Draft

Heave Investigation and Minimization Study Report

Dundalk Marine Terminal Baltimore, Maryland

Prepared for

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Executive Summary

Objectives

This report summarizes the results of the Heave Investigation and Minimization Study (HIMS) for the Dundalk Marine Terminal (DMT), Baltimore, Maryland. The HIMS was prepared to satisfy the requirements of the April 2006 Consent Decree entered into, by and among Honeywell International Inc., the Maryland Port Administration (MPA), and the Maryland Department of the Environment (MDE). The HIMS has been undertaken pursuant to the HIMS Work Plan approved by MDE on 23 March 2007. The scope of work for the HIMS was developed to address and satisfy the following requirements of the Consent Decree:

- Define and validate a conceptual model of the expansion and heave of the chromium ore processing residue (COPR) at the site by evaluating and investigating the mineralogy, expansion mechanisms, and manifestations of heave;
- Establish, through application and evaluation of field investigations, models, engineering studies, and pilot studies, that COPR expansion and heave phenomena can be classified, monitored, modeled physically, and accommodated; and
- Evaluate, through the application of engineering studies, models, and pilot studies, COPR movement and heave mitigation measures that are viable, effective, constructible, and that can be both monitored and maintained.

The data and conclusions presented herein satisfy the objectives of the Consent Decree. The findings of the HIMS demonstrate that COPR lateral displacement and heave at DMT can be readily mitigated through monitoring, maintenance, and the application of engineering solutions, and that COPR heave manifestations do not present a significant environmental or public health issue.

Investigative Approach

The investigative approach used in the HIMS included:

(i) Obtaining the field and laboratory data that were needed to develop a comprehensive site model of COPR and heave;

(ii) Assessing the data to develop an understanding of COPR mineralogical transformation mechanisms;

(iii) Estimating the present magnitude and rate of COPR lateral displacement and heave;

(iv) Obtaining field data on the performance and effectiveness of various heave mitigation measures; and

(v) Evaluating the effectiveness of these measures.

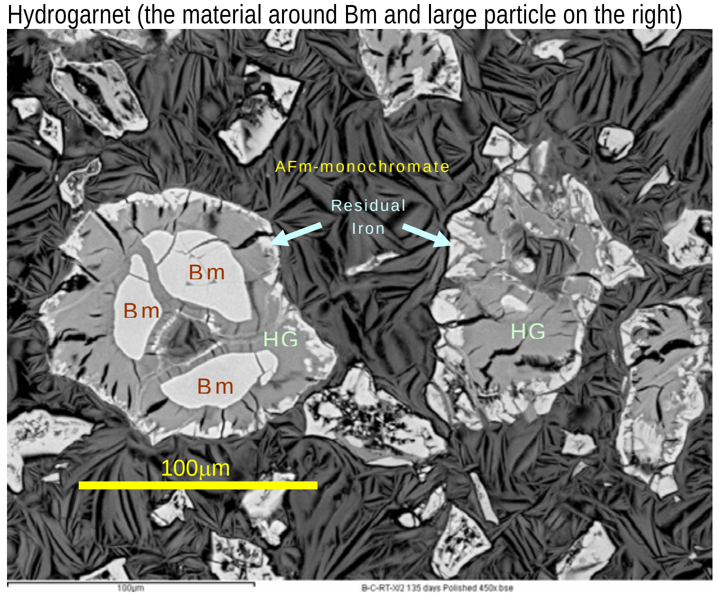
The findings and conclusions of the HIMS are also supported by observations and data derived from historical studies, the companion COPR Investigation Report (CH2M HILL, 2009a), and other sources.

COPR Transformation and Expansion

A conceptual model of COPR expansion and heave has been defined and validated for the site. As presented in the COPR Investigation Report (CH2M HILL, 2009a), the physical, geochemical, and mineralogical properties of COPR at DMT were defined during field investigations to support the identification and delineation of different stages of COPR and to understand the mechanisms that lead to its mineralogical transformation and expansive behavior. Two basic stages of COPR, gray-black (GB) and hard brown (HB), have been identified at DMT. GB COPR transforms to HB COPR in the presence of suitable geochemical conditions and water.

GB COPR, the original (parent) material placed at the site, is rich in the mineral brownmillerite. Brownmillerite plays a central role in COPR mineralogical transformations that can result in expansion and heave. Brownmillerite (marked 'Bm' on Figure ES-1) reacts with water to form new minerals, such as hydrogarnet ('HG' on Figure ES-1). Some of the transformation products of brownmillerite have a tendency to lithify (i.e., to cement or become "rock-like") and expand. Some of the conditions at DMT that contribute to COPR hydration and transformation include:

FIGURE ES-1
Transformation of Brownmillerite (Bm particle on the left) to Hydrogarnet (the material around Bm and large particle on the right)



(i) Repeated wet–dry cycles and groundwater level fluctuations;

(ii) Infiltration from precipitation and/or storm water;

(iii) Infiltration from leaking or broken utilities; and

(iv) Changes in pore water pH and geochemistry.

Mineralogical transformations that cause significant expansion are limited to geochemical conditions found in the unsaturated or vadose zone above the water table. Because these conditions do not occur in the saturated zone, COPR below the water table does not expand.

Monitoring Programs

The rate of COPR expansion and movement at DMT has been extensively investigated through monitoring of:

(i) Horizontal ground movement using inclinometers;

(ii) Movement of surface and underground structures using extensometers; and

(iii) The performance of structures and pavement surfaces.

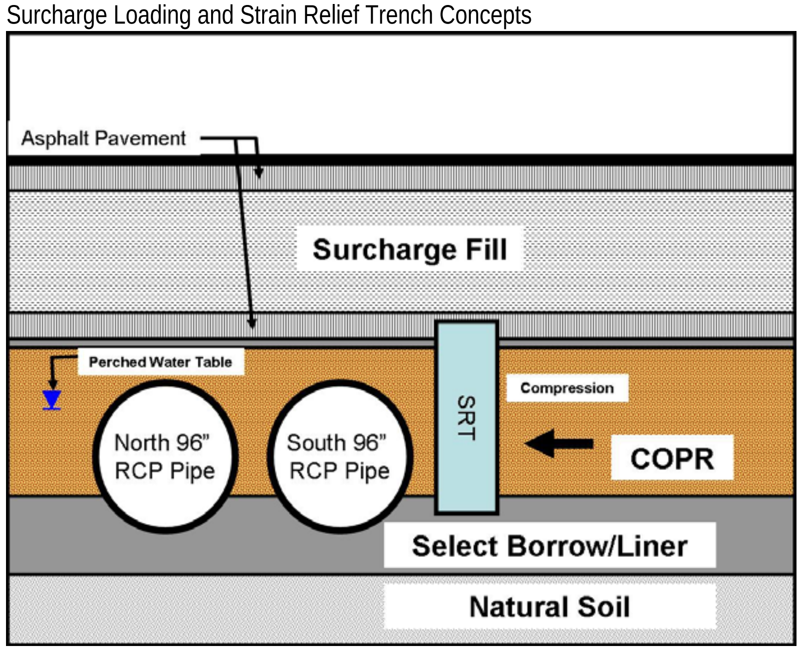
These monitoring programs have helped to demonstrate that present-day COPR lateral displacement and heave is slow, steady, and measurable through observation, and that it can be detected and mitigated well before significant damage occurs to pavements or structures.

Proven Technologies for Heave Mitigation

A number of technologies have been used successfully at DMT to manage the effects of COPR lateral displacement and heave on site infrastructure.

Surcharge Loading (Figure ES-2) involves placing a thick layer of soil (i.e., surcharge fill) on top of COPR to provide vertical confinement. Surcharge loading has been used effectively to restrain heave in Areas 1501 and 1602.

FIGURE ES-2
Surcharge Loading and Strain Relief Trench Concepts



Strain Relief Trenches (SRTs, as shown in Figure ES-2) are trenches filled with soft material that accommodates COPR lateral movement, thereby protecting nearby underground structures from those movements. Strain relief trenches have been used effectively at DMT in Areas 1501, 1602, and 1800.

Special Pavements (i.e., roller-compacted concrete, MatCon™, articulated block cover (ABC), and modified conventional pavements) are various modifications of surface covers that prevent infiltration into underlying materials and experience less damage from heave than conventional pavements. These pavements have been used effectively in Areas 1702 and 1800.

