure 6A) or along shear-slip planes across fracture or bedding planes (Figure 6B).

A number of firsthand observations were made of actual heaving triggered by rapid influx of water into the bedrock. Such observations came from locations where a site had been graded 1.5 to 6 months previously without significant ground deformations taking place. The triggering events consisted of natural precipitation from large, summer thunderstorms, which induced differential movement of up to 7.5 cm over a period of several hours (e.g., Figure 7 and cover photo). Other, longer term observations of heaving were made at a subdivision in which the site was graded and paved roads were built in the late 1980s and homes were constructed in 1993. Minor heaving occurred in the roads during the period preceding home construction. However, major heaving occurred within a year after the homes were constructed and lawn irrigation was initiated. The heaving has affected both the roads and the homes.

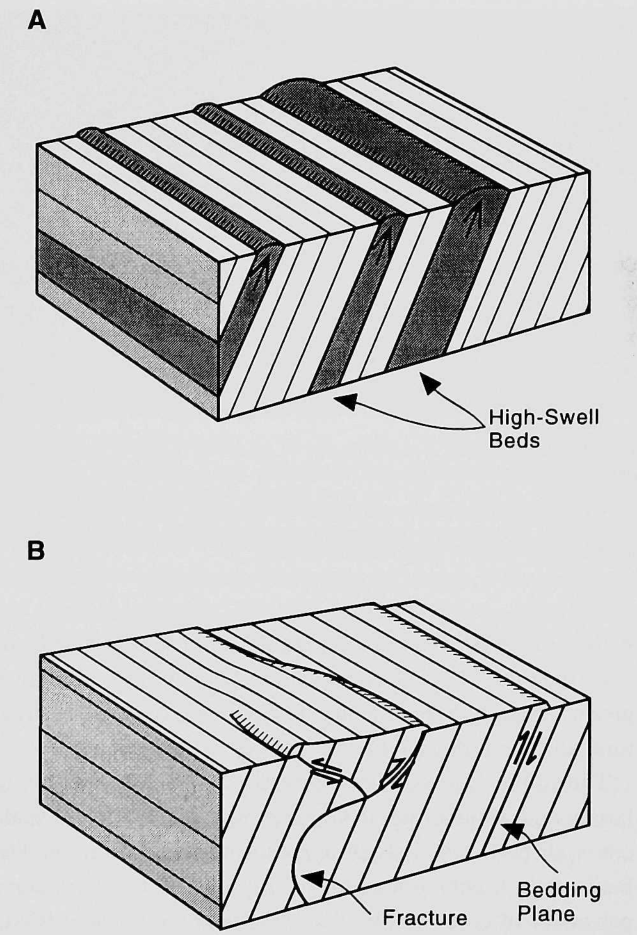

FIGURE 6: Block diagrams showing different types of heave features associated with heaving bedrock (modified form Noe and Dodson, 1995). (A) Near-symmetrical heave features formed by differential swelling and/or rebound of individual bedrock layers, each having a different swell potential. This type of heaving results in straight-crested, longitudinal uplift of the ground surface, oriented parallel to bedding strike. (B) Strongly asymmetrical heave features formed by thrust-like, shear-slip movement along bedding planes or fracture surfaces. The bedding-plane features are straight crested and are oriented parallel to bedding strike, whereas the fracture-plane features have curvilinear crests and may not necessarily be oriented parallel to bedding strike.

Preliminary research by the CGS and Colorado School of Mines found that claystone composition and physical engineering properties (e.g., Atterberg limits, void ratio, and water content) vary systematically across certain heave features, especially those cored by beds of pure bentonite. The water content of the bedrock layers varies considerably, as does the groundwater system in general. This appears to be due to the presence of segregated groundwater domains

FIGURE 7: Asymmetrical heave feature in a graded cut caused by sudden, thrust-like heaving of the bedrock block on the right. This feature formed along a preexisting fracture plane. More than 30 cm of prior Holocene displacement was evident along the plane (at a point in the cut wall marked by the wooden stake) when the cut was first exposed. The heaving episode shown here occurred within 24 hr after a rainstorm and resulted in another 8 cm of total displacement.

within the bedrock, each containing numerous water-bearing fractures. The domains are separated by subsurface groundwater barriers (bentonite beds or gouge-filled fracture zones that behave like natural slurry walls).

