OPEN-FILE REPORT 02-8

Soil and Bedrock Conditions and Construction Considerations, North-Central Douglas County, Colorado

By
Karen A. Berry, David C. Noe, Monica C. Pavlik, and James M. Soule

Colorado Geological Survey
Department of Natural Resources
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FOREWORD

Open-File Report 02-8 describes the soil and bedrock conditions of north-central Douglas County, Colorado, and associated geology-related construction considerations. The report is intended for use by county and municipal planning and building departments, homebuilders, geotechnical engineers, and engineering geologists.

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David C. Noe
Chief, Engineering Geology

Vicki J. Cowart
State Geologist and Director

HOW TO USE THIS REPORT

This report contains three map plates that show the geology (Plate 1) and potential areas of collapsible soils (Plate 2) and expansive soils (Plate 3) in north-central Douglas County, Colorado. The report describes these map units and how they were derived. These maps have been compiled from a variety of sources, and are intended as a general guide to show where certain geologic and soil conditions may exist. However, site-specific subsurface conditions may vary markedly throughout the map area. This report and the accompanying maps are not a substitute for professionally prepared, site-specific geologic-hazard studies and designs

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INTRODUCTION

Douglas County has been one of the fastest-growing counties in the United States in the 1990s and early 2000s. Much of the growth has occurred in the north central part of the county, on the fringe of the Denver Metropolitan Area. The unincorporated Highlands Ranch subdivision is the major growth center in this area. Additional population growth has occurred in newer subdivisions constructed in or near the towns of Lone Tree and Parker.

This area has been the scene of widespread and, sometimes severe damage to residences, commercial and government buildings, and county-owned roads. The damage may be largely attributed to two geologic phenomena: swelling soil and bedrock and collapsible soil. Since 1990, several class-action lawsuits have been filed over swelling-soil damage in the metropolitan Denver area, including several significant lawsuits in north-central Douglas County. These lawsuits pitted more than fifteen thousand homeowners versus the builders of those houses, and the resulting judgements were decided in favor of the homeowners.

This study by the Colorado Geological Survey (CGS) is in an effort to understand the geologic and soil conditions that affect construction in north-central Douglas County, and to evaluate currently used methods of site investigation, earth-materials testing, engineering design, and construction inspection for assessing and mitigating these conditions.

In order to evaluate this problem, data were obtained from geotechnical reports for 185 subdivisions located within the study area. The data set contains 4,900 samples from 4,200 test borings. The data were segregated into groups according to engineering properties and the underlying soil type and geologic unit.

The behavior of each soil type and geologic unit was characterized using the data obtained from test borings and soil surveys. Windblown surficial deposits and soils derived from these deposits appear to be prone to collapse or significant settlement when wetted and/or loaded. Bedrock containing claystone or interbedded claystone and the soils derived from these geologic units contain highly swelling clays, and are prone to expansion and heave when wetted.

The test-hole data shows that the engineering properties of soil, surficial deposits, and bedrock vary significantly, both laterally and vertically, across the study area. Due to this variability, it is important that adequate geologic and geotechnical investigations be done during all phases of the planning and construction process. In particular, site-specific geologic and geotechnical investigation should be done for each lot or building pad. The investigations for each lot should include a test boring and swell-consolidation testing at foundation and floor levels.

PURPOSE AND OBJECTIVES

The purpose of this report is to describe and characterize critical construction-related problems that occur in soil and bedrock in the north-central part of Douglas County, and to evaluate currently used site-assessment and mitigation methods.

The specific objectives of the study are as follows: 1) Describe the soil, surficial geologic, and bedrock units and characterize the engineering properties of samples recovered from these units; 2) Identify typical and unusual construction-related problems that may be attributed to the geology in the area; and 3) Describe how to recognize the potential for these problems using key geologic and engineering-property criteria.

LOCATION

The study area encompasses approximately 70 square miles in north central Douglas County (Fig. 1). It is bounded on the north by the Douglas-Arapahoe County boundary; on the west by Plum Creek, Chatfield Lake and Dam, and the South Platte River; on the south by the 39º30' North Latitude line; and on the east by Parker Road (State Highway 83). This area generally corresponds to the area of Douglas County shown in the Littleton, Highlands Ranch, and Parker 1:24,000-scale topographic quadrangle maps.

The major landforms associated with the study area include high escarpments and plateaus, rolling upland plains, and modern stream valleys. A prominent bedrock escarpment and plateau area, known locally as the Bluffs, rises abruptly along the south-central part of the study area. Most of the study area consists of a series rolling upland plains that slope gently to the north, away from the base of the Bluffs. A series of small, intermittent-stream valleys dissect the upland plains and radiate outward from the Bluffs. From west to east, these stream valleys include Highlands Gulch, Spring Gulch, Marcy Gulch, Dad Clark Gulch, Big Dry Creek, Cook Creek, Willow Creek, Cottonwood Creek, Happy Canyon Creek, Badger Gulch, and Newlin Gulch. The study area is flanked by two large, modern alluvial valleys: Plum Creek and the South Platte River along the western boundary and the valley of Cherry Creek along the eastern boundary.

Elevations within the study area range from a low point of 5,365 feet where the South Platte River exits Douglas County to a high point of 6,400 feet in the west central part of the Bluffs. Most of the topography consists of gently sloping ground. There is 100-150 feet of local relief along the escarpment at the Bluffs, and up to 80 feet of local relief occurs along some reaches of the small, dissected stream valleys that radiate away from the bluffs.

GEOLOGY

The following section contains a summary of the bedrock and Quaternary geology of the study area. Unless otherwise noted, these descriptions are derived from the geologic maps of the 1:24,000 Littleton (Scott, 1962), Highlands Ranch (Maberry and Lindvall, 1974; 1977), and Parker (Maberry and Lindvall, 1972) quadrangles. Plate 1 contains a digital reproduction of these geologic maps. In certain areas, most notably the Parker quadrangle, the geology has been modified according to the 1:100,000 geologic map of the greater Denver area and the Front Range Urban Corridor map series (Trimble and Machette, 1979). The map-symbol abbreviations used in this discussion and on Plate 1 are shown in Table 1.

BEDROCK GEOLOGY

The Dawson and Denver Formations are the most prevalent bedrock units in the northern tier of Douglas County. These units were deposited during the late Cretaceous to early or middle Eocene, beginning 97.5 Ma (million years ago) and ending 36.6-57.8 Ma (Morse, 1979). They were deposited simultaneously in adjacent basins, the Denver Formation to the north and the Dawson Formation to the south. Another, less-prevalent bedrock unit is the Castle Rock Conglomerate, which overlies the Dawson Formation in the southern part of the Highlands Ranch and Parker quadrangles.

Dawson Formation

The Dawson Formation (late Cretaceous - Eocene) was deposited in two main episodes. The lower Dawson Formation in northern Douglas County is about 400 ft thick; the upper Dawson Formation ranges from about 1,900 ft to less than 100 ft thick, due to an ancient episode of post-depositional erosion (Morse, 1979). The formation was deposited in alluvial-fan, stream, and floodplain environments. The source area was located on a granite highland to the southwest of Colorado Springs.

The Dawson Formation is distinguished by containing lenses of coarse, arkosic sandstone. It also contains lenses of siltstone, claystone, and conglomerate. In the study area, the formation is subdivided into six facies, based on the primary bedrock lithology:

1) *Arkosic sandstone facies* (*TKda*). Coarse-grained sandstone, consisting chiefly of quartz and feldspar; local clay lenses.
2) *Conglomerate facies* (*TKdc*). Cemented, boulder-bearing conglomerate.
3) *Sandstone facies* (*TKds*). Friable, fine-grained sandstone, composed chiefly of quartz, containing a clay binder.
4) *Claystone facies* (*TKdo*). Soft, olive-gray claystone and siltstone.
5) *Variegated (multicolored) claystone facies* (*TKdv*). Soft, silty claystone in a variety of pastel colors.
6) *Interbedded sandstone and claystone facies* (*TKdso*). Sandstone and claystone too thinly interbedded to separate at the map scale.