Evaluation of these technologies demonstrates that engineering measures to prevent or mitigate damage due to COPR lateral displacement and heave are available. Also, the evaluation shows that these technologies can be used individually or customized in combination for a specific area or infrastructure to be maintained or protected.

Conclusions

The HIMS has been undertaken in accordance with the approach defined in the Work Plan. The data are extensive and sufficient to:

(i) Define and validate a conceptual model of COPR expansion and heave;

(ii) Establish that COPR expansion and heave phenomena can be classified, monitored, modeled physically, and accommodated; and

(iii) Validate the viability, effectiveness, constructability, monitorability, and maintainability of COPR movement and heave mitigation measures.

The HIMS satisfies the objectives of the Consent Decree by demonstrating that the factors that cause mineralogical transformation and volumetric expansion of COPR are well understood, and that the mechanisms of COPR movement, manifested as lateral displacement or heave, have also been defined. COPR movement can be monitored and its potential impacts can be mitigated. Heave mitigation measures, such as surcharge loading, SRTs, and special pavements have been successfully applied at DMT to prevent or mitigate damage due to COPR movement. Heave manifestations do not present a significant environmental or public health issue because they are not likely to result in the exposure of COPR at the surface. Appropriate protocols are in place to protect workers and others from exposure during any excavations into COPR.

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SECTION 1

1 Introduction

1.1 Purpose

This report provides the results of the Heave Investigation and Minimization Study (HIMS) conducted at the Dundalk Marine Terminal (hereafter referred to as DMT, or site) located in Baltimore, Maryland. This study was conducted pursuant to the requirements of Section III.B.6 of the 5 April 2006 Consent Decree (CD) entered into, by and among the Maryland Department of the Environment (MDE), the Maryland Port Administration (MPA), and Honeywell International Inc. (Honeywell). This HIMS report has been prepared for Honeywell and the MPA by Geosyntec Consultants (Geosyntec), with contributions from a team of consultants including CH2M HILL, Mueser Rutledge Consulting Engineers (MRCE), Battelle Memorial Institute (Battelle), and University of Wisconsin-Madison. The findings presented in this report are based in part on the results of: (i) a comprehensive investigation of the site (CH2M HILL, 2007c, 2007g, and 2009a) concerning the nature and extent of chromium ore processing residue (COPR); (ii) a multi-year effort undertaken by Battelle concerning the mineralogy, geochemistry, and thermodynamics of COPR diagenesis (i.e., mineralogical transformation); (iii) pilot tests for evaluating engineering controls for heave management conducted by MRCE; and (iv) various types of monitoring conducted by MRCE and Geosyntec.

1.2 General Site Description

DMT is located in Baltimore Harbor, on the north side of the Patapsco River, as indicated on Figure 1-1. DMT is located on a peninsula that is bounded on the northwest by Colgate Creek, on the west and south by the Patapsco River, and on the northeast by Broening Highway and Norfolk Southern Railroad. A portion of DMT is located on land that was created by the placement of COPR fill in water. Grades throughout the terminal were also raised by filling. The fill materials used both to raise grades and make land include mixtures of COPR, man-made fill, and locally available fill materials. The extent of COPR fill is shown on Figure 1-1. COPR is composed primarily of compounds of calcium, iron, aluminum, magnesium, and chromium, which comprise more than 90 percent of its inorganic mass (CH2M HILL, 2009a). Trace amounts of other metals, including manganese and vanadium, are also present. Chromium occurs in both the trivalent [Cr(III)] and hexavalent [Cr(VI)] forms. COPR transforms and expands under certain conditions, which are described in Section 5 of this report; this expansion can result in both lateral movement and vertical movement (the latter is referred to as 'heave' throughout this report). Although the term 'heave' is used in this report only to refer to vertical movement, the subject of this HIMS Report is both lateral movement and heave that result from COPR mineralogical transformation and expansion.

1.3 Objectives

The HIMS has been undertaken pursuant to the HIMS Work Plan authored by CH2M HILL on 2 August 2006 (CH2M HILL, 2006a and 2006b) and approved by MDE on 23 March 2007 (MDE, 2006b and 2007b). As described in Section 1.1 of the Work Plan (CH2M HILL, 2006a and

2006b), the scope of work for the HIMS was developed to address and satisfy the following requirements of the CD:

- Define and validate a conceptual model of COPR expansion and heave at the site by evaluating and investigating the mineralogy, expansion mechanisms, and manifestations of heave;
- Establish, through application and evaluation of field investigations, models, engineering studies, and pilot studies, that COPR expansion and heave phenomena can be classified, monitored, modeled physically, and accommodated; and
- Evaluate through the application of engineering studies, models, and pilot projects, the viability, effectiveness, constructability, monitorability, and maintainability of COPR movement and heave mitigation measures.

Additional work undertaken as part of the HIMS included: (i) collection and development of geochemical and geomechanical information related to COPR expansion; and (ii) assessment of past investigations performed at the site to evaluate heave at DMT.

The following four required components of the HIMS are identified in Section 3 of the HIMS Work Plan (CH2M HILL, 2006a and 2006b):

- Review and Summary of the Physical, Chemical, and Expansive Properties of COPR;
- Field Investigations;
- Baseline COPR Expansion and Heave Monitoring Program; and
- Heave Mitigation Engineering Evaluation Plan (i.e., this report).

The proposed elements of the HIMS as presented in the Work Plan are summarized in Table 1-1 along with a reference to where each element is addressed in this report. Results and information presented in this HIMS report will be integrated in the Corrective Measures Alternatives Assessment (CMAA), which is required pursuant to Section III.B.8 of the CD.

1.4 Overview of Related Studies

The findings and conclusions of the HIMS are supported by observations and data derived from historical studies, a companion COPR Investigation Report (CH2M HILL, 2009a) developed pursuant to Section 3.B.5 of the CD and a Surface Cover Inspection and Maintenance Plan (CH2M HILL, 2007e) developed pursuant to Section III.B.4 of the CD. Historical studies of heave at DMT are further described in Section 3 of this report. The COPR Investigation Report (CH2M HILL, 2009a) provides a characterization of the nature and extent of COPR within the COPR fill area at DMT. A summary of the pertinent findings of the COPR Investigation Report is provided in this report to facilitate a comprehensive understanding of COPR and heave. Data derived from inspections undertaken pursuant to the Surface Cover Inspection and Maintenance Plan are incorporated into this report for the purpose of evaluating the performance of the surface cover and special pavements.

1.5 Organization of the HIMS Report

The remainder of the HIMS Report is organized into the following sections.

- *Section 2: Investigative Methods* – provides a summary of the methods that were used to conduct the HIMS.
- *Section 3: Fill History, Placement Conditions, and Heave* – provides an overview of the DMT site development, history of COPR filling, fill placement conditions, and heave manifestations.
- *Section 4: Site Conceptual Model* – provides a summary of previous site investigations, relevant results of the COPR Investigation Report, descriptions of the extent and nature of COPR, and a geomechanical characterization of COPR.
- *Section 5: COPR Transformation and Expansion Mechanisms* – contains a summary of the mineralogy of COPR, the main aspects of COPR mineralogical transformation, and a unifying concept of the transformation, hydration, and expansion of COPR.
- *Section 6: Analysis and Assessment of Heave Mitigation Measures* – contains a description of various technologies that have been tested at the site for their ability to mitigate or control the effects of COPR movement and heave, including special cover systems, strain relief trenches (SRTs) and vertical stress control.
- *Section 7: COPR Monitoring and Maintenance Programs* – presents a summary of maintenance programs that have been used at DMT to protect infrastructure. In addition, a summary is provided of monitoring and maintenance programs that have been used to address COPR expansion and heave at the site, and a discussion of the manner in which monitoring data have been used to detect COPR-related movements before significant infrastructure damage occurs and the success that has been achieved using this approach.
- *Section 8: Conclusions* – synthesizes the main aspects of the HIMS report.
- *Section 9: References* – provides the references used during the preparation of this report.

The following supporting documentation is provided electronically as appendices to this report:

- Appendix A Past Investigations;
- Appendix B Geomechanical Characterization;
- Appendix C COPR Mineralogy Compendium;
- Appendix D Literature Review of COPR;
- Appendix E Inclinometer Data;
- Appendix F Structural Movement Monitoring Data; and
- Appendix G SRT Information.