The author has documented evidence of deep water circulation and weathering from five 30-m-deep Pierre Shale cores, drilled at two study areas located 4.5 km apart. The bedrock is highly fractured, having one to three fractures per meter of core. Many of the fractures are gypsum filled. The cores exhibit nearly uniform weathering profiles and are completely oxidized to a depth of 14.7 m and partially oxidized along fracture planes to a depth of 24.5 m. The evidence suggests that water has infiltrated the claystone during the Holocene and has altered its composition by leaching and precipitation. Therefore, water has played a role in modifying the bedrock's physical and engineering properties.

Outreach and Education

Armed with the scientific observations listed above, the CGS began a campaign that involved outreach and education. At first the author met individually with many of the area's stakeholders to compare observations and experiences. Much of the information gathered from these engineers, geologists, water and sanitation managers, road-crew supervisors, builders, warranty insurers, and homeowners substantially supported the CGS's field and laboratory observations.

The author led the first of many field trips in the Front Range piedmont in August 1993. The first trip was given for the county commissioners, planning commissioners, and planning staffs of Douglas and Jefferson counties. The participants, many of whom lack formal training in geology or engineering, were generally aware that there were problems in the area. However, most were completely unaware of the enormity of the problem, both in terms of its distribution and general destructiveness. The CGS trip raised their consciousness and resulted in agreement that a new approach to the problem was needed.

The positive response to the first field trip resulted in three more field trips, one for state legislators in September 1993 and two for professional geologists, engineers, builders, and warranty insurers in October 1993. The professional trips, in particular, were punctuated with thought-provoking discussions between the participants. These trips marked the first time that the various stakeholders had experienced a common, "on-site" view of the problem. And, although there was a general lack of consensus about what should be done, most of the participants had strong feelings that the status quo approach to building in the piedmont area was unacceptable.

The next step was a day-long technical transfer conference, "Everything You Should Know About the Pierre Shale," in April 1994. This conference was facilitated by the CGS and sponsored by Jefferson County, Douglas County, and several professional geological, engineering, and building organizations. Stakeholders from various professions served on the organizing committee. The conference featured many of the leading individuals in the various stakeholder professions, and presentations were given on topics that included the state of engineering practice, geological overviews and case studies, planning issues, design of foundations, pavements, and utilities, remedial mitigation, homebuilder experiences (both for and against existing designs), warranty insurance issues, landscaping and water-use options, and legal issues. More than 300 attendees were exposed to the idea that the problem went beyond the simplified theoretical confines of expansive soils and that an additional level of professional understanding was needed to understand and address the problem. Lively discussions ensued throughout the day, and there was again agreement voiced by many of the participants that a change in practice and policy was needed.

A key presentation was made at this meeting by a geotechnical engineer, R. M. McOmber, who extended the findings of Thompson (1992a, 1992b) regarding depth of overburden thickness to include mitigative practice. He introduced the concept of large-scale overexcavation in which a deep cut would be made to at least 3 m below the anticipated base of building foundations. The cut would then be partially refilled with on-site or imported materials under controlled moisture and compaction conditions. Large construction equipment could be used for most sites. The cost of the overexcavation could be lessened in many cases because shallow, footing-type foundations and slab-on-grade floors could be used instead of the more expensive drilled pier foundations and structural floors. The advantages of an overexcavation and fill replacement include: (1) destruction of bedrock discontinuities; (2) dissipation of any heaving of the excavation floor within the overlying fill material; (3) control of fill compaction and moisture by the project engineer; (4) a more exact knowledge of the substrate for foundation design purposes; and (5) control of water-seepage rates by emplacing a horizontally bedded substrate.