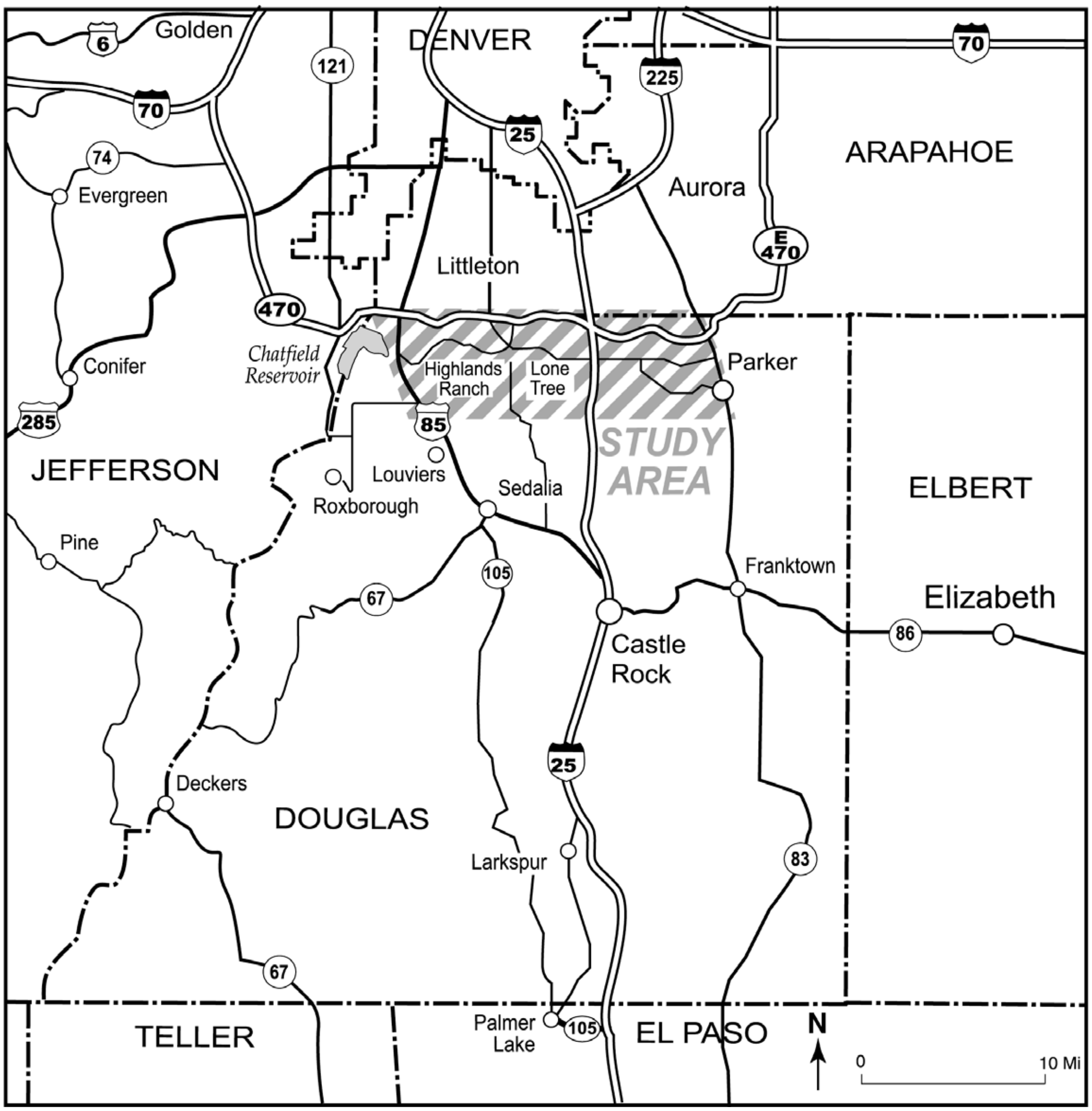

Figure 1. Index map showing study area in north-central Douglas County.

Denver Formation

The Denver Formation (late Cretaceous - Eocene) was deposited simultaneously and interfingers with the Dawson Formation. The maximum thickness of the Denver Formation is nearly 800 ft near Golden, in Jefferson County (Van Horn, 1976). In northern Douglas County, it occurs as a southward-thinning tongue that separates the lower and upper Dawson Formation. The tongue is described as being 20-50 ft thick (Maberry and Lindvall, 1972). The Denver Formation was deposited in an alluvial fan, stream, and floodplain environment. Van Horn (1976) postulates that the source area was located on a volcanic highland to the west of Golden.

The Denver Formation is distinguished as having sandstone and claystone lenses that contain andesitic volcanic debris. It is subdivided into three facies in the study area, based on the primary bedrock lithology:

1) *Sandstone facies* (*TKdes*). Friable, fine-grained sandstone, generally in various shades of brown, composed of quartz, feldspar, clay, containing weathered fragments of volcanic rock (andesite).
2) *Claystone facies* (*TKdec*). Soft, gray, and brown claystone, containing weathered fragments of volcanic rock (andesite).
3) *Rocks undifferentiated as to lithology* (*TKde*). Sandstone and claystone; interbedded too thinly separate at map scale.

Castle Rock Conglomerate

The *Castle Rock Conglomerate* (*Tcr*) (Oligocene) overlies the Dawson Formation, capping the bluffs in the southern part of the Highlands Ranch and Parker quadrangles. It consists of cemented boulders, cobbles, gravel, and sandstone. The unit is about 40 ft thick, cross-bedded, and poorly sorted. It contains isolated blocks of angular Wall Mountain Tuff, a bedrock unit that has been completely eroded away in the study area but occurs to the south in other parts of Douglas County. The Castle Rock Conglomerate was deposited in an alluvial fan and stream environment.

QUATERNARY GEOLOGY

The Quaternary geologic units in northern Douglas County consist of three main types of unlithified deposits based on their mode of deposition and their geomorphology. These include modern and ancient alluvial (river) terraces and valley fill, eolian (windblown) sand and silt deposits, and colluvial (slope) deposits. These deposits date from the Pleistocene to the present. In engineering terms, they are equivalent to soil deposits.

Alluvial Deposits

The alluvial-terrace and valley-fill deposits mapped in the study area are composed of poorly sorted weathered cobbles, gravel, sand, and clay. They were originally deposited in a stream and floodplain environment, during the interglacial cycles of the Pleistocene and Holocene. From oldest to youngest, these deposits include the Slocum Alluvium (corresponding to the Illinoian glacial period), the Louviers Alluvium (Bull Lake; 15,000 ya), the Broadway Alluvium (Pinedale; 12,000-13,000 ya), the Piney Creek Alluvium (Holocene; 2,800 ya), and post-Piney Creek alluvium (Holocene; 1,100 - 1,300 ya) (Scott, 1963; Van Horn, 1976).

The Slocum Alluvium forms the highest-elevation alluvial terraces in the study area. These terraces are scattered along the tops and sides of low hills, especially near the larger stream valleys. The Louviers Alluvium forms intermediate terraces along the larger stream valleys. The Broadway Alluvium forms low terraces above modern streams, typically on the western bank or on the inside curve of stream meanders. The Piney Creek Alluvium fills the modern stream valleys and is far more extensive than the Post-Piney Creek Alluvium, which forms the terrace just a foot or two above the present stream levels. The following is a more-detailed description of these five alluvial deposits:

1) *Slocum Alluvium* (*Qs*) (Pleistocene). Pebbly clay, silt, sand, and gravel, grayish-brown to yellowish-brown and grayish-red to dark-reddish-brown, well stratified. Deposits generally grade

Table 1. Map symbols used for geologic units.

Geologic Unit	Geologic Sub-Unit	Littleton Quad (Scott, 1962)	Highlands Ranch Quad (Maberry and Lindvall, 1974)	Parker Quad (Maberry and Lindvall, 1972)	Front Range Urban Corridor (Trimble and Machette, 1979)	This Study (Plate 1)
Bedrock Geologic Units:						
Dawson Formation	arkosic	TKda	Tda	Tda	TKda	**TKda**
	conglomerate	---	Tdc	Tdc	---	**TKdc**
	sandstone	---	Tds	Tds	---	**TKds**
	claystone	---	Tdo	Tdo	---	**TKdo**
	variegated	---	Tdv	Tdv	---	**TKdv**
	interbedded	---	Tdso	Tdso	---	**TKdso**
Denver Formation	sandstone	---	Tdes	---	---	**TKdes**
	claystone	---	Tdec	---	---	**TKdec**
	undifferentiated	TKd	Tde	Tde	TKd	**TKde**
Castle Rock Conglomerate	---	---	Tcr	Tcr	Tcr	**Tcr**
Quaternary Geologic Units:						
Slocum Alluvium	upper	---	---	Qsu	---	**Qs**
	lower	---	---	Qsl	---	**Qs**
	undifferentiated	---	Qs	---	Qs	**Qs**
	pediment	Qs	---	---	---	**Qs**
	fill terrace	Qst	---	---	---	**Qs**
Louvers Alluvium	upper	---	---	Qlu	---	**Qlo**
	lower	---	---	Qll	---	**Qlo**
	undifferentiated	Qlo	---	---	Qlo	**Qlo**
Broadway Alluvium	---	Qb	Qb	Qb	Qb	**Qb**
Piney Creek Alluvium	---	Qp	Qp	Qp	Qp	**Qp**
Post Piney Cr. Alluvium	---	Qpp	Qpp	Qpp	Qp	**Qpp**
Eolian Sand	---	Qes	Qes	Qes	Qes	**Qes**
Loess	young	Qyl	---	---	---	**Ql**
	old	Qol	---	---	---	**Ql**
	undifferentiated	---	Ql	Qlo	Ql	**Ql**
Colluvium	---	---	Qco	---	Qco	**Qco**
Artificial Fill	---	---	af	af	---	**af**

upward from gravel into sand, silt, and clay. A strongly developed, calcium carbonate-enriched zone (an ancient soil horizon) occurs in the upper part of the deposit. Terrace surfaces are 50-200 ft above principal streams. The deposit is generally 15-20 ft thick in the Highlands Ranch quadrangle, but may be more than 65 ft thick in the Parker quadrangle.

2) *Louviers Alluvium* (*Qlo*) (Pleistocene). Pebbly feldspar-and-quartz sand and silty clay, moderate-reddish-brown to moderate yellowish-brown; poorly sorted, bouldery gravel at the base forms slopes steeper than those above and below the gravel. Deposits commonly grade upward from gravel into sand, then into silt and clay. Terrace surfaces are 30-80 ft above principal streams. As much as 100 ft thick.

3) *Broadway Alluvium (Qb)* (Pleistocene). Tan to light-brown, generally well-stratified silt, sand, and gravel; abundant plant debris. Forms low terraces about 10-25 ft above modern streams. The deposits are generally small and on the west banks or on the bank of the stream on the inside of the curve. As much as 30 ft thick.

4) *Piney Creek Alluvium (Qp)* (Holocene). Light gray to light brown clay, silt, sand, and gravel; humic material common in upper part. Underlain by older gravelly alluvium or bedrock; transitional into colluvium on hillsides. Occupies valley floors; in some places forms low terraces adjacent to modern stream channels. Commonly 5-15 ft thick; locally as much as 30 ft thick.

5) *Post-Piney Creek alluvium (Qpp)* (Holocene). Light brown to tan silt, sand, and fine gravel; minor amounts of clay and plant material. Occurs in modern stream channels, on flood plains, and in modern alluvial fills. Thickness about 5-10 feet thick; locally as much as 20-30 ft thick.

Eolian Deposits

The eolian deposits consist of windblown sand and silt. The eolian sand is well-sorted, medium to fine-grained sand deposited by wind during warm, interglacial periods. The eolian silt, called loess, has a similar origin as the sand but the size of the grains is smaller. Occasionally, coarse sand is found mixed with the loess in this area.