SECTION 2

2 Investigative Methods

2.1 Overview

The purpose of this section of the report is to provide a brief description of the various investigative methods that were used to conduct the HIMS. The methods described in this section were used for: (i) obtaining the field and laboratory data that were needed to develop a comprehensive site model of the thickness, extent, characteristics, and geomechanical properties of COPR ; (ii) assessing data to develop an understanding of COPR mineralogical transformation mechanisms; (iii) estimating the present magnitude and rate of COPR lateral movement and heave; (iv) obtaining field data on the performance and effectiveness of various approaches for preventing or mitigating damage to pavements or structures caused by COPR lateral movement or heave; and (v) evaluating the effectiveness of these approaches for mitigating damage caused by COPR lateral movement or heave.

2.2 Methods Used for Assessing Fill Placement History

The history of fill placement at DMT is described in Section 3 of this HIMS report. The methods that were used to assess the fill placement history and sequence of COPR placement at the site included: (i) review of numerous design and construction drawings of DMT supplied by MPA; and (ii) review of various aerial photographs of the site obtained from private vendors. The aerial photographs that were reviewed cover the time period from 1938 through 2008. The aerial photographs dated between 1938 and 1967 provided information to ascertain the progression and timeframe of the placement of COPR and earth fill over the different sections of DMT. The data were also evaluated using computer-aided design techniques to interpret the extent and thickness of COPR across the site.

2.3 Methods Used During Site Conceptual Model Development

The site conceptual model is described in Section 4 of this HIMS report. As discussed in Section 4, the model was developed using information related to the lateral and vertical extent of COPR and natural soils mineralogical and geomechanical properties of COPR and natural soils, geochemistry of vadose zone pore water and groundwater (CH2M HILL, 2007c and e, and 2009a; MDE, 2006b and 2007b) and pavements and subsurface structures at DMT. The investigative methods used to obtain and evaluate this information included the following:

<u>Field Investigation Techniques</u>

- *Borings* used to access subsurface materials so that they could be sampled and logged, to delineate subsurface stratigraphy, and to delineate the limits of COPR;
- *Cone Penetrometer Testing* (CPT), including conventional CPT, resistivity CPT, Gamma CPT, and pore pressure dissipation CPT testing, to evaluate geomechanical properties of COPR;

- *Sampling* of COPR specimens, using various sampling techniques including grab, disturbed, and undisturbed sampling, to obtain samples of COPR for characterization and laboratory testing;
- *Pressuremeter testing* to assess COPR geomechanical properties;
- *Piezometers and monitoring wells* to evaluate the occurrence and elevation of groundwater;
- *Test trenching* to investigate conditions of shallow COPR, to obtain samples of COPR for geomechanical and geochemical testing, and to carefully log detailed COPR structure;
- *In situ field plate load testing* to assess COPR geomechanical properties;
- *Geophysics* (both surface and downhole) to obtain data related to the stratigraphy of subsurface soils, and to evaluate other subsurface conditions;
- *Air-Monitoring* during field activities to verify that safe working conditions exist continuously at the site and that there are no COPR-related chromium releases from the site;
- *Survey*s to establish permanent survey benchmarks, and to monitor the movement of COPR across the site; and
- *Visual observations and documentation* of COPR movement and heave manifestations at DMT.

Laboratory Investigation Techniques

- *Geotechnical laboratory testing* for soil classification purposes and estimation of geomechanical properties.

Data Assessment Investigative Techniques

- *Aerial photography interpretation* to assist with COPR boundary determinations and with the development of the conceptual site model; and
- *Digital terrain modeling* to develop both single- and multiple-layer representations of the extent and thickness of COPR.

2.4 Methods Used to Ascertain COPR Transformation and Expansion Mechanisms

Mineralogical transformation and volumetric expansion of COPR are discussed in Section 5 of this report. The theory of COPR mineralogical transformation and expansion presented in Section 5 is based on information obtained from the technical literature, geomechanical testing of samples of COPR from the site, laboratory analytical testing of the chemical and mineralogical composition and reaction thermodynamics of COPR, and laboratory and field testing of the geochemical conditions of vadose zone pore water and groundwater at the site. The investigative methods that were used to ascertain COPR transformation and expansion mechanisms included the following:

Field Investigation Techniques – Field techniques that were used to obtain samples for performing field and laboratory characterization of COPR have been identified above in Section 2.3. Field techniques that were used to identify COPR movement and heave rates are discussed in Section 2.6.

Laboratory Investigation Techniques

- *Chemical laboratory testing* to assess the elemental composition of COPR;
- *Mineralogy laboratory testing*, including x-ray diffraction, scanning electron microscopy, and electron microprobe analysis, to assess the mineralogical composition of COPR;
- *COPR reactivity laboratory experiments* to evaluate COPR reactivity under simulated vadose zone conditions;
- *COPR transformation rate laboratory experiments* for various simulated vadose zone conditions to evaluate the effects of temperature and COPR particle size on COPR transformation;
- *Laboratory expansion tests* of COPR/cement bars under controlled conditions to assess COPR expansion potential;
- *Geochemical laboratory and field evaluation* of the geochemical characteristics of vadose zone pore water and groundwater, including collection of vadose zone pore water samples using lysimeters and groundwater samples using conventional sampling techniques, followed by laboratory analysis of the collected samples (Area 1800) to provide data for evaluation of the moisture conditions and pH of COPR in the vadose zone; and
- *Monitoring of temperature, air pressure, and* CO_2 in the ground within COPR (Area 1800).

Data Assessment Investigation Techniques

- *Statistical analyses* of laboratory data to establish trends and validity of the laboratory test results; and
- *Review of existing literature* on COPR geochemistry and mineralogy.

2.5 Methods Used for Evaluation of Engineering Controls

Section 6 of this report contains an evaluation of various engineering controls that were used at DMT to prevent or mitigate damage resulting from COPR lateral movement and heave. To evaluate these engineering controls, the following methods were used:

Field Investigation Techniques

- *Pilot programs for alternative pavement evaluations*, including:
- proof-of-concept application of an Articulated Block Cover (ABC) pavement system for heave maintenance in Area 1800 (CH2M HILL, 2006c and 2007d; MDE, 2006a and 2007a; and MPA, 2007);
- use of MatCon™, ABC pavement, and modified conventional pavements in the Area 1800 pilot test area (CH2M HILL, 2007a and 2008a);

- *Use of SRTs* in Area 1800 pilot test area; and
- *Monitoring of lysimeter pore water pH and soil gas CO_2* in the Area 1800 pilot test area (CH2M HILL, 2008b and 2009b).

Data Assessment Investigation Techniques

- *Review of records* of construction, reconstruction, or repair of pavements in various DMT areas including:
  - COPR engineered cell in Areas 1501 and 1602;
  - roller compacted concrete (RCC) pavement area in Area 1702 (MPA, 1988);
  - pavement reconstruction and test pilot program in Area 1800 (CH2M HILL, 2008a);
  - Areas 1501 and 1602 surcharge fill;
- *Evaluation of SRT performance with inclinometer data*; and
- *Evaluation of the monitoring results* of ABC pavement infiltration and storm water detention (near-surface trench drains in Area 1800 pilot test area) (CH2M HILL, 2008b and 2009b).

2.6 Methods Used for COPR Monitoring and Maintenance

The methods used to monitor lateral movement and heave of COPR and to maintain the site to prevent or mitigate these movements are described in Section 7 of this HIMS report. As discussed in Section 7, monitoring was performed to detect and measure COPR lateral movement and heave, and maintenance activities have been performed to prevent or repair damage resulting from the COPR heave and movement. The investigative methods that were used to obtain and evaluate this information included the following:

Field Investigation Techniques used for Monitoring

- *Inclinometers* to monitor lateral ground movement across the COPR fill area;
- *Tape extensometers* to monitor the deformation of subsurface structures (e.g., 15th Street drain pipe) and the ground deformation near structures (i.e., Shed 11);
- *Visual survey and crack mapping and measurements* of Shed 11 and Building 1300;
- *Inspection and related visual monitoring*, including Global Position System (GPS) documentation of site-wide cover systems to identify pavement conditions and areas that have experienced damage resulting from COPR movement and heave;
- *Non-destructive testing of pavement surfaces* in several DMT areas to identify locations that are experiencing heave and are in need of repair;
- *Topographic surveys* to monitor heave across the site;
- *Data assessment;* and
- *Compilation of historic heave data* from MPA sources.