The term "heaving bedrock" was introduced by the author in a CGS technical presentation in 1994. The term is the result of an overall effort to differentiate this geologic hazard, in which heaving is preferentially associated with discontinuities in bedrock, from the general case of expansive soils, in which a homogeneous, flat-lying substrate is assumed. Other terms such as "expansive shale," "expansive bedrock," "dipping bedrock," "heaving ground," and "heaving shale," in addition to "expansive soil," had been used by various participants at the previous field trips and conferences. In particular, the term "expansive bedrock" was considered but was rejected because (1) most Denver-area engineers and builders have long considered "expansive bedrock" and "expansive soil" to be indistinguishable in practice; (2) expansive, flat-lying bedrock in the Denver area can be mitigated with conventional expansive-soil technology and only rarely is linear, differential heave observed; (3) the term implies that hydration-induced swelling of the matrix is the only important process, and no indication is given that rebound may be a factor; and (4) it does not alert the practitioner to the complex styles of differential movement that occur because a laterally homogeneous substrate is assumed for design purposes.

The term "heaving bedrock" alerts the various technical and nontechnical stakeholders that (1) the substrate is bedrock, not soil; (2) differential heaving may occur along nonhorizontal stratigraphic and/or structural surfaces; and (3) a variety of heaving processes must be considered, including hydration-induced swelling and rebound. The term is consistent with the definition of "heave" used by Bates and Jackson (1987) and Allaby and Allaby (1990). Heaving bedrock is therefore seen as being generally related to expansive soils, while being more complex in terms of its distinctive variety of uplift morphologies, deformation mechanisms, and geological setting.

Technical Assistance for Policy Making

Jefferson and Douglas counties, the two Colorado counties most affected by heaving bedrock, responded to the previously mentioned outreach efforts by taking steps to assure the mitigation of heaving bedrock. Jefferson County had experienced much suburban growth in the Front Range piedmont over 20 yr and was experiencing significant pressure for continued development. Douglas County's piedmont area was relatively rural, and the development pressure there was somewhat less.

Jefferson County formed and convened the Expansive Soils Task Force in late spring 1994, with directions to delineate an administrative zone and draft a revised set of land-development and zoning regulations based on geologic parameters for the piedmont area. The task force included about 70 individual stakeholders in various capacities. Technical subcommittees were formed to address geologic and geotechnical investigations, design of foundations, roadways, and utilities, remedial repairs, and other criteria. A policy subcommittee was convened to assemble the various technical pieces into the county's land-development regulations. The author and W. P. Rogers of the CGS assisted by chairing two of the subcommittees and participating in several other subcommittees. The task force delineated an administrative overlay zone called the Designated Dipping Bedrock Area (DDBA), based on the distribution of bedrock that is steeply dipping (i.e., having strata dipping >30 degrees from horizontal) and composed at least in part of expansive claystone. Minimum standards were proposed for site investigations and special mitigative designs. These standards included trenching in addition to traditional drill-hole investigations, and the preferential use of overexcavation and fill replacement in areas of a subdivision where potentially heaving, near-surface bedrock is positively identified. Geological investigations for subdivisions within the DDBA were to be conducted by a professional geologist, as defined by Colorado Revised Statute 34-1-201-(3). The geotechnical and geological reports could be combined if coinvestigated and cosigned by a geologist and a geotechnical engineer. An Engineering Advisory Board was proposed to provide peer review in cases where mitigation strategies other than overexcavation and fill replacement were recommended by a project engineer. The task force recommendations went through two periods of public testimony, in which minor changes were added, and were adopted by Jefferson County in April 1995.