The two main sources for the eolian deposits are the South Platte River and Cherry Creek (Hunt, 1954; Scott, 1963). Winds, predominantly from the southwest and later the northwest, stripped sand and finer particles from the floodplains and deposited them on the uplands to the east of these streams, covering older bedrock and alluvial deposits. These deposits are sandier near the stream valleys and fine eastward. The following is a more detailed description of the eolian deposits:

1) *Eolian Sand (Qes)* (Holocene and Pleistocene). Light-brown, fine sand and sandy silt deposited by wind. Commonly structureless, but may be cross-bedded in places. Occurs on upland surfaces. Thickness generally less than 10 ft thick; locally as much as 40 ft thick.

2) *Loess (Ql)* (Holocene and Pleistocene). Pale-brown to grayish-red fine eolian silt and clay, commonly mixed with fine sand. The upper 2-4 ft is commonly very clayey. Occurs on upland surfaces; exhibits columnar structure; slightly calcareous; hard when dry; slightly sticky when wet. Thickness as much as 15 ft thick; thickest deposits on moderate, northeastern-facing (lee) slopes.

Colluvial Deposits

The colluvial deposits are a mixture of materials derived from alluvium, eolian sand and loess, and bedrock. Colluvium is mapped extensively on the Highlands Ranch and Parker quadrangles, where the deposits are found on the tops and sides of hills. Other types of slope deposits are not mapped, such as landslides and debris fans, although they are known to exist within the study area. Site-specific studies should be done to evaluate slope creep, landslides, debris flows, and mass wasting. The colluvium is undifferentiated with regard to age and is mapped as a singular unit, described below:

Colluvium (Qco) (Holocene and Pleistocene). Brown to light brown sand, sandy silt, and clay. In places may contain pebbles, cobbles, and boulders. Found on steep to gentle slopes; generally transitional down slope into Piney Creek Alluvium. Generally less than 5 ft thick.

Artificial Fill

Artificial fill (*af*) is mapped at certain locations throughout the study area including dams, road embankments, and sanitary landfill cover areas. No fill areas are mapped on Plate 1 that are associated with earthwork for subdivisions.

METHODOLOGY

The project methodology involves using site-specific data from geotechnical engineering reports, and comparing this data with regional geology, geologic-hazards and soil data from published literature. This was done spatially, using Geographic Information Systems (GIS). The sources of data, engineering classifications and tests, relationships between engineering tests and soil behavior, and methods of data analysis are discussed in this section.

REGIONAL DATA

The regional geologic data consists of published geologic and soil maps. This includes a basic suite of geologic maps (Scott, 1962; Maberry and Lindvall, 1972, 1974, 1977; Trimble and Machette, 1979), an interpretive swelling-soil hazards map (Hart, 1974), and a suite of interpretive geologic-hazard maps (Soule, 1978). These maps generally relate to geologic units that are exposed at the ground surface. They are not particularly useful for investigating site-scale, subsurface geologic conditions that could affect engineered facilities. Drill-hole data were used in the making of some of the maps; however, the drill holes are few in number and their locations are not shown on the maps.

Regional soil data were obtained from the Natural Resources Conservation Service (NRCS) (1974; 1985) soil surveys for the study area. Soil surveys contain information that is useful in urban development and land use planning. The information contained in a soil survey can be used to identify limitations for each soil for specific land uses.

In examining the soil surveys within the study area, data were collected and engineering classification determinations about soil behavior were made about each mapped soil type. Engineering properties such as plasticity index, grain-size distribution and shrink-swell potential are listed for each soil type.

SITE-SPECIFIC DATA

In order to investigate geologic and soil conditions and associated hazards in north central Douglas County in detail, we found it necessary to augment the regional data with site-specific data. We compiled and analyzed geologic and engineering-properties data from pre-existing, public-record geotechnical reports for 185 subdivisions scattered across the study area. These reports, prepared by private geologic and engineering firms, were obtained from the Douglas County Building Department, the City of Parker Building Department, and the Colorado Geological Survey (CGS) archives. The data set consists of 4,906 samples from 4,206 test holes. Each test hole was located and digitized on a base map supplied by the Douglas County Geographic Information Systems Division.

A test hole database was created containing information listed in Table 2. These data include identification, location, elevation, groundwater, and geologic information. The depth data are based on information recorded in the reports or measured directly from test-hole logs. The Quaternary geologic unit and bedrock geologic unit at each test-hole location were identified using available geologic maps (i.e., those shown in Plate 1).

Table 2. Test hole database categories.

Symbol	Description
N-ID	Unique identification number that ties the test hole to a location on ARC/INFO
FILE/LOCATION	Identifies the subdivision and filing where the test hole is located
TITLE	Detailed information about the location
THN	Test hole number from the report; often this number is the block and lot number
TD	Total depth of the test hole (ft)
ELE_IN	Initial elevation of the test hole (ft); often associated with a relative benchmark
ELE-FI	Elevation after grade work has been finished (ft)
CUT/FILL	Thickness of soil cut or filled (ft)
D_BR_IN	Depth to bedrock prior to any grading (ft)
D_BR_FI	Final depth to bedrock after grading (ft)
ELE_BR	Elevation of bedrock (ft)
SUR_MAT	Quaternary geologic unit at test hole; from geologic maps
BR_MAT	Bedrock geologic unit at test hole; from geologic maps
NOTES	Any extraneous information related to the test hole data

Sample information from the test holes was recorded in a separate database (Table 3). This database contains data from engineering tests performed on the samples, along with information that ties the test hole and sample databases together. The engineering classifications and tests shown in Table 3 are described in more detail later in this section.

We looked at test holes from three types of geotechnical studies. One type comes from preliminary geotechnical studies that are conducted before a property is developed. These pre-development test holes are used to assess general geologic conditions across a broad area in support of site planning; they are typically few in number and widely spaced. The second type comes from lot-by-lot geotechnical studies that are conducted at the building-permit stage of development, following grading and other earthwork operations. These post-development test holes are used for site-specific design of house foundations; they are closely spaced and provide for a detailed assessment of local geologic conditions. The third type comes from geotechnical studies that are conducted for road-and-pavement design. These holes are typically shallow (5-10 feet deep), and are drilled within proposed roadways and/or parking lots.

We used all available preliminary test hole data to provide a broad coverage of the study area. Unfortunately, the available preliminary reports did not provide a uniform coverage across the developed portions of the study area. It was therefore necessary to include dense clusters of lot-by-lot test holes in a number of locations. This was done to augment the preliminary-report data, and to provide areas of more-detailed coverage within a number of representative geologic areas. It was not possible to incorporate all existing and available lot-by-lot test holes into the database because of time and funding constraints. Road-and-pavement test holes were used sparingly in areas where other geotechnical information was not readily available.

Table 3. Sample database categories.

Symbol	Description
N-ID	Unique identification number; locates the sample with regards to the test hole location on ARC/INFO
FILE	Subdivision and filing associated with the sample location
THN	Test hole number from which the sample originated
DEPTH	Depth from which the sample was taken (ft)
MC	Moisture content (%)
DD	Dry density (pcf)
LL	Liquid limit (%)
PL	Plastic limit (%)
PI	Plasticity index (%)
%FINES	Percent of clay- and silt-sized particles in the sample (%)
%S/C	Percent swell or consolidation from swell-consolidation test (%)
SUR	Surcharge at which swell-consolidation test was performed on the sample (ksf)

ENGINEERING CLASSIFICATIONS AND TESTS

This section contains descriptions of standard earth-material classification methods and engineering properties tests that are included in our sample database (Table 3). In general, geotechnical engineers and soil scientists use these classifications and tests to evaluate soil conditions as a basis for designing foundations, roads, and other public works. Also listed are the ASTM (American Society for Testing and Materials) standard procedures for each test.

Moisture Content

The moisture content is the ratio of the mass of water to the mass of soil solids for a given volume of soil, measured in percent. It is computed by comparing the mass of a soil sample in its field (natural) condition with its mass after oven drying in the laboratory. The moisture content is used in several calculations; for example, it is used to calculate the dry density and to evaluate the soil's compaction characteristics. (ASTM D2216-92)

Dry and Bulk Density

The dry density is the ratio of the mass of the solids to the total volume of the soil, measured in pounds per cubic feet (pcf). It is computed using other measured parameters (dry weight and volume), rather than by direct measurement. The dry density is closely related to the amount of void space (porosity) in a soil. Soils with high dry density values are more compact and, accordingly, they have a lower porosity than those having low dry density values. Loose soils have low dry density values and, accordingly, high porosity.

The Natural Resources Conservation Service uses a soil property called bulk density in soil surveys. Bulk density one-tenth bar or one-third bar is the oven-dried weight of the less than 2 mm soil materials per unit volume of soil at a water tension of 1/10 bar or 1/3 bar. Bulk density influences plant growth and engineering applications. It is used to convert measurements from a weight basis to a volume basis. Bulk density is used to calculate porosity. For non-expansive soils, the 1/10 –bar and 1/3-bar densities are the same. (430-VI-National Soil Survey Handbook, 2001)

Grain-Size Analysis
The purpose of this analysis is to quantify the relative abundance and distribution of different-sized soil particles in a sample. Typically, a grain-size distribution is measured by passing a sample through one or more sieves. Materials with greater than 50% passing the No. 200 sieve are classified as clay and silt (referred to as "fines"), and soils with less than 50% passing the No. 200 sieve are classified as sand and gravel. Typically, a soil will consist of a mixture of coarse and fine fractions. The fine fraction is of interest to engineers because those components may be prone to swell or collapse. For the purpose of this study, only the percent passing a No. 200 sieve ("percent fines") was recorded.

A *hydrometer* test is needed in order to analyze the relative abundance and distribution of clay versus silt-sized particles; however, this test is seldom performed for general engineering purposes. Grain-size analyses should be performed according to ASTM D422-63(90) for the general particle-size analysis of soil, and ASTM D1140-92 for soils finer than the No. 200 sieve where a hydrometer is used.