Field Maintenance Techniques

- *Establishing a baseline* of pavement surface conditions (CH2M HILL, 2007f and g);
- *Conducting pavement repairs* during the period 2008 through 2009;
- *Data assessment*; and
- *Installing strain relief trench (SRT) systems* to prevent or mitigate impact to infrastructure due to COPR expansion and lateral movement.

SECTION 3

3 Fill History, Placement Conditions, and Heave

3.1 Overview

The purpose of this section is to provide an overview of historic and current conditions at DMT related to COPR fill placement and subsequent COPR heaving at the site. The locations, sequence, and conditions of placement of COPR at DMT are described in Sections 3.2 through 3.4. The nature and locations of COPR heaving at DMT are described in Section 3.5. A summary of previous investigations that were performed to study heave is provided in Section 3.6.

3.2 Site Description

DMT is a marine shipping terminal that was built on land reclaimed from the Patapsco River using a combination of general fill and COPR. DMT is subdivided into lots, including Areas 900 through 1800 (Figure 3-1) that are located within the streets that traverse the terminal. COPR was stockpiled at the site and used as fill primarily south of East Service Road. The COPR originally placed at the site was gray-black (GB) in color and granular in nature. As described in Section 5 of this report, at some locations at DMT, the GB COPR transformed into hard brown (HB) COPR, primarily by hydration of certain COPR minerals exposed to moisture in the vadose zone (i.e., above the water table). Today, GB COPR occurs at the site as a granular particulate, friable, weakly cemented solid, which can be disaggregated by hand pressure. HB COPR, the material that results after GB COPR has been transformed, grades in color from reddish brown to dark brown. This material is weakly to strongly cemented or lithified. Lateral displacements and heave observed at DMT are principally associated with HB COPR. The aerial extent of COPR at DMT (Figure 3-1) is approximately 148 acres. The total volume of COPR placed at DMT has been estimated to be approximately 2,400,000 yd^3, of which 1,700,000 yd^3 are GB COPR and 700,000 yd^3 are HB COPR (CH2M HILL, 2009a).

3.3 COPR Fill History

COPR filling originated in what is now Area 1800 and progressed through Areas 1700, 1701, 1600, 1601, portions of Areas 1500 and 1400, and a small portion of Area 1300, to the approximate limits of a historical bulkhead (Figure 3-1). The original shoreline was progressively extended to the southwest by this filling activity. COPR filling continued beyond the historical bulkhead and into Area 1702 during the terminal expansion that occurred in the late 1960s and early 1970s, when the Terminal was expanded to reach its current shoreline. COPR was also stockpiled in Area 1800 and adjacent areas during this expansion. Finally, in the early 1980s, COPR was placed in an engineered cell in Areas 1501 and 1602.

Areas 1501 and 1602 present a unique circumstance in that COPR was placed into an engineered cell. Between 1975 and 1977, non-COPR fill was placed over the natural river sediments approximately 2 feet (ft) above the river mean level. Subsequently, a 1 ft thick layer of impervious borrow was placed overlying the fill to approximately elevation 3 ft per the Baltimore City Datum (BCD), which is the datum used in this project, unless noted otherwise. A dike was then created around the perimeter of this area as a containment feature. The core of the dike reportedly consisted of a mix of COPR, dredge, and common fill. The inside and outside faces of the core were covered by a 1 ft thick layer of low-permeability soil. Once the dike was completed, a mix of COPR fill and dredge material was placed within the contained area. The COPR was then capped with a 1 ft thick layer of low-permeability borrow soil. The area was then paved, bringing final elevations in this location to approximately 15 ft. The exterior of the dike along the shoreline was subsequently protected using rip-rap and stone-filled wire-mesh baskets. Between 2000 and 2002, non-COPR fill was placed on top of Areas 1501 and 1602 to raise the grades to approximate elevation 21 ft.

Some filling historically at DMT did not involve COPR placement. For example, MPA construction documents indicate that portions of the port were reclaimed using primarily non-COPR fill and that COPR was used only in designated areas. Examples include the construction of port Berths 11 and 12 and adjacent areas (between 1969 and 1973), parts of Areas 1300 and 1400 (from 1980 through 1982), and Berths 9 and 10 (between 1969 and 1972). The area within approximately 50 ft of the sheet pile wall along the 1967 limit of Areas 1300 and 1400 was dredged and subsequently filled with non-COPR fill (CH2M HILL, 2009a). For the construction of Berths 9 and 10 in Areas 900 and 1000, the area within 15 ft inboard of the bulkhead existing in this location was filled using non-COPR material after being dredged.

3.4 COPR Placement Conditions

COPR placement conditions varied over time and by location. Factors that affected the conditions to which COPR was exposed upon placement include: placement on land or into the river and resultant proximity of the COPR fill to groundwater; total thickness of COPR; total thickness of COPR above groundwater, and mechanical stresses applied to the COPR during placement. Post-placement COPR conditions also varied over time and by location. These post-placement conditions included exposure to the atmosphere, wet-dry cycles, and confinement by placement of fill over the COPR. These factors affect the potential for rate, and magnitude of COPR transformation and subsequent expansion and heave.

COPR within the historical bulkhead line was initially placed under partially submerged or shallow submerged conditions. As filling progressed, the land surface became elevated above the level of the river. As a consequence, a large proportion of the COPR placed within the historical bulkhead line remained more or less unsaturated since placement, experiencing cycles of infiltration, exfiltration, and moisture variation. Areas 1700, 1701, and 1800 were reclaimed from lands located close to the original, ancestral shoreline; therefore, they have remained largely unsaturated (except as noted in the next paragraph). The total thickness of COPR in these areas is between 5 and 10 ft (see Figure 4-6, CH2M HILL, 2009a). The depth from the ground surface to the top of COPR varies from approximately 4 to 7 ft (see Figure 4-3, CH2M HILL, 2009a). Also, the thickness of COPR that remained above the groundwater table in these areas is generally larger than elsewhere across the site (except for the COPR in the engineered cell area, created in Areas 1501 and 1602, as described in this section).

Certain locations in Areas 1800, 1700, 1701, 1600, and 1601 appear to have been periodically inundated by ponding and storm water infiltration, contributing to prolonged conditions favoring hydration reactions and COPR transformations. A COPR stockpile located in Area 1800 remained exposed to the atmosphere and infiltrating water for prolonged periods (CH2M HILL, 2009a). After paving, some of the COPR in these areas remained susceptible to wet-dry cycles of infiltrating water, which contributed to further hydration of the COPR. For example, the installation of a network of subsurface drains and sunken ballast for railroad tracks in Area 1800 (CH2M HILL, 2009a) provided water pathways that contributed to COPR wet-dry cycles.

In some other areas (e.g., portions of Areas 1300 and 1400, Area 1500, and areas located beyond the historical bulkhead), COPR was placed into relatively deep dredge channels or deeper portions of the river, resulting in the total COPR thickness in excess of 15 ft (Figure 4-6). COPR placed into dredge channels and into the river was immediately submerged and saturated. As filling in these areas progressed to levels above the former level of water in the river, the upper lifts of COPR were compacted by construction equipment, which likely contributed to the mechanical disaggregation of the COPR.

Most of the COPR in Areas 1300 and 1400, and near Consolidation Sheds 11 and 12, was placed on soft, compressible river sediment and, due to the natural outward displacement of these soft sediments and consolidation of the sediment over time, most COPR in these locations is now situated generally below the groundwater table. COPR in this setting was exposed to fully saturated moisture conditions after the period of initial COPR fill placement and settlement. This COPR was likely placed with little to no compaction effort. The depth from the ground surface to the top of COPR varies from approximately 4 to 7 ft in Areas 1300 and 1400, and is more than 7 ft near Consolidation Sheds 11 and 12 (see Section 4 and Figure 4-3). The COPR thickness above the groundwater table is typically less than 2 ft (CH2M HILL, 2009a).

COPR in the engineered cell in Areas 1501 and 1602 was placed mostly in unsaturated conditions. Some perched water existed in this area. During placement, COPR was subject to considerable mechanic stresses, as the material was first mixed with dredged material and then compacted. The COPR located in the engineered cell has also been subjected to significant wet-dry cycles due to the influence of exfiltration from, and infiltration to, the 15th Street storm drain pipe and its laterals. As a consequence, much of the GB COPR placed in the cell has been transformed into HB COPR. Prior to 2000, this area exhibited larger heave features than other areas at DMT. Heaving in this area was addressed in 2000-2002 by the addition of a 6- to 7 ft thick layer of non-COPR surcharge fill placed over the COPR and original pavement (as described in Section 3.3) to provide vertical restraint (as discussed in more detail in Section 6.4).