In Douglas County, the CGS provided technical assistance by delineating an administrative overlay zone called the Dipping Bedrock Overlay District (DBOD) (Figure 8) and mapping and ranking 14 stratigraphic units for heaving-bedrock hazards based on geologic, engineering, water-well, and construction-damage data (Noe and Dodson, 1995, 1997). The 1995 report by Noe and Dodson represents the first publically available report and map addressing heaving bedrock in Colorado, and nearly 300 copies have been distributed to date. Douglas County is in the process of drafting a revised set of land-development and zoning regulations for the DBOD, based on the new Jefferson County regulations. Since 1994, the county and the CGS have worked together to ensure that proposed subdivision plans in the piedmont area consider heaving-bedrock hazards (see the next section), despite the absence of formal land-use regulations for heaving bedrock.

In late 1995, the city of Colorado Springs contacted the CGS with concerns about landslides and heaving bedrock

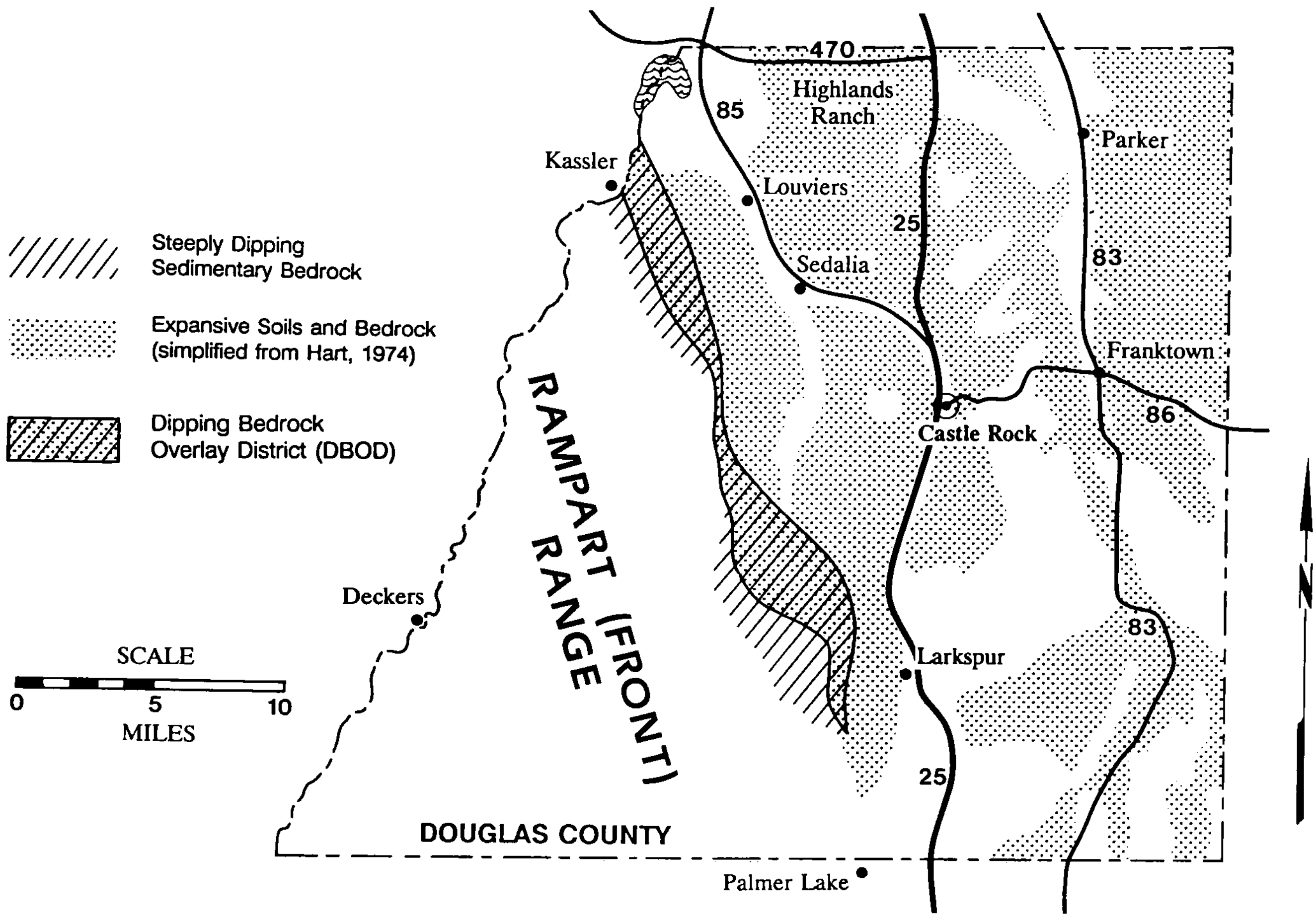

FIGURE 8: Map of Douglas County showing areas of steeply dipping bedrock and expansive soils/bedrock (from Noe and Dodson, 1995). The Dipping Bedrock Overlay District is defined as the overlapping portion of the two areas.

along the western edge of the city. The CGS assisted the city in drafting its first comprehensive geologic hazards ordinance and participated in the public hearings. The ordinance was adopted by the Colorado Springs Planning Commission and City Council in April 1996. Currently, the CGS is creating a map of potential areas of heaving bedrock in the Colorado Springs area.

Technical Assistance in Practice