Swell-Consolidation Test
The swell-consolidation test is used to assess how a soil sample changes in volume under conditions of increased moisture and loading. There are three parts to this test. First, a sample is placed in the testing apparatus and an initial loading (surcharge load) is added, usually 500 psf or 1,000 psf. Second, the sample is saturated after it equilibrates to the surcharge. At this point, one of three reactions occurs: the sample volume remains constant (no change), the sample decreases in volume (consolidates), or the sample increases in volume (swells). The amount of volume change, expressed as a percentage, is known as the *swell potential* or the *settlement potential*, depending on the reaction. Third, if the sample swells, the loading pressure is further increased in increments to bring the sample back to its equilibrated, pre-saturated volume. This loading is called the *swell pressure*.

The swell-consolidation test is used extensively in the Front Range area as design criteria for foundations, roads, and concrete flatwork. The test is performed according to the one-dimensional swell or settlement potential for cohesive soils. (ASTM D4546)

Linear Extensibility Percent (LEP)
This is the test used to determine the soil limitations for shrink/swell used in Natural Resources Conservation Service (NRCS) soil surveys. Shrink-swell classes are based on the change in length of an unconfined clod as moisture content is decreased from a moist to dry state.

The coefficient of linear extensibility is measured directly as the change in clod dimension for moist to dry conditions. It is expressed as a percentage of the volume changes to the dry length:

$$\text{LEP} = \frac{\text{Moist Length} - \text{Dry Length}}{\text{Dry Length}} \times 100$$

(430-VI-National Soil Survey Handbook, 2001)

Atterberg Limits
Atterberg limits are a measure of the moisture contents at which a soil undergoes changes in its material properties. The *plastic limit (PL)* is the percent moisture content when the soil passes between a solid state and a plastic (deformable) state. The *liquid limit (LL)* (ASTM D4318) is the percent moisture content when the soil passes between a plastic state and a viscous-liquid state. The *plasticity index (PI)* is the difference between the liquid limit and the plastic limit.

Generally, the amount of clay- and silt-size particles, the organic matter, and the type of minerals determine the liquid limit. Soils that have a high liquid limit have the capacity to hold much water while retaining a plastic or semisolid state. Estimates of liquid limit are made on soils during soil survey investigations and mapping. The liquid limit is usually inferred from clay mineralogy and clay content. The plasticity index, when used with the liquid limit, indicates a measure of the plasticity of a soil. The plasticity chart, given in ASTM D 2487, is a plot of the liquid limit (LL) versus the plasticity index (PI) and is used in classifying soil in the Unified and AASHTO Soil Classification Systems. Soils that have a high plasticity index have a wide range of moisture content in which they behave as plastic materials. Moderately and highly plastic clays have high PI values.

Determination of Swelling Behavior

In general, certain engineering properties or a combination of properties may be used to predict a soil's behavior (in terms of swelling or collapse), as well as the expected magnitude of that behavior. The initial moisture content is closely related to the amount of swell potential for high-plasticity, expansive soils. In such soils, the lower the initial moisture content, the more the soil can be expected to swell (Chen 1988). There is evidence that shows moisture content below 15% allows for maximum swelling, and moisture content above 30% has a much lower volume change.

The plasticity index has been found to be a useful independent property to correlate with swell potential (Chen 1988; Snethen and others, 1977). Table 4 contains Chen's criteria for using measured plasticity index values to estimate a soil's swell potential. This relationship can be used where swell-test data are not available.

Table 4. Swell potential ratings based on plasticity index

Plasticity index (%)	Swell Potential Rating
0 – 15	Low
10 – 35	Medium
20 – 55	High
> 35	Very High

(source: Chen, 1988)

In the Denver Metropolitan Area, the results of swell-consolidation tests are commonly used to assess the swelling behavior of a soil. It is difficult to compare data from different locations, however, because the tests are often performed using different surcharge pressures. A rating system that relates swell potential with the two most commonly used surcharge pressures was developed by the Jefferson County Expansive Soils Task Force in 1994 (Table 5).

Table 5. Swell potential ratings based on swell-consolidation tests, Front Range, Colorado.

Test Surcharge Pressure (psf)	Swell Potential Rating and Swell (% total volume change)			
	Low	Moderate	High	Very High
500	0 – 3	3 – 5	5 – 8	> 8
1,000	0 – 2	2 – 4	4 – 6	> 6

(source: Jefferson County Expansive Soils Task Force, 1994)

Another rating system for estimating probable swell potential for expansive soils was developed by Chen (1988). This rating system uses a comparison of several different types of engineering-test criteria, as shown in Table 6. One criterion used in this system, the swell pressure, is an estimation of the uplift force exerted by the swelling soils onto a foundation, or concrete work. The swell pressure is independent of the surcharge load, initial moisture content, degree of saturation, and thickness of the stratum (Chen, 1988). Typically, the swell pressure of a material increases as dry density is increased.

Table 6. Swell potential ratings based on suite of soil mechanics tests

Percentage Passing No. 200 Sieve (%)	Liquid Limit (%)	Standard Penetration Resistance (blow/ft)	Probable Expansion (% total volume change)	Swelling Pressure (ksf)	Swell Potential Rating
< 30	< 30	< 30	< 1	1	Low
30 – 60	30 – 40	10 – 20	1 – 5	3 – 5	Medium
60 – 95	40 – 60	20 – 30	3 – 10	5 – 20	High
> 35	>60	> 30	> 10	> 20	Very High

(source: Chen, 1988)

Linear Extensibility Percent (LEP) is used by the Natural Resources Conservation Service to estimate the shrink/swell potential of soil. LEP is the linear expression of the volume difference of natural soil fabric at 1/3 bar or 1/10 bar water content and oven dryness. The volume change is reported as a percent change for the clod (Finstad, 2000). The shrink-swell classes based on LEP are listed in Table 7.

Table 7. Swell potential ratings based on linear extensibility percent.

LEP (%)	Swell Potential Rating
<3	Low
3-6	Moderate
6-9	High
>9	Very High

(Source: Finstad, 2000)

Determination of Collapse Behavior

The collapse or settling of soil can be just as destructive as swelling of soil. Soils with low dry density often have a greater tendency to undergo collapse, whereas soils with high dry density tend to swell. Dudley (1970) found that the dry density is a valuable criterion for recognizing soils with greater potential to collapse or consolidate. In general, dry density values have varied from 65 to 105 pcf (1.1 g/cm^3 to 1.7 g/cm^3) where collapse has occurred. Generally, soil with a dry density value greater than 110-pcf exhibit higher swell potential (Chen, 1988).

The Natural Resources Conservation Service (NRCS) soil surveys contain information regarding the strength of soils. Soil horizons with bulk densities less than those indicated in Table 8 have low strength and may be subject to collapse if wetted to field capacity or above without loading. Soil horizons with a low bulk density may require special foundation designs.

Another criterion for recognizing collapse potential is associated with critical clay content. Bull (1964) demonstrated that maximum collapse is shown to occur with a clay content of 12%, by mass, in debris flow deposits. Below 5% clay content, collapse is unlikely. Above 30% clay content, a soil will tend to swell instead of collapse. In between, there are many cases where the soil would swell under a small load and collapse under a large load (Dudley, 1970). Common types of deposits known to have a tendency to collapse are eolian (including loess and sand), colluvium, mudflow, alluvial, residual, and man-made fills.

Table 8. Soils Prone to Collapse Based on Soil Texture and Bulk Density.

Family Particle Size	Bulk Density (g cm^{-3})
Sandy	<1.60
Coarse-Loamy	<1.40
Fine-Loamy	<1.40
Coarse-Silty	<1.30
Fine-Silty	<1.40
Clayey	<1.10

(Source, National Soil Survey Handbook, 2001)

MAP INVESTIGATIONS

Map investigations were conducted to delineate areas of potentially swelling and potentially collapsible soils in the study area. This involved comparing data from regional geologic and soil maps with site-specific engineering-properties data from the GIS sample database. Plates 2-3 were prepared by plotting data for samples recovered from soil (surficial) and bedrock units with an engineering classification overlay derived from the NRCS soil surveys for the Castle Rock and Golden areas.

Because of the large number of data points plotted on plates 2-3, and the close proximity of many of the point clusters, it was not possible to plot data values for each test hole. Instead, the data were plotted using colored dots, each of which represents a particular range of data values that were segregated using a digital algorithm. The criteria that are used to delineate each data-range category are shown on the plate explanations.

Because there was insufficient test hole data to evaluate the entire study area, soil characteristics were taken from soil surveys and used to evaluate the engineering properties of surficial deposits. Soil surveys characterize the top five feet of a soil horizon. However, soil is formed in part by the weathering of parent materials and the engineering properties of soil are related to the parent material from which the soil formed.

The characteristics of soil are determined by several factors including the physical and mineralogical composition of the parent material. The engineering properties of each soil type are similar to the underlying surficial and bedrock deposits from which the soil formed and are useful in evaluating the behavior of soil and bedrock on a regional basis.

STATISTICAL INVESTIGATIONS

Statistical investigations were performed on sample data to further characterize the swelling or collapse behavior of each geologic unit. The samples were separated into stratigraphic geology groups based on the mapped surficial and bedrock units.

For the investigation of stratigraphic groups, each sample was assigned to a geologic unit in the digital database. If the sample is identified as a soil in its source engineering report, it is assigned to the mapped surficial-geologic unit for that location. If the sample is bedrock, it is assigned to the mapped or interpolated bedrock-geologic unit for that location.

Basic statistics were computed and tabulated for each geologic unit after assigning and grouping the samples. The statistical data includes the range (highest and lowest data values) and certain quartile or percentile values (25%, 50%, and 75%) for different engineering test results. Quartiles are often used to divide data into groups. For example, the data file for the first quartile is 25^{th} percentile and the median value is the 50^{th} percentile. The data were then interpreted in terms of anticipated engineering behavior.

MAP INVESTIGATION RESULTS

GEOLOGIC MAP

Plate 1 contains a geologic map for the study area derived from USGS geologic maps. The map shows the occurrence of bedrock and surficial units at the ground surface. For descriptions of these geologic units, see the "Geology" section of this report.