3.5 Description of COPR Expansion and Heave

3.5.1 Description of COPR Expansion

At the time of its deposition at DMT, GB COPR was composed primarily of three minerals: brownmillerite, periclase, and portlandite. Brownmillerite is a mineral formed under high-temperature (i.e., over 1,000°C), oxygen-rich conditions, which occurred during chromite ore processing. This mineral is a component of ordinary cement and has cementitious properties. More than 50 percent of the mineral content of the original GB COPR at DMT was brownmillerite. However, brownmillerite is thermodynamically unstable in water and may react to form new minerals in water-rich environments. Conditions that favor COPR transformation include an elevated pH (which is typical of materials that contain lime), availability of divalent anions (such as chromate and sulfate), access to water in wet-dry cycles (commonly encountered in unsaturated conditions in the vadose zone), and mechanical disaggregation of particles (e.g., disruption of the COPR structure resulting from mixing during trench excavation, from grinding during lateral movement due to COPR expansion, or from mechanical compaction during fill placement). Under these conditions, which were present with different intensity and at different times in some areas of DMT, GB COPR may undergo the hydration reactions and transform into HB COPR that are explained in more detail Section 5. Transformation products of brownmillerite include hydrated phases that have lower densities (and hence larger volumes) than the parent brownmillerite mineral. Several of these hydration phases are cementitious. As a result, the transformed material tends to both harden (i.e., lithify or indurate) and expand.

3.5.2 Description of Heave and Lateral Movement

COPR expansion has historically manifested itself at DMT in the following ways:

1. *General Heave*. In some areas, heave (i.e., upward movement) has occurred more or less uniformly over a relatively large area as a direct result of an increase in COPR thickness caused by the vertical component of expansion. General heave has a small magnitude because of the limited thickness of COPR and occurs over a long period of time (i.e., decades), usually causing no damage to the surface cover. General heave is not typically noticeable but can be measured by comparison of the results of conventional ground surveys over long periods of time.

2. *Rounded Heave Features*. These are heave features typically less than 2 ft high that occur over a relatively large area and can produce hummocky ground. Rounded heave features have tended to develop rapidly during the initial placement of COPR but, afterwards, have developed slowly, as is the case in the present setting.

3. *Upthrust Heave Features*. These are abrupt ridges (up to 4 ft high, but usually smaller) that typically have developed over a period of a few years. These ridges tend to follow the alignment of buried utilities or other subsurface structures; however, they can also deviate from the utility alignment and propagate across other areas. These heave features were observed in Areas 1501 and 1602 before the placement of surcharge fill between 2000 and 2002 and, to a lesser extent, in portions of the initial fill area, notably in Area 1800.

4. *Lateral Displacement Features*. Subsurface lateral ground movements can occur as a result of COPR expansion. The potential magnitude of lateral displacement is higher than vertical displacement after placement of the surface cover because the horizontal extent of HB COPR is greater than its vertical thickness. While the magnitude of lateral displacement is typically small in the interior of the COPR fill area (i.e., locations with lateral confinement, termed an “interior condition” below), the magnitude of lateral displacement has been observed to be greater where there is an unconfined edge, such as along the outside perimeter of COPR fill (termed a “free edge condition” below).

The lateral displacement of COPR has been monitored using inclinometers (see Section 7). Based on inclinometer measurements, two types of lateral displacement conditions have been observed at DMT. These types are described generally below and in more detail in Appendix E.

1. *Free Edge Condition.* This condition occurs at a free edge, where there is a horizontal limit of a COPR deposit and this limit is not bounded by a rigid structure or a massive body of contiguous fill. As an example, a SRT is an engineered edge. Large utilities (e.g., 96-in. diameter pipe in Area 1501) can also represent a free edge condition caused by a structural discontinuity. Under free edge conditions, COPR lateral displacements typically occur in the direction of least resistance, which is toward the free edge.

2. *Interior Condition.* This condition arises at locations away from free edges, where lateral displacement is restrained by adjacent COPR, soil, or possibly a rigid, massive structure. Under this condition, magnitudes of lateral displacement are significantly smaller and the rates of movement much slower (about 90 percent less) than movement near a free edge.

3.6 Previous Heave Investigations

In addition to the extensive monitoring of COPR movement that is currently being performed (see details in Section 6), numerous investigations and surveys have been completed at DMT to date to study the causes, occurrences, and impacts of COPR lateral displacement and heave. Appendix A presents a list of the most relevant studies. Brief descriptions of some of the studies are given below.

Century Engineering (1980) mapped existing heave ridges and prepared a heave location map. Detailed field surveys were conducted to obtain surface elevations of pavements and utilities for comparison with drawings of as-built conditions. In addition, this report presents the earliest available documented descriptions of heave manifestations, both on pavements and in the subsurface. The report provided an estimate that total heave magnitude (i.e., since the COPR was first placed) was approximately up to 4 in. in most of the areas investigated and up to 10 in. as heave ridges occurring over utility trenches. The report also provides evidence for the first time of the large magnitude of heave observed near some buried utilities. In addition, the heave magnitude was reportedly larger over trenches backfilled with COPR than the heave magnitude in ground adjacent to the backfilled trenches.

PCS-Law (PCS-Law, 1991) conducted topographic and utility distress surveys. Non-destructive testing (NDT) of pavements was conducted to identify possible structural weaknesses or non-uniformities in the tested pavements or in the underlying materials.

Several topographic surveys have been conducted in Area 1800, 1974, 2003, 2004 (CH2M HILL, 2008, personal communication; CH2M HILL, 2008b). More recently, semi-annual topographic surveys have been conducted in the pilot study area within Area 1800 (see CH2M HILL, 2008a and Sections 6 and 7).

The recent baseline surface inspections (CH2M HILL, 2007f) and the recent, first and second semiannual cover system evaluations (CH2M HILL, 2008b and 2009b, respectively) document the conditions of pavement at DMT as a baseline for future comparisons and assessment of heave.

Historic and current monitoring of heave indicate that, in most of the COPR fill areas that have undergone heave, COPR expansion has produced a heave rate, on average, of less than 0.1 inch per year (in./yr). In a few locations of DMT, heave ridges were observed to form and increase by several inches in only a few years. However, observations indicate that heave ridge formation activity at DMT has been decreasing in recent years, both as a result of a reduced COPR reactivity (see Section 5) and a proactive COPR maintenance program. Inclinometer monitoring shows that the rate of COPR lateral displacement near a free edge condition has been 1.5 to 1.8 in./year. In contrast, for interior conditions, the rate of COPR lateral displacement is relatively low (typically less than 0.15 in./year).

Additional information related to COPR movement and heave is presented in Section 7.

3.7 COPR Expansion Heave and Exposure

As part of the HIMS, an evaluation was conducted to establish whether COPR expansion and heave-related phenomena have produced significant adverse impacts to the environment or public health.

The review of the results of the current monitoring and surface inspection programs (see Section 7) show that heave manifestations do not result in exposure of COPR at the surface. In addition, a review of historic site conditions and information obtained during the site-wide COPR investigation (CH2M HILL, 2009a) indicates that the thickness of non-COPR fill placed above COPR at DMT ranges from approximately 4 to 17 ft, with an average of approximately 6 ft (see contours of depth to top to COPR deposits on Figure 4-3). The range of thickness of non-COPR fill placed above COPR is significantly larger than the range of heave observed on pavement surfaces, including a few features that formed to a considerable height without being maintained. In the current DMT practice for maintenance of pavement surfaces affected by heave, heave features are repaired before they achieve a few inches in height.

Exposure of COPR can only take place when excavations are performed to a depth sufficient to reach the underlying COPR. However, this situation is not directly related to COPR movement and heave. In the case of excavations, the requirements of the site Health and Safety Plan (HASP) must be followed. Currently, when an excavation is performed and the excavation exposes COPR, appropriate personal protective equipment (PPE) is used and continuous air monitoring is conducted at and around the excavation. This task is followed by an evaluation of the air monitoring results to ensure that working conditions are safe at the site. Honeywell and MPA have also conducted routine air monitoring at the perimeter of DMT and the results do not detect COPR-related chromium releases from the site.

In summary, due to the thick layer of fill over COPR at DMT, coupled with a proactive surface cover maintenance program (CH2M HILL 2007e), the likelihood of COPR exposure as a result of heave is extremely low. This evaluation shows that heave is a not significant environmental or public health issue.