In addition to policy assistance, the CGS has provided technical assistance to county planning departments since 1972 under provisions of the Colorado Revised Statute 30-28-101, *et seq.* This assistance involves reviewing geological and geotechnical reports for actual subdivision projects. As more information about heaving bedrock became available in the 1990s, it became apparent that drillhole surveys used for site exploration in dipping bedrock of the Front Range piedmont had severe limitations. In 1994, the CGS began recommending that trenches be dug in addition to drillhole surveys in areas within the piedmont where near-surface bedrock is encountered. The trenches, when dug perpendicular to strike, provide detailed information about the bedrock. Potential high-swelling layers are evident, as are various types of shear-slip surfaces. Jefferson County included trenching in its 1995 DDBA regulations, and Douglas County is requiring trenching for subdivision sites located within the DBOD on a case-by-case basis. Trenches have been dug at fifteen sites in these counties since 1994. The initial engineering plans for certain projects have changed based on findings from trenching (Figure 9). CGS engineering geologists have been present at many of these trenches on behalf of the counties to offer guidance to the consulting geologists and engineers.

In addition to technical assistance to counties, the CGS regularly answers telephone queries about expansive soils and heaving bedrock. Most of these calls come from homebuyers and sellers, real estate agents, and developers. The CGS has also updated its popular expansive soils booklet for homeowners to include heaving bedrock issues (Noe et al., 1997). This booklet is often bought by homebuilders for distribution to buyers of new homes built on expansive soils, in compliance with Colorado's disclosure laws (i.e., Colorado Revised Statute 6-6.5-101).