Relatively young alluvial deposits make up the modern floodplains of the South Platte River, Plum Creek, and Cherry Creek along the eastern and western edges of the study area. These deposits include the Broadway Alluvium, the Piney Creek Alluvium, and the post-Piney Creek alluvium (which contains present-day floodplain deposits).

The upland plains that make up most of the study area contain a host of bedrock and surficial deposits. The predominant bedrock unit is the Dawson Formation and its component facies. The Denver Formation occurs in a few areas, most notably near the intersection of Broadway and Highlands Ranch Boulevard in the northwestern part of the study area. The surficial deposits may be divided into those found along the bottom of tributary stream valleys and those found in intertributary upland areas. The valley bottom surficial deposits include the Broadway Alluvium, the Piney Creek Alluvium, and the post-Piney Creek alluvium. The upland surficial deposits include eolian sand, loess (i.e., eolian silt), colluvium, and several older alluvial-terrace units, the Slocum Alluvium and Louviers Alluvium. Unconsolidated sand deposits dominate the eolian-sand upland plains adjacent to and east of Plum Creek and Cherry Creek. Minor, ribbon-like deposits of Piney Creek Alluvium are mapped along the valleys of tributary streams that cross these sand plains.

The bluff and plateau area in the south-central part of the study area contains mostly Dawson Formation and Castle Rock Conglomerate bedrock. A tongue of the Denver Formation is mapped along the base of the Bluffs in several areas. An isolated deposit of loess is mapped on top of the plateau in the central part of the study area generally east of I-25, west of Parker Road and south of Lincoln Avenue.

COLLAPSIBLE SOILS MAP

Plate 2 contains a map of surficial soils that may be prone to collapse or excessive settlement, as derived from bulk density data from NRCS soil surveys. Soil types with bulk densities less than indicated in Table 8 may be of low strength and may be subject to collapse or significant settlement upon wetting and/or loading.

In general, soil types that have low bulk densities also had similar values for plasticity and the soil fraction passing the #200 sieve (% fines). Plasticity index values of soils, with low bulk densities, generally ranged from NP to 15 with the majority of values in the low to non-plastic range. The amount of fines tended to be 30 percent or less passing the #200 sieve.

Site-specific plasticity index data from the test hole database is also shown on the map as data points. The site-specific plasticity index data tended to correlate with the soil information obtained from soil surveys. Areas identified by the soil survey as being "prone to collapse" due to low bulk densities also tended to have a plasticity index of low to non-plastic.

EXPANSIVE SOILS MAP

Plate 3 contains a map of surficial soils and bedrock that may be prone to expansion and heaving. The mapped soil types and data plots show different categories of swell potentials of the surficial deposits.

The polygon swell potential data were derived from engineering index properties included in NRCS soil surveys for the study area. The swell potential ratings are based on linear extensibility percent as shown in Table 7.

The data points are from the test hole database. Swell-consolidation testing was used to determine the swell potential of each data point as shown in Table 5.

STATISTICAL INVESTIGATION RESULTS

Combining the engineering properties and the geological unit helps to distinguish areas that may have similar soil behavior. The behavior of a number of geological units is erratic, while others are uniform. In this section we will separate the surficial geological units into the following groups: alluvial, eolian, and colluvial deposits, and weathered and unweathered bedrock. The bedrock units are further subdivided to distinguish between respective facies of the Dawson and Denver Formations.

ALLUVIAL DEPOSITS

The engineering properties of the different aged alluvial material are similar, with only a few variations (Table 9). The median dry density for the following geological units are: combined Piney Creek and post-Piney Creek Alluvium (Qp and Qpp), 104 pcf; Broadway Alluvium (Qb), 89 pcf; Louviers Alluvium (Qlu), 109 pcf; and Slocum Alluvium (Qsl and Qsu), 105 pcf.

The Atterberg limits are moderate for all of the different alluvial units. The median liquid limits are below 40 percent and the median plastic indices are greater than 20 percent. However, there is a wide spread of liquid limit values that range from 77 to 17 percent and the plastic indices that range from 2 to 54 percent.

The percent passing the #200 sieve increased as the alluvial units increased in age. For the combined Piney Creek and post-Piney Creek Alluvium, the median was 47 percent; Broadway Alluvium, 60 percent; Louviers Alluvium, 64 percent; and the Slocum Alluvium, 71 percent.

The Broadway Alluvium has the highest collapse potential of all the alluvium. It has a relatively low dry density and low initial moisture content. This may increase its potential to collapse with an increase in load or moisture content. The collapse potential of the Broadway Alluvium is followed by that of the combined Piney Creek and post-Piney Creek Alluvium.

The Slocum Alluvium has the highest swell potential. This rating is based on the plasticity index, liquid limit, and swell-consolidation tests (from Tables 5 and 6).

Insufficient data were available to completely evaluate the Louviers Alluvium.

Table 9. Swell/collapse potential ratings of alluvial deposits based on criteria from Tables 4–8.

Geologic Unit:	**Qp; Qpp—Piney Creek and Post-Piney Creek Alluvium**						
Total No. of Samples:	**376**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	53	-2.0	8.6	-0.5	0.6	3.5	Low-Low-Mod/**Low-Low-Low**
Swell under 1.0 ksf load (%)	71	-5.7	10.5	0.4	1.3	4.1	Low-Low-Mod/**Low-Low-Low**
Dry Density (pcf)	326	65.7	126.5	95.3	104.0	110.7	**Intermed-Intermed-Dense**
Liquid Limit (%)	4/60 NP	17.0	77.0	27.7	38.5	49.6	Low-Med-High
Plasticity index (%)	9/60 NP	2.0	54.0	13.7	21.0	30.1	Low to Med-Med to High-Med to High
Passing 200 sieve (% fines)	89	3.0	98.0	18.2	47.0	79.5	Low-Med-High/**Med-Low-Low**

Notation: "4/60 NP" means that there are 60 samples, 4 of which are non-plastic (NP)
Collapse potential interpretations are shown in **bold** type

Table 9. (continued)

Geologic Unit: Qb—Broadway Alluvium (soil) Total No. of Samples: 119							
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	5	-2.4	4.1	-	0.4	-	Low/**Low**
Swell under 1.0 ksf load (%)	1	-	-	-	6.7	-	V.High/**Low**
Dry Density (pcf)	111	69.6	123.3	81.5	88.8	97.7	**Loose-Intermed-Dense**
Liquid Limit (%)	6/30 NP	19.0	54.0	29.5	33.5	43.5	Low-Med-High
Plasticity index (%)	8/30 NP	1.0	32.0	12.9	19.0	24.3	Low to Med-Med to High-Med to High
Passing 200 sieve (% fines)	46	10.4	96.5	25.5	59.7	83.6	Low-Med-High/**Med-Low-Low**

Geologic Unit: Qlo—Louviers Alluvium (soil) Total No. of Samples: 18							
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 1.0 ksf load (%)	1	-	-	-	0.6	-	Low/**Low**
Dry Density (pcf)	15	85.8	122.6	101.3	108.8	112.4	**Intermed-Intermed-Dense**
Liquid Limit (%)	5	36.0	46.0	15.0	36.0	37.9	Low-Med-Med
Plasticity index (%)	5	13.0	22.0	13.6	19.0	19.5	Low to Med-Med-Med
Passing 200 sieve (% fines)	7	8.7	85.2	15.9	64.0	74.0	Low-High-High/**Med-Low-Low**

Geologic Unit: Qs—Slocum Alluvium (soil) Total No. of Samples: 97							
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	13	0.4	6.3	1.0	2.4	3.8	Low-Low-Mod/**Low-Low-Low**
Swell under 1.0 ksf load (%)	29	-1.4	8.0	0.8	2.2	3.5	Low-Mod-Mod
Dry Density (pcf)	80	83.0	130.5	100.2	105.3	110.0	**Intermed-Intermed-Intermed**
Liquid Limit (%)	21	30.0	57.0	40.7	49.0	52.3	Med-Med-High
Plasticity index (%)	21	9.0	39.0	17.7	27.0	33.0	Med-Med to High-Med to High
Passing 200 sieve (% fines)	27	6.0	97.0	43.3	71.0	82.3	Med-High-High/**Low-Low-Low**

EOLIAN DEPOSITS

The eolian sand and loess (Qes and Ql) have a wide range of variability. The median value for dry density of both the sand and the loess is around 106 pcf. However, they differ greatly in their characteristic of percent passing the #200 sieve. The sands have a median value of 23 percent passing and the loess 68.2 percent passing.

Although Atterberg limits from plastic samples are similar, the most important fact is that from 157 samples of eolian sand, 101 tested as non-plastic. Three samples out of 78 tested non-plastic for the loess. The median liquid limit for 56 samples of sand and loess was 41 percent and the median plasticity index was around 25 percent.

In some places on the western side of the study area, the loess and sand deposits interfinger. Site-specific sampling and testing may show evidence of the presence of loess in areas mapped as eolian sand.

The sand and loess have both the potential to swell and collapse in various degrees. Values from the swell-consolidation test range from below (-)11 percent consolidation to greater than 13 percent swell. Table 10 shows the relative ratings for the windblown materials.

Table 10. Swell/collapse potential ratings of eolian deposits based on criteria from Tables 4-8.