3.8 Summary

The history of COPR fill placement and the more recent conditions at the site are relevant to understanding the nature and distribution of COPR lateral displacement and heave at DMT. Proximity to the groundwater table and wet-dry cycles has a strong observational correlation to COPR mineralogical transformation and expansive behavior. The largest manifestations of COPR heave have historically been observed in the COPR engineered fill area (i.e., Areas 1501 and 1602), and to a lesser extent, in areas where COPR was first placed. In addition, expansive behavior has been observed to correlate with the locations of utility corridors and subsurface structural discontinuities. Vertical ground movement rates are very small (i.e., less than 0.1 in./yr) at most locations of DMT. Historically, a few of the heave ridges were observed to increase by several inches in only a few years. However, observations indicate that heave ridge formation activity at DMT has been decreasing in recent years, in part due to reduced COPR reactivity (see Section 5) and in part due to the proactive COPR maintenance program being conducted by MPA. The observed rate of COPR lateral displacement is very small for most of DMT. Near free edge, the rate of COPR lateral displacement has been measured to be substantially larger than for interior conditions.

SECTION 4

4 Site Conceptual Model

4.1 Introduction

The purpose of this section is to present information on the subsurface conditions and engineering properties of COPR that serves to build a conceptual model of the site.
A description of the most recent and relevant site investigations conducted to date is presented in Section 4.2. Section 4.3 provides a summary of the subsurface conditions revealed during these investigations. Section 4.4 presents a discussion of the extent and distribution of COPR at the site. Section 4.5 provides a brief description of the engineering properties of COPR relevant to this HIMS report.

4.2 Site Investigations

4.2.1 COPR Investigation

A comprehensive site-wide field and laboratory investigation has recently been completed by CH2M HILL (2009a). This site-wide investigation consisted of three phases: Phase I (from October 2006 to March 2007), Phase II (from June 2007 to January 2008), and a Supplemental Investigation (December 2008).

In Phase I, a preliminary delineation of COPR was developed based on historical data, visual observations, and sample data collected during the field investigation. The information obtained in Phase I helped to identify through laboratory testing the physical, chemical, and mineralogical properties of COPR and natural soils underlying COPR at the site. The information obtained also allowed development and calibration of field and analytical techniques to characterize different types of COPR and transformation/hydration conditions of COPR in the fill area. In-situ testing, including SPT and CPT, was performed over extensive areas of DMT.

In Phase II, the COPR lateral extent and depth across the site obtained during Phase I were confirmed in most areas and adjusted in a few other areas. Samples were obtained to perform additional mineralogical evaluations to confirm the Phase I findings.

In the Supplemental Investigation, field activities were conducted to address Cr(VI) detections in samples collected during site-monitoring activities and to further delineate the lateral and vertical extent of COPR along the northern property boundary and at five locations within DMT where limited quantities of COPR were identified outside of the historic COPR fill area boundary.

In total, 229 soil borings, 107 CPT soundings, six geophysical surveys, numerous surficial survey points, and one test pit were completed during the COPR investigation (Figure 4-1). Additional details related to the COPR investigation are included in CH2M HILL (2009a).

4.2.2 Previous Investigations

A number of investigations were performed at DMT prior to the COPR investigation described above. These investigations include those by Century Engineering (1980), EA Engineering (1987 and 1989), PCS-Law (1991), STV Group (1992), LYON-WBCM (1996), UMD (1997, 1998, and 2000), and Geosyntec (2004 and 2005). During these investigations, borings and test trenches (among other techniques) were performed at the site to characterize and delineate the extent of COPR and natural soils underlying the site. Electronic copies of these reports are presented in Appendix A.

4.3 Subsurface Conditions

The subsurface conditions at DMT are described in CH2M HILL (2009a). Figure 4-2 shows a representative geologic cross section of the site developed using the available data. A generalized geologic model of the site is presented in Table 4-1. A summary description of the representative subsurface conditions at DMT is presented below.

The soils underlying DMT in the areas investigated consist of: non-COPR fill, COPR fill (or simply COPR), alluvial sediments, and Potomac Group sediments. Non-COPR fill, alluvial sediments, and the Potomac Group sediments are described in this section. COPR is described in Sections 4.4 and 4.5.

Non-COPR fill consists of soil materials that were placed to achieve the grades needed to develop the port facility or to cover COPR. The area where non-COPR fill is thickest is in the western portion of the site, where no COPR was placed; in this area, fill thickness ranges between 20 and 30 ft. In areas where COPR was used as fill, the overlying non-COPR fill thickness ranges between 4 and 17 ft (Figure 4-5).

Relatively thick layers of alluvial sediments typically occur below the COPR deposits. The alluvial sediments are composed of three distinct units: upper silt, alluvial sand, and lower silt. The upper silt is typically soft, contains organic material, and is interbedded with loose-fine sand. The upper silt is also referred to as harbor sediment. The alluvial sand is fine to medium grained, medium dense to dense, and typically of uniform gradation. The lower silt unit is typically soft, and classifies as silt or low-plasticity clay according to the Unified Soil Classification System (USCS). The lower silt is very thin to nonexistent at the eastern portion of DMT and thickens to between 40 and 50 ft at the western portion of the site.

The alluvial sediments are believed to represent Quaternary, low-land sediments that were deposited in an estuarine environment within the Patapsco River basin. The alluvial sediments appear to have been deposited within an erosional channel that was carved into the underlying Potomac Group sediments by the ancient Patapsco River. The erosional channel was filled with sediments over approximately the western two-thirds of the fill area that reflect a relatively low-energy environment of deposition (CH2M HILL, 2009a).

4.4 Extent and Distribution of COPR

4.4.1 Introduction

The horizontal and vertical extent of COPR was delineated in the COPR Investigation Report (CH2M HILL, 2009a) based on a review of various data sources, including historical construction documents and aerial photos. In general, the COPR stratigraphy and boundary delineation was produced by interpolating the information obtained in borings.

4.4.2 COPR Horizontal Extent

Of the 342 locations sampled during the COPR investigation, 232 were interpreted to contain COPR fill material. The locations of these samples, and the results of tests on these samples, provided the data used to demarcate the COPR fill area boundaries.

The horizontal limits of COPR at DMT are shown on Figure 4-1. The COPR fill area is approximately 148 acres in size. The vast majority of COPR fill has been placed to the south of the East Service Road, which is one of the main internal roads at DMT. The northern boundary of the COPR area lies almost parallel to the historic shoreline and bulkhead that existed at DMT prior to land reclamation using soil and COPR.

4.4.3 COPR Stratigraphy

Figure 4-3 presents contours of the depth to COPR (i.e., depth below ground surface). As described above, across most of the site, COPR is encountered below approximately 4 to 10 ft of non-COPR fill for most of the site. The exception is an area under Consolidation Sheds 11 and 12, where COPR is overlain by more that 13 ft of fill. In this area, COPR fill was first placed and then overlain by a surcharge fill to help consolidate the soft sediments underlying the site. Because of settlements of the soft sediments, additional fill was placed to level the ground surface, ultimately covering the COPR in this area with non-COPR fill. In Areas 1501 and 1602, COPR is overlain by a 6 to 7 ft thick layer of fill, as previously described. The overburden placed over COPR in Areas 1501 and 1602 is thicker than most of the surrounding areas; as a consequence, ground elevations in these areas are higher than the rest of the site.

Figure 4-4 presents contours of the depth to bottom of COPR. The bottom of COPR correlates well with original underwater grades and fill history. The review of historic placement information revealed that COPR is generally encountered at progressively deeper depths from east to west, which corresponds to the observed deepening of the river channel to the west. Local variations in depth can be attributed to: (i) horizontal displacement of underlying, soft soil caused by rapid placement of fill (i.e., mud waves); and (ii) settlement of underlying soft sediments. In the site-wide COPR investigation, the maximum observed depth of COPR below ground surface was 38.5 ft, near the historic bulkhead. This can be attributed to the fact that, on one side of the bulkhead, the river channel was likely dredged to a depth deeper than the adjacent original mudline to accommodate ship traffic.