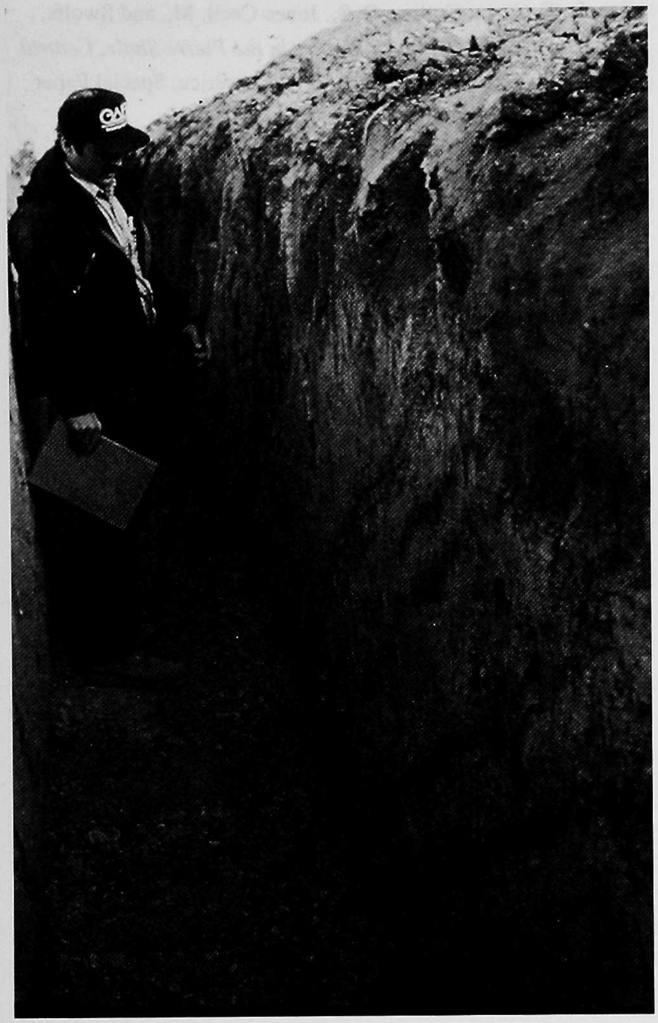

FIGURE 9: This trench has exposed dipping beds of bentonite (dark layers) at a high school site. Earlier drillhole surveys had not encountered the bentonite. The foundation design for the school was subsequently changed from a drilled-pier system to an overexcavation design.

Future Activities

Much remains to be done to fully address the heaving-bedrock problem, despite the advances discussed in this article. Scientific research is needed to better define the causes and mechanics of heaving-bedrock deformations, especially with respect to characterizing the relative contributions of hydration swelling and rebound. Much of the preliminary research done by the CGS and Colorado School of Mines is to be reported in publications or in master's and Ph.D. theses over the next few years. Engineering design analyses need to be advanced so that numerical methods can be used in addition to empirical methods. Continued outreach and educational activities are needed so that heaving bedrock is understood among all of the piedmont area stakeholders, including a large number of real estate agents, homebuyers, and homeowners who have no technical experience. These activities must be mindful of the present residents and should strive to minimize adverse effects on property value.

CONCLUSIONS ●

This article has discussed the role of the Colorado Geological Survey and other stakeholders in addressing an unusual but serious geological hazard called heaving bedrock along Colorado's Front Range piedmont. The process involved more than scientific research alone. It involved outreach and education activities to convince the stakeholders that the problem could not be addressed by using conventional designs based on expansive soils. It was necessary to name heaving bedrock as a separate geological hazard for cases in which nonhorizontal discontinuities within the bedrock allow for more complex mechanisms of expansion and movement than for expansive soils. Site exploration methods needed to be modified to account for the highly variable bedrock characteristics, and trenching was introduced as a necessary means of site evaluation. A new standard of practice with regard to mitigative technologies and designs was needed to replace the old standard that was based on expansive soils theories and was often unsuccessful. Revisions to existing county land-use regulations were needed to facilitate prudent planning and construction practices and to protect citizens from unnecessary exposure to heaving-bedrock hazards.

These changes were accomplished within a relatively short time period of 3 years, after nearly 20 years of limited success. The CGS emerged as a leader in information transfer and consensus building, and the stakeholders provided previously unavailable information and committed themselves to work toward a common goal. This history is given with the hope that other state geological surveys can use similar means of broad-based involvement to affect changes in their communities.

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On the Cover: Surface view of a near–vertical bentonite layer in the Upper Cretaceous Pierre Shale in Jefferson County, Colorado. The layer heaved with a differential displacement of 8 cm within 24 hours after a rainstorm at this construction area. Note the hump in the fence aligned with the trend of the bentonite layer. Heaving bedrock damage is occurring in the 2.5-year-old subdivision in the background. Photograph by David C. Noe.