Geologic Unit:	**Ql—Loess (soil)**						
Total No. of Samples:	**568**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	186	-4.2	11.1	0.5	2.1	4.3	Low-Mod-Mod
Swell under 1.0 ksf load (%)	257	-11.1	24.0	0.0	1.5	3.5	Low-Low-Mod
Dry Density (pcf)	543	72.0	132.4	98.9	106.3	113.2	**Intermed-Intermed-Dense**
Liquid Limit (%)	2/77 NP	23.0	62.0	37.0	41.0	46.0	Med-Med-High
Plasticity index (%)	3/77 NP	NP	39.0	20.0	24.0	28.0	Med to High-Med to High-Med to High
Passing 200 sieve (% fines)	95	5.0	99.0	50.9	68.2	77.7	Med-High-High/**Low, Low, Low**

Geologic Unit:	**Qes—Eolian sand (soil)**						
Total No. of Samples:	**1115**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	636	-8.0	12.9	-0.9	-0.1	2.0	Low- Low-Low/**Low-Low-Low**
Swell under 1.0 ksf load (%)	172	-11.2	8.0	-0.7	0.8	2.5	Low- Low-Low/**Low-Low-Low**
Dry Density (pcf)	896	70.0	130.0	101.1	107.0	114.1	**Intermed-Intermed-Dense**
Liquid Limit (%)	101/157 NP	15.0	57.0	30.2	41.0	46.0	Med-Med-Med
Plasticity index (%)	101/157 NP	0.0	39.0	14.2	25.0	29.2	Low to Med-Med to High-Med to High
Passing 200 sieve (% fines)	185	8.0	99.0	15.1	23.0	54.2	Low-Low-Med/**Med-Med-Low**

COLLUVIAL DEPOSITS

The properties of the colluvial material, similar to the other surficial deposits, are variable. The median values of its engineering properties are: dry density, 106.5 pcf; liquid limit, 43 percent; plasticity index, 27.5 percent; passing 200 sieve, 44 percent; and swell, 1.1 percent. Table 11 shows the relative ratings for the colluvial deposits.

WEATHERED BEDROCK

These facies were classified as overburden or surficial soils in the geotechnical reports where they are found at the surface. Their properties vary, but can be grouped according to the facies, for example, Tds is a sand facies whereas Tdo is a clay facies. Their engineering properties are similar to their counterparts classified as bedrock except for swell potential. The swell potential values are 1-3 percent lower than the (unweathered) bedrock. This may be due to a repeated cycle of wetting and drying. Chen (1988) has shown that after repeated cycles of wetting and drying, soil materials reach fatigue where they do not have an extreme volume change. This is not to say that the weathered bedrock material is stable, rather, it is very similar to unweathered bedrock in terms of swelling potential. The data are shown in Table 12.

Table 11. Swell/collapse potential ratings of colluvial deposits based on criteria from Tables 4–8.

Geologic Unit:	**Qco—Colluvium (soil)**						
Total No. of Samples:	**116**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	17	0.0	7.2	1.0	2.0	5.0	Low-Low-Mod/**Low-Low-Low**
Swell under 1.0 ksf load (%)	56	-1.9	8.6	0.1	1.1	2.6	Low-Low-Mod/**Low-Low-Low**
Dry Density (pcf)	104	80.0	123.0	97.8	106.5	112.0	**Intermed-Intermed-Dense**
Liquid Limit (%)	2/14 NP	35.0	53.0	37.7	43.0	47.6	Med-High-High
Plasticity index (%)	2/14 NP	17.0	36.0	23.3	27.5	29.3	Med to High-Med to High-Med to High
Passing 200 sieve (% fines)	21	6.0	82.4	26.1	44.0	59.0	Low-Med-Med/**Med-Low-Low**

Table 12. Swell/collapse potential ratings of weathered bedrock facies based on criteria from Tables 4–8.

Geologic Unit:	**Tkda—Dawson Formation, arkosic facies (soil)**						
Total No. of Samples:	**318**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	164	-4.6	9.5	-0.5	0.6	2.3	Low-Low-Low/**Low-Low-Low**
Swell under 1.0 ksf load (%)	112	-5.4	9.0	-0.1	0.8	2.2	Low-Low-Mod/**Low-Low-Low**
Dry Density (pcf)	308	77.3	129.0	103.8	109.0	115.0	**Intermed-Intermed-Dense**
Liquid Limit (%)	31	19.0	61.0	32.8	45.0	48.9	Med-High-High
Plasticity index (%)	31	4.0	43.0	19.1	27.0	31.5	Med-Med to High-Med to High
Passing 200 sieve (% fines)	41	17.0	89.0	39.9	54.0	71.8	Med-Med-High/**Low-Low-Low**

Geologic Unit:	**Tkde—Denver Formation, undifferentiated (soil)**						
Total No. of Samples:	**21**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	10	-0.5	4.8	0.0	0.9	3.9	Low-Low-Mod/**Low-Low-Low**
Dry Density (pcf)	19	82.0	123.0	95.2	103.0	108.5	**Intermed**
Liquid Limit (%)	3	24.0	48.0	-	35.0	-	Med
Plasticity index (%)	3	12.0	27.0	-	15.0	-	Low to Med
Passing 200 sieve (% fines)	4	21.0	68.0	21.0	55.0	62.1	Low-Med-High/**Med-Low-Low**

Table 12. (continued)

Geologic Unit:	**Tkdo—Dawson Formation, claystone facies (soil)**						
Total No. of Samples:	**65**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	3	-0.4	3.4	-	0.2	-	Low/**Low**
Swell under 1.0 ksf load (%)	38	-5.1	8.0	-0.2	1.1	3.2	Low-Low--Mod/**Low-Low-Low**
Dry Density (pcf)	63	78.0	124.0	99.1	106.0	111.9	**Intermed-Intermed-Dense**
Liquid Limit (%)	10	25.0	55.0	30.6	43.5	51.9	Med-High-High
Plasticity index (%)	10	9.0	36.0	14.9	26.5	31.0	Low to Med-Med to High-Med to High
Passing 200 sieve (% fines)	17	8.0	86.0	28.0	37.0	75.0	Low-Med-High/Mod-Low-Low

Geologic Unit:	**TKds—Dawson Formation, sandstone facies (soil)**						
Total No. of Samples:	**10**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	3	-0.3	1.6	-	-0.2	-	Low/**Low**
Swell under 1.0 ksf load (%)	3	0.4	8.0	-	0.8	-	Low/**Low**
Dry Density (pcf)	8	95.0	112.5	103.8	107.1	110.0	**Intermed-Intermed-Intermed**
Liquid Limit (%)	3	34.0	42.0	-	39.0	-	Med
Plasticity index (%)	3	13.0	23.0	-	19.0	-	Med
Passing 200 sieve (% fines)	3	8.0	69.0	8.0	55.0	61.4	Low-Med-High**/Mod-Low-Low**

Geologic Unit:	**Tkdso—Dawson Formation, interbedded sandstone and claystone facies (soil)**						
Total No. of Samples:	**71**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	13	0.6	6.6	1.1	2.6	4.0	Low-Low-Mod/**Low-Low-Low**
Swell under 1.0 ksf load (%)	26	-8.0	6.1	0.6	3.2	4.6	Low-Mod-High/**Low-Low-Low**
Dry Density (pcf)	64	81.5	123.6	103.4	109.0	113.1	**Intermed-Intermed-Dense**
Liquid Limit (%)	11	30.0	51.0	34.9	39.0	47.7	Med-Med-High
Plasticity index (%)	11	9.0	33.0	17.6	22.0	28.9	Low to Med-Med to High-Med to High
Passing 200 sieve (% fines)	20	11.0	88.0	30.3	61.5	80.0	Med-High-High/**Low-Low-Low**

BEDROCK

The different bedrock facies have some characteristic properties. The Arkosic facies of the Dawson Formation (Tda) is quite variable. It ranges from relatively stable bedrock to extremely expansive and problematic. The sandy facies (Tds) is relatively stable, but still has an ability to be highly expansive. Limited data were obtained for the clay facies (Tdo) that occurs sporadically within the study area and is interbedded with Tds and Tdso. However, the limited data indicate that the clay facies can be highly expansive. The conglomerate facies (Tdc) is found in the southern central part of the study area near and in the bluffs. The topography of this area precludes high-density subdivisions; however, slope movement in this facies should be a concern. Insufficient data were available to evaluate the Tdv facies. Table 13 contains the relative ratings for the bedrock facies.

Table 13. Swell/collapse potential ratings of bedrock facies based on criteria from Tables 4–8.

Geologic Unit:	**TKds—Dawson Formation, sandstone facies (bedrock)**						
Total No. of Samples:	**7**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 1.0 ksf load (%)	2	1.5	2.0	-	1.8	-	Low/**Low**
Dry Density (pcf)	6	97.0	111.0	-	101.0	-	**Intermed**
Passing 200 sieve (% fines)	1	-	-	-	38.0	-	Med/**Low**

Geologic Unit:	**Tkda—Dawson Formation, arkosic facies (bedrock)**						
Total No. of Samples:	**1092**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	203	-4.5	15.3	0.0	2.0	4.7	Low-Low-Mod/**Low-Low-Low**
Swell under 1.0 ksf load (%)	342	-4.9	11.7	1.2	2.5	4.1	Low-Mod-High/**Low-Low-Low**
Dry Density (pcf)	968	74.0	133.0	101.2	107.0	112.2	**Intermed-Intermed-Dense**
Liquid Limit (%)	17/166 NP	0.0	84.6	32.1	44.0	55.8	Med-High-High
Plasticity index (%)	18/166 NP	0.0	56.0	9.2	24.0	36.0	Low-Med to High-Med to High
Passing 200 sieve (% fines)	258	5.0	100.0	13.9	29.0	65.0	Low-Low-High/**Mod-Mod-Low**

Geologic Unit:	**TKde -- Denver Formation Undifferentiated (bedrock)**						
Total No. of Samples:	**25**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	5	1.3	18.0	0.5	2.7	5.4	Low-Low-High/**Low-Low-Low**
Swell under 1.0 ksf load (%)	5	2.3	6.2	0.8	1.7	2.4	Low-Low-Mod/**Low-Low-Low**
Dry Density (pcf)	21	78.0	124.0	85.8	95.0	107.0	**Loose-Intermed-Intermed**
Liquid Limit (%)	5	32.5	65.0	-	59.0	-	High
Plasticity index (%)	5	13.0	43.0	-	36.0	-	Med to High
Passing 200 sieve (% fines)	5	34.0	97.0	-	95.0	-	V.High/**Low**

Geologic Unit:	**Tkdes—Denver Formation, sandstone facies (bedrock)**						
Total No. of Samples:	**7**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	5	0.0	5.6	-	2.2	-	Low/**Low**
Dry Density (pcf)	5	93.0	113.0	-	108.0	-	**Intermed**
Liquid Limit (%)	2	34.0	52.0	-	43.0	-	Med to High
Plasticity index (%)	2	13.0	33.0	-	23.0	-	Med-High
Passing 200 sieve (% fines)	2	47.0	96.0	-	71.5	-	High/**Low**