4.4.4 COPR Thickness

Figures 4-5 and 4-6 present contours of the total thickness of non-COPR fill and COPR fill, respectively. It can be inferred that, in general, COPR gradually thins toward the southeastern portion of the site. COPR thickness not only varies across the site as a result of original channel grades and differing COPR filling procedures and sequence (as described in Section 3), but also as a result of potential mud-wave effects and settlement of soft underlying sediments in certain areas. COPR is typically 15- to 25 ft thick under Areas 1300, 1400, and 1500, where COPR was used as fill. The maximum observed thickness of COPR is approximately 32 ft under the center of Area 1500, near the historic bulkhead. COPR thickness ranges from about 10 to 20 ft under Consolidation Sheds 11 and 12. Because COPR fill may have been placed on a steep shoreline or abutting a bulkhead in this area, COPR abruptly pinches out and is essentially absent toward the northern side of the consolidation sheds. A fairly uniform layer of COPR approximately 6 to 7 ft in thickness is observed under Areas 1501 and 1602; this uniform thickness reflects COPR placement under controlled conditions in the engineered cell.

4.4.5 COPR Volume at DMT

Based on the subsurface information collected from 235 soil borings (i.e., 229 borings obtained during the COPR investigation and 6 additional historic borings) and 100 CPT soundings during the COPR investigation, CH2M HILL (2009a) used a multi-layer (i.e., interlayered) model to estimate that approximately 2.4 million cubic yards (mcy) of COPR were placed at DMT. Of this volume, approximately 1.7 mcy are comprised of GB COPR and 0.7 mcy and comprised of HB COPR. Using the multi-layer model, it is also estimated that the volume of non-COPR fill interlayered with COPR represents approximately 0.65 mcy.

4.4.6 COPR Distribution as Related to Groundwater

Based on boring dates (CH2M HILL, 2009a), it is estimated that approximately 63 percent of all COPR is located below the groundwater table and 37 percent is located above the groundwater table. HB COPR is typically observed near or above the groundwater table. Above the groundwater table, 50 percent of all COPR is HB COPR, whereas only 17 percent of COPR below the groundwater table is HB COPR. Contours of COPR thickness above the groundwater table are shown on Figure 4.7.

The HB COPR that exists below the groundwater table typically occurs as thin layers, typically less than 1 ft thick. Of the 145 borings where HB COPR was encountered, 110 (i.e., 76 percent) of these were logged with a total thickness of COPR below the groundwater table that was less than 1 ft.

Based on a review of the available aerial topographic information, it is interpreted that much of the HB COPR now below the groundwater table was originally placed at other locations above the groundwater table and subsequently moved and placed at a location now below the groundwater table. An example of this is when HB COPR was excavated from an area above the water table and placed as fill where the consolidation sheds now stand below the water table. The remainder of the HB COPR occurring now below the groundwater table may be accounted for by subsidence or outward displacement of soft organic sediments into which the COPR was placed as fill.

4.5 Engineering Properties of COPR

4.5.1 Introduction

This section presents descriptions of the main engineering characteristics and properties of both GB and HB COPR. A database listing the results of all relevant laboratory and in-situ tests performed on COPR from 1987 up to 2007 is presented in Appendix B. The data were compiled from several studies (e.g., EA Engineering, 1987 and 1989; Geosyntec, 2004; and CH2M HILL, 2009a). The engineering characteristics and properties of both GB and HB COPR of most relevance to this report are described in the following sections and are summarized in Table 4-2.

4.5.2 Gray-Black COPR

GB COPR is a granular material, typically classified in accordance with the USCS as fine to medium, poorly-graded sand (SP) or silty sand (SM), and occasionally between poorly-graded sand and silty sand (SP-SM). It is typically black to dark gray, with a particulate to moderately lithified texture. This material occasionally has a distinct mottled appearance with whitish, pale yellow, maroon, or bright-green yellow particles, which are usually encountered as lumps of cemented material. The specific gravity of the GB COPR particles has an average of 3.10. On average, GB COPR contains 5 percent gravel-sized particles, 70 percent mostly fine to medium sand-sized particles, and 25 percent fines. Occasionally, GB COPR contains up to approximately 9 percent of gravel-sized particles. In the vadose zone, the moisture content of GB COPR varies between 8 and 42 percent, with an average of 25 percent. In the saturated zone, GB COPR moisture content is typically above 30 percent.

GB COPR is classified as dense based on SPT N-values (i.e., blow counts, ASTM D 1586), having an average of 24 blows per foot (bpf). When tested using CPT, GB COPR exhibits patterns characteristic of coarse-grained soils for cone tip resistance, sleeve resistance, and dynamic pore pressure response (Tinjum et al. al, 2008). With GB COPR, the cone tip resistance generally ranges between 50 to 250 tons per square feet (tsf). On rare occasions, tip resistances can be as low as 5 tsf or as high as 400 tsf. The degree of GB COPR cementation affects its degree of compactness.

Slug tests (EA Engineering, 1992) indicate that in situ GB COPR has an average hydraulic conductivity of about 2×10^{-5} (cm/sec). In addition, the hydraulic conductivity of laboratory-prepared samples of GB COPR was estimated by the University of Wisconsin-Madison (2009, report in preparation) according to ASTM D 5084 and comparable tests. Hydraulic conductivity test results ranged from 1.0×10^{-2} cm/sec for loose (i.e., uncompacted) GB COPR, to about 3×10^{-6} cm/sec for compacted GB COPR with modified Proctor compaction effort (ASTM D1557). This range indicates that the in-situ hydraulic conductivity of GB COPR is comparable to the lower bound of the hydraulic conductivity range measured in the laboratory.

The undrained shear strength of lithified GB COPR as measured in the undrained unconsolidated (UU) triaxial test (ASTM D 2850), varies between 1.3 and 2.0 tsf with an average of 1.6 tsf. Secant stiffness modulus at 50 percent maximum stress level ranged from approximately 79 to 86 tsf, with an average of 83 tsf. The modulus for reloading and unloading was approximately seven times the measured secant modulus. Based on correlations based on SPT N-values for fine to medium sand (i.e., Kulhawy and Maine, 1990), the effective-stress friction angle for particulate GB COPR is estimated to be in the range of 32 to 36 degrees.

4.5.3 Hard Brown COPR

HB COPR could be geologically classified as a shale- or cemented sandstone-like material because of its degree of cementation and can be classified as a soil-equivalent of dense to very dense, poorly to well-graded sand with gravel (SP to SW), or occasionally silty sand (SM) to gravelly sand (SW) according to the USCS, although the high degree of lithification makes the use of USCS classifications questionable. Optical microscopy shows features commonly found in lateritic deposits. HB COPR is encountered as a weakly to strongly cemented material. Its color is commonly light brown; however, at some locations, it grades to reddish brown or dark brown and it is interspersed with nodules of yellow, light greenish, and occasionally, whitish coloration. With depth, and in the vicinity of GB COPR, HB COPR exhibits increasing numbers of blackish and grayish nodules. These blackish and grayish nodules can be partly GB COPR.

The typical grain-size distribution of HB COPR, after some effort for mechanically breaking down the structure, is somewhat comparable to that of GB COPR, although there is a trend for HB COPR to contain a larger percent of fine- and gravel-size particles than GB COPR. The accuracy of the grain-size distribution tests for HB COPR is questionable because there is no standard for how much mechanical effort needs to be applied to break down the material before the test is performed; for example, the gravel component commonly contains fragments of cemented HB COPR, which could have been broken down further. The sand fraction in HB COPR is typically fine. Fines content varies between 10 and 47 percent. In the vadose zone, HB COPR is moist, with an average moisture content of 20 percent. In the saturated zone, the average moisture content of HB COPR is higher, typically around 30 percent.

In general, the specific gravity of HB COPR is more variable and commonly lower than that for GB COPR. The average measured specific gravity of HB COPR is 2.79, compared to 3.10 for GB COPR.

HB COPR is generally hard to very hard, with SPT N-values commonly greater than 50 bpf. CPT tip resistance in HB COPR typically ranges from 250 to 500 tsf; however, larger values were measured at several locations. Thin layers of HB COPR tend to produce “spikes” of cone tip and sleeve friction resistances in the CPT soundings. Both positive and negative dynamic pore pressures were commonly observed in HB COPR. Negative values of dynamic pore pressure are typical of cemented material that tends to generate pore water suction while the CPT probe is advanced. In situ, HB COPR has often been observed to have a broken structure, particularly near the bottom of the layer and at upthrust heave features.

The average hydraulic conductivity of HB COPR obtained from laboratory test is 3×10^{-5} cm/sec. Because HB COPR is typically above or near the groundwater table, no in-situ hydraulic conductivity testing was performed for this material.

The undrained shear strength of intact, lithified HB COPR, as measured in the UU test, varies from 0.8 to 5.3 tsf with an average of 2.7 tsf. Secant stiffness modulus averages 240 tsf, which is significantly higher than that of GB COPR. However, the unloading and reloading modulus of HB COPR is only slightly higher than that of GB COPR. The effective-stress friction angle and cohesion of HB COPR, which is derived from consolidated undrained (CU) triaxial tests, have averages of about 32 degrees and 1.5 tsf, respectively.

SECTION 5

5 COPR Transformation And Expansion

5.1 Overview

The mechanisms responsible for the mineralogical transformation and volumetric expansion of COPR are described in this section. Section 5.2 presents a brief description of the composition and mineralogy of the COPR found at DMT. Section 5.3 provides a summary of the mineralogical processes involved in the transformation of COPR. The unified concept for transformation, hydration, and expansion of COPR is presented in Section 5.4. Section 5.5 presents a discussion on the potential magnitude and rate of COPR volumetric expansion. Finally, Section 5.6 provides a summary description of COPR transformation and expansion mechanisms.

5.2 Composition and Mineralogy

5.2.1 Composition

The geochemistry of COPR at DMT has been described in previous reports by CH2M HILL (2009a), and the mineralogy of COPR has been described by Battelle (2007a and 2007b). Results of mineralogical studies conducted by Battelle are presented in Appendix C of this HIMS report. In addition, an extensive review of the existing literature related to the geochemical and mineralogical characterization of COPR was conducted by Battelle in conjunction with preparation of this report. A summary of the literature review and the reviewed references are presented in Appendix D. In the following paragraphs, the geochemistry and mineralogy of the COPR at DMT is summarized based on the information provided in the reports referenced above and in Appendices C and D.

Recent studies (CH2M HILL, 2009a) indicate that four metals present in the original chromite ore (i.e., aluminum, chromium, iron, and magnesium), and one metal added during ore processing as calcined lime (i.e., calcium added as oxide) are the primary metals present in the COPR used as fill at the site. These five metals constitute approximately 50 and 42 percent of the mass of GB and HB COPR, respectively. Further, compounds of these five metals, plus manganese and vanadium (all of them as oxides), make up more than 90 percent of the average mass distribution of the inorganic chemistry of COPR (see Figure 5-1). The lower mass proportion of metals in HB COPR compared to GB COPR is mostly the result of the incorporation of water into the HB COPR, as described below.

The aspects of COPR chemistry most relevant to its volumetric expansion at DMT are the presence of chromium, high pH, and carbonate, as described below. Sulfate can be relevant to expansive behavior under theoretical conditions but is not a significant contributor to the geochemical setting at DMT.

- *Chromium*. The total concentration of chromium in HB COPR is comparable to or slightly higher than the concentration of chromium in GB COPR. However, the concentration of hexavalent chromium (i.e., Cr(VI)) in HB COPR is on average 45 percent higher than the concentration in GB COPR.

- *pH*. The average pH of both GB and HB COPR are in the range of 12.3 to 12.4 Standard Units (SU), with the GB COPR pH being, on average, slightly higher than the HB COPR pH when measured in a slurry of COPR and deionized (DI) water.
- *Carbonate*. Carbonate alkalinity exhibited no significant difference between GB and HB COPR concentrations overall (CH2M HILL, 2009a). However, the transformation and products in HB COPR are related to the position of COPR in the soil column, with slightly higher proportions of carbonate phases occurring in the vadose zone. The higher carbonate phases in the vadose zone are attributed to the uptake of atmospheric carbon dioxide into COPR transformation products. Experiments by the University of Maryland (2000) show that carbonate uptake at high levels can also lead to COPR lithification.

The chemical mass balance indicates that GB and HB COPR are essentially of the same chemical composition and thus are reacting largely within a closed system. The one exception to the closed system is the potential addition of carbon dioxide from the atmosphere in the upper portion of the vadose zone.

5.2.2 Mineralogy

The average mass distribution of the crystalline content of GB and HB COPR is shown on Figure 5-2. The mineral species in COPR can be classified according to its origin (i.e., those mineral species present in the roasting process) and final product (i.e., hydrated products and non-COPR products). The classification of the main COPR minerals, as well as their chemical formula, is provided below. Cement chemistry nomenclature is used in the discussion of COPR mineralogy due to similarities between the chromate manufacturing process and the production of cement:

Parent Minerals (i.e., minerals present in or added to the chromite ore roasting process)

• Brownmillerite	$Ca_2(Fe,Al)_2O_5$	in the chrome ore
• Periclase	MgO	
• Spinel	$MgAl_2O_4$	
• Lime or quicklime	CaO	added to roasting process
• Portlandite	$Ca(OH)_2$	resultant

Pure Hydration Products (from Brownmillerite)

- Hydrogarnets, including:
  - Katoite series: $(CaO)_3Al_2O_3(H_2O)_6$
  - Amorphous residual iron-rich phase $Ca_3Fe_2(OH)_{12}$
- Hydrotalcites, including:
  - Sjoegrenite $Mg_6Fe_2(CO_3)(OH)_{16}\bullet 4H_2O$
  - Quintinite $Al_2Mg_4(CO_3)OH)_{12}\bullet 3H_2O$
- Hydrocalumite $Ca_2Al(OH)_{6.5}Cl_{0.5}\bullet 3H_2O$

- Calcium Aluminum Chromium Oxide Hydrates (also referred to as an aluminum ferrite-mono-phase, ferric oxide, monosulfate or AFm phase) — $Ca_4Al_2O_6(CrO_4)\bullet nH_2O$
- Aluminates, including:
  - Monocarboaluminate — $Ca_4Al_2(OH)_{12}(CO_3)(H_2O)_5$
  - Hemicarobaluminate — $Ca_8Al_4O_{14}CO_2\bullet 24H_2O$

In addition, precursor phases (calcium, aluminum, and water, or C-A-H) can be identified.

<u>Other Hydration and Related Products (i.e., those containing chromate, carbonate, and sulfate)</u>

- Brucite (hydration of periclase) — $Mg(OH)_2$
- Portlandite (hydration of lime) — $Ca(OH)_2$
- Calcite (by water/air infiltration) — $CaCO_3$
- Ettringite (or Aft phase) (by sulfate infiltration) — $Ca_6Al_2(SO_4)_3(OH)_{12}\bullet 26H_2O$

<u>Non-COPR Products</u>

- Quartz (e.g., sand in soil) — SiO_2

The proportions of the mineral species in GB and HB COPR are different, although no phase is completely unique to one type of COPR (see Figure 5-2). The minerals produced in the high-temperature roasting process included brownmillerite (40 to 60 percent, with an average of approximately 45 percent in GB COPR), periclase (approximately 10 percent), and small percentages of an iron-rich spinel. In addition, portlandite was present in the original GB COPR due to the incorporation of calcined lime during the roasting process. Today, periclase, spinel, and portlandite typically make up 5 to 10 percent of the GB COPR mineral composition.

In the solid phase, HB COPR has significantly higher concentrations of Cr(VI) (median concentration of approximately 6,200 µg/L) than GB COPR (median concentration of approximately 4,100 µg/L).

HB COPR typically contains less than 10 percent brownmillerite. Under the conditions that the COPR was placed at DMT, the brownmillerite reacted (as described in Section 5.3) to form other minerals including hydration products (i.e., see list above). The proportion of hydrogarnets and monochromate hydrates is larger in HB COPR than in GB COPR. Quartz (SiO_2) was detected in some samples, particularly in areas where COPR was encountered at relatively shallow depths and was in direct contact with non-COPR fill. This finding suggests that sand was mixed with COPR at the time of deposition in these areas (e.g., in Areas 1501 and 1602 dredge spoils were reportedly mixed with the COPR fill material).

More complete and detailed discussions of COPR geochemistry and mineralogy, mineralogical analyses, and statistical evaluations of COPR samples are presented in CH2M HILL (2009a) and in Appendix C.

5.3 COPR Mineral Transformation

5.3.1 Introduction

After the high-temperature roasting process was completed, the COPR was placed in fill areas at the site in lower-temperature conditions under which brownmillerite is thermodynamically unstable. After placement and when exposed to a thermodynamically-favorable transformation environment, the brownmillerite reacted to form one of the several types of hydration products described in Section 5.2. The reactions mostly involved intra-system reactions, except for reactions with water and carbon dioxide. The only intra-