Table 13. (continued)

Geologic Unit:	**Tkdo—Dawson Formation, claystone facies (bedrock)**						
Total No. of Samples:	**125**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 1.0 ksf load (%)	73	-0.8	7.1	1.0	2.0	3.3	Low-Low-Mod/**Low-Low-Low**
Dry Density (pcf)	124	66.0	120.0	98.0	104.0	109.1	**Intermed**
Liquid Limit (%)	7	43.0	122.0	44.8	50.0	59.2	High-High-High
Plasticity index (%)	7	16.0	83.0	29.3	30.0	35.8	Med to High-Med to High-Med to High
Passing 200 sieve (% fines)	24	7.0	100.0	17.2	28.0	42.9	Low-Low-Med/**Med-Med-Low**

Geologic Unit:	**Tkdso—Dawson Formation, interbedded sandstone and claystone facies (bedrock)**						
Total No. of Samples:	**136**						
Test	*Samples*	*Low*	*High*	*25%*	*50%*	*75%*	*Interpretation for Swell/**Collapse** Potential for each quartile*
Swell under 0.5-ksf load (%)	7	-0.5	8.4	2.8	5.7	6.8	Low-High-High/**Low-Low-Low**
Swell under 1.0 ksf load (%)	68	-2.6	10.5	2.2	3.7	5.3	Mod-Mod-High/**Low-Low-Low**
Dry Density (pcf)	126	71.3	122.0	104.1	109.0	113.3	**Intermed-Intermed-Dense**
Liquid Limit (%)	10	36.0	72.0	46.4	49.5	58.1	High-High-High
Plasticity index (%)	10	12.0	51.0	30.3	32.5	37.7	Med to High-Med to High-Med to High
Passing 200 sieve (% fines)	23	10.0	99.9	17.5	44.1	85.6	Low-Med-High/**Mod-Low-Low**

DISCUSSION OF RESULTS

"It is my personal experience that engineering descriptions alone do not permit a sufficiently rational classification of subsurface materials for the design and construction of many engineering works in even the best known urban areas. Only if the data are organized on the basis of stratigraphic units does the mass of engineering test data become meaningful."

(Peck, 1968)

GEOLOGIC HAZARDS

Collapsible Soil

Generally, windblown deposits of loess and eolian sand have the greatest potential for collapse or excessive settlement based upon swell/consolidation testing (Plate 2). A significant portion of the test data indicates that these surficial deposits generally have a low plasticity. This correlates with soil types identified in the soil surveys as being of low strength and prone to collapse. However, median values for swell-consolidation testing and dry density show that areas underlain by loess and eolian sands can be stable. In terms of low dry density values, the Broadway alluvium (Qb) poses the greatest risk of collapsible soils.

Expansive Soil and Bedrock

Claystone and interbedded sandstone and claystone facies pose the greatest risk of expansive bedrock. The bedrock units/facies have a slightly higher risk than corresponding weathered bedrock units/facies. The windblown surficial deposits of loess and eolian sand appear to have the lowest potential for expansive soils. Nevertheless, as outlined in the statistical investigations, nearly all surficial deposits and bedrock present within the study area appear to contain highly expansive clays that can cause structural damage (Plate 3).

Dipping Bedrock

Dipping bedrock is found in the northwest and west-central parts of Douglas County, several miles away from the presently considered study area. Accordingly, this study does not address construction-related problems that occur in dipping bedrock. For a report on heaving-bedrock hazards associated with dipping bedrock in other areas of Douglas County, we refer interested readers to see CGS Special Publication 42 (Noe and Dodson, 1998).

Potentially Unstable Slopes

Local slope instability and landsliding is possible in the vicinity of the Bluffs, especially where clay-rich facies from the Dawson and Denver Formations are exposed, and along the banks of incised stream valleys. This report does not map potentially unstable slopes and landslides and it is important that detailed site-specific investigations be done in areas that may be prone to slope instability.

POTENTIAL SOURCES OF ERROR

The information contained in a soil survey has limitations. The data generally apply only to that part of the soil within a depth of 5 to 6 feet. The information contained in a soil survey is not site-specific and does not eliminate the need for onsite geologic and soil investigations.

Test-hole locations are typically only roughly located on a small-scale map for each subdivision. It is not possible to accurately depict the location of test holes using the information from geotechnical reports.

The test-hole data in this report came from many different engineering firms with different quality control and testing practices. It is reasonable to assume that the database contains errors or differences in sample identification, location, preparation, testing, and classification.

The data presented in this report are useful in describing the general behavior of soils and geologic units within the study area for general land use or master planning purposes. As with any regional-scale mapping project, the data and results should not be used for large-scale, site-specific planning. A site-specific geologic and geotechnical investigation should be done for each individual site or project.

RECOMMENDATIONS FOR LAND USE

Site Investigation Considerations

The study shows that generalizations can be made about the engineering properties of specific soil types and bedrock units. It also appears that the engineering properties within each soil type and bedrock unit can vary significantly. For example, the Piney Creek (Qp) and Post Piney Creek (Qpp) Alluvium swell-consolidation test data shows the potential for swell as high as 10.5 percent and for consolidation of as much as (-) 5.7%. This indicates the portions of the alluvium may be prone to significant collapse and other portions may be prone to significant swelling.

It is important that adequate geologic and geotechnical testing be done to accurately characterize conditions across a site. Engineering properties can vary significantly within a few feet and can affect the uses of a property. Without adequate geologic and geotechnical information, it is difficult to determine appropriate land uses and/or mitigation measures.

For a preliminary plan, it is important that enough testing be done to accurately characterize site conditions for planning purposes. Facing similar geologic and soil conditions, Jefferson County adopted standards for what should be included in a geologic and geotechnical report (Jefferson County Land Development Regulation, 2001). The standards outline geotechnical test methods and testing frequency and are considered the standard of practice in the Denver Metro area. It may be prudent for local governments within Douglas County to consider adopting standards similar to those of Jefferson County.

Individual Lot or Building Site Considerations

A preliminary geologic and geotechnical report is used to determine appropriate land uses and proposed mitigation measures. The test-hole data show that the engineering properties of soil horizons and bedrock unit can vary significantly within a few feet both vertically and horizontally. Additional geologic and geotechnical information are necessary for each individual lot or building site in order to determine pavement, foundation, and floor designs.

Soil testing, including a test boring, should be done within the footprint of each building or lot. In order to determine appropriate designs, it is important that the engineering properties be determined at or near pavement, foundation, and floor levels. For each lot or building site, swell-consolidation testing should be done near or at pavement, floor and foundations levels. A site-specific geotechnical report, including a test boring and swell-consolidation testing, should be done for each lot or building site before issuance of building permits.

Design and Construction Considerations

Adequate surface and ground water drainage systems can help to reduce damage from swelling and collapsible soils by removing excess water. Most geotechnical engineers recommend that perimeter drains be installed near the base of foundations and sloped to a gravity outlet (daylight point), sump or connected to an area drain. An area drain system is typically located beneath the sanitary sewer or at the lowest point in a development and helps to lower ground water levels throughout a development. An area drain system not only protects individual buildings it helps to protect roads, utilities, and other improvements.

Area drains have been used extensively throughout the Highlands Ranch development. In order for these systems to work, they must be designed, installed, and maintained properly. Area drains must have adequate cleanouts, continuous bedding and positive drainage, and gravity discharge points.

Many of the swelling-soil lawsuits filed within the study area have focused on damage to floors in residential homes. The primary types of floor used in the area are floating slab and structural floors. Floating slab floors are the oldest type of flooring designed for swelling soils. Floating slab floors perform well for soils that have a low swell potential. Structural floor systems are isolated from the soil surface and are normally used for soils that have a moderate to high swell potential. In areas with such soils, many geotechnical engineers will recommend that structural floors be used but allow the builder to choose whether a floating slab or structural floor will be installed.

Due to the high variability in soil and bedrock behavior within the study area, designs of foundations and floor systems should be based upon conservative swell-consolidation testing for each lot within a subdivision.

Inspection Considerations

In areas prone to swelling or collapse, it is important that foundations, floors, and other mitigation measures be properly installed. For example, one subdivision in Jefferson County constructed on expansive bedrock experienced foundation damage rates of 40 percent. In each of the damaged homes, it was documented that design and/or quality control problems contributed to foundation damage. There are also many examples or perimeter drains that were constructed without positive drainage or gravity discharge points, or were connected to the sanitary sewer rather than the area drain system as designed.

All elements of subdivision and individual building construction should be inspected and the inspections should be documented. If local building and public works departments cannot adequately inspect all elements of construction, it may be prudent to require as-built engineering certifications. Local governments should establish standards for these certifications.

CONCLUSIONS

1) The north-central part of Douglas County is underlain by soil, surficial deposits and bedrock that can be highly expansive or prone to collapse or excessive settlement, resulting in damage to pavements, homes, utilities, and other structures. Generally, windblown deposits such as loess and eolian sand have the greatest collapse potential. Surficial deposits and bedrock units containing or derived from claystone or interbedded claystone can contain highly swelling clays that can cause extensive damage.

2) Soil and bedrock characteristics within the study are highly variable both laterally and vertically. Engineering properties can vary within a few feet. Because of this variability, it is important that adequate geologic and geotechnical investigations be done at all stages of the planning and construction process. Site-specific geotechnical testing, including a test boring, should be done for each lot. Swell-consolidation testing should be done at pavement, foundation, and floor levels for each lot or building site.

3) Natural Resources Conservation Service soil surveys were found to be useful for evaluating the behavior of soil and bedrock, especially for regional-scale analyses when limited field data is available. Derivative soil survey maps, such as those generated for this project, are useful tools for master planning.

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COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE REPORT 02-8
SOIL AND BEDROCK CONDITIONS AND CONSTRUCTION CONSIDERATIONS
NORTH-CENTRAL DOUGLAS COUNTY, COLORADO
PLATE 1: GEOLOGIC MAP
2002

Digital map prepared by Karen Morgan

Street data modified from Douglas County

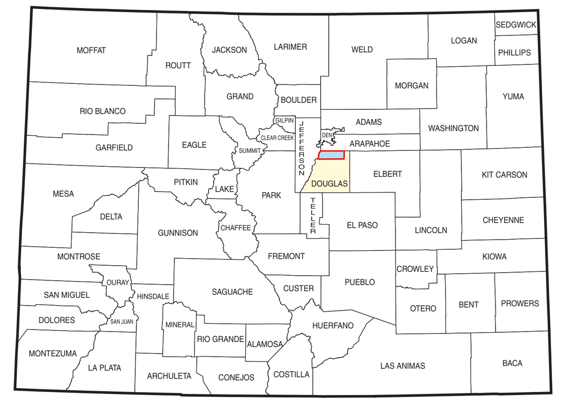
Township/Range/Section data from Tobin Land Grid

Stream data from Colorado Division of Water Resources

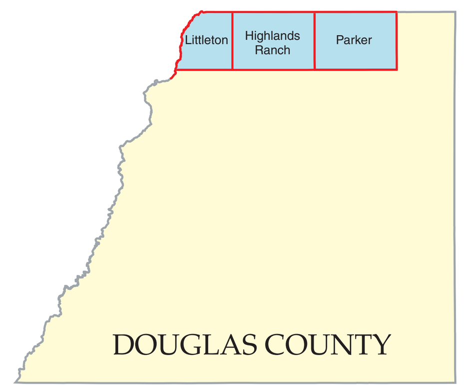
Water body data from ESRI

Universal Transverse Mercator projection,
1927 North American Datum

COLORADO INDEX MAP



QUADRANGLE
INDEX MAP



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SCALE 1:24,000

1 0.5 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 0.5 0 1 KILOMETER

CONTOUR INTERVAL 10 FEET

GEOLOGIC MAP OF NORTH-CENTRAL DOUGLAS COUNTY, COLORADO

By Karen A. Berry, David C. Noe, and Monica C. Pavlik

2002

Street

Township/Range

Section

Stream

Water body

MAP UNITS

(After Scott, 1962; Mayberry and Lindvall, 1972, 1974 and 1977; and Trimble and Machette, 1979)
Descriptions can be found in accompanying report booklet

Surficial Units (Quaternary)

- af — Artificial fill
- Qpp — Post-Piney Creek Alluvium
- Qp — Piney Creek Alluvium
- Qb — Broadway Alluvium
- Qlo — Louvirs Alluvium
- Qs — Slocum Alluvium
- Qv — Verdos Alluvium (not studied)
- Qes — Eolian sand
- Ql — Loess
- Qco — Colluvium

Bedrock Units (Cretaceous and Tertiary)

- Tcr — Castle Rock Conglomerate
- TKdes — Denver Formation, sandstone facies
- TKdec — Denver Formation, claystone facies
- TKde — Denver Formation, undifferentiated
- TKda — Dawson Formation, arkosic sandstone facies
- TKdc — Dawson Formation, conglomerate facies
- TKds — Dawson Formtion, sandstone facies
- TKdo — Dawson Formation, claystone facies
- TKdv — Dawson Formation, variegated claystone facies
- TKdso — Dawson Formation, interbedded sandstone-claystone

HOW TO USE THIS MAP

This map shows the geology in north-central Douglas County, Colorado. The accompanying report describes these map units and how they were derived. The map has been compiled from a variety of sources, and is intended as a general guide to show where certain geologic bedrock formations and surficial deposits may exist. However, the site-specific geology at any location may exhibit small-scale variations that are not shown at this map scale. This map is not a substitute for professionally prepared, site-specific geologic-hazard studies and designs.

COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
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DENVER, COLORADO

OPEN-FILE REPORT 02-8
SOIL AND BEDROCK CONDITIONS AND CONSTRUCTION CONSIDERATIONS
NORTH-CENTRAL DOUGLAS COUNTY, COLORADO
PLATE 2: COLLAPSIBLE SOILS MAP
2002

Digital map prepared by Karen Morgan

Street data modified from Douglas County

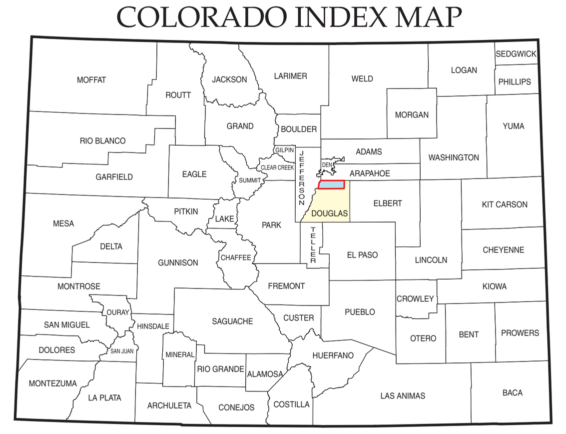
Township/Range/Section data from Tobin Land Grid

Stream data from Colorado Division of Water Resources

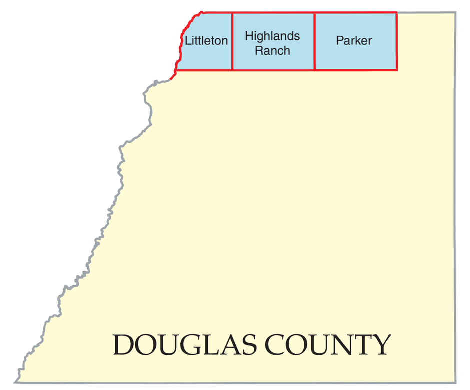
Water body data from ESRI

Universal Transverse Mercator projection,
1927 North American Datum

COLORADO INDEX MAP



QUADRANGLE
INDEX MAP



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SCALE 1:24,000

CONTOUR INTERVAL 10 FEET

MAP UNITS

Descriptions can be found in accompanying booklet

- Street
- Township/Range
- Section
- Stream
- Water body

Plasticity Index*

- Non-Plastic (0%)
- Low (0.1-10%)
- Moderate (10.1-20%)
- High (20.1-35%)
- Very High (>35%)

* From test hole data. Rating criteria modified from Chen (1988).

Collapsible Soil - From soil properties contained in the Natural Resources Conservation Service Soil Surveys of the Golden and Castle Rock Areas (NRCS, 1974; 1985)

HOW TO USE THIS MAP

This map shows potential areas of collapsible soils in north-central Douglas County, Colorado. The accompanying report describes this map unit and how it was derived. The map has been compiled from a variety of sources, and is intended as a general guide to show where certain geologic and soil conditions may exist. However, site-specific subsurface conditions may vary markedly throughout the map area. This map is not a substitute for professionally prepared, site-specific geologic-hazard studies and designs.

COLLAPSIBLE SOILS OF NORTH-CENTRAL DOUGLAS COUNTY, COLORADO

By Karen A. Berry, David C. Noe, and Monica C. Pavlik

2002

COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE REPORT 02-8
SOIL AND BEDROCK CONDITIONS AND CONSTRUCTION CONSIDERATIONS
NORTH-CENTRAL DOUGLAS COUNTY, COLORADO
PLATE 3: EXPANSIVE SOILS MAP
2002

Digital map prepared by Karen Morgan

Street data modified from Douglas County

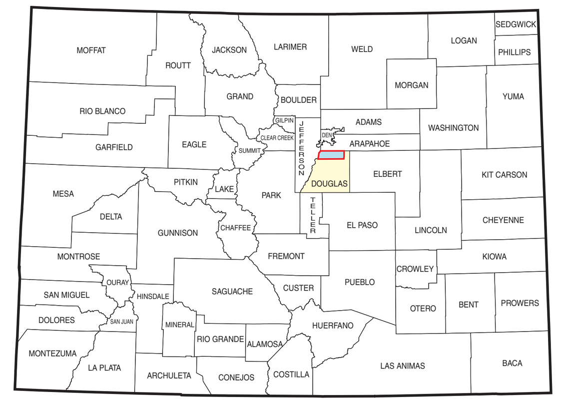
Township/Range/Section data from Tobin Land Grid

Stream data from Colorado Division of Water Resources

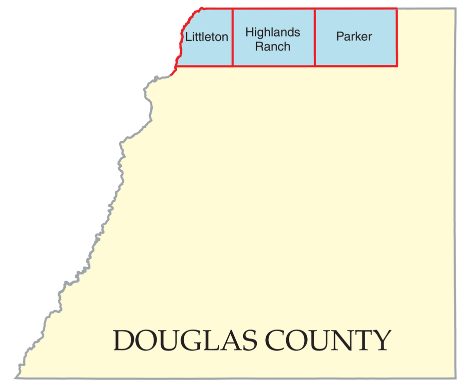
Water data from ESRI

Universal Transverse Mercator projection,
1927 North American Datum

COLORADO INDEX MAP



QUADRANGLE
INDEX MAP



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SCALE 1:24,000

1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 KILOMETER

CONTOUR INTERVAL 10 FEET

MAP UNITS

Descriptions can be found in accompanying booklet

- Street
- Township/Range
- Section
- Stream
- Water body

Swell Potential - From test hole data. See Tables 4 and 5 in text for rating criteria

- Low
- Moderate
- High
- Very High

Expansive Soil - From soil properties contained in the Natural Resources Conservation Service Soil Surveys of the Golden and Castle Rock Areas (NRCS, 1974; 1985)

- Low
- Moderate
- Moderate to High
- High

HOW TO USE THIS MAP

This map shows potential areas of expansive soils in north-central Douglas County, Colorado. The accompanying report describes these map units and how they were derived. The map has been compiled from a variety of sources, and is intended as a general guide to show where certain geologic and soil conditions may exist. However, site-specific subsurface conditions may vary markedly throughout the map area. This map is not a substitute for professionally prepared, site-specific geologic-hazard studies and designs.

EXPANSIVE SOILS OF NORTH-CENTRAL DOUGLAS COUNTY, COLORADO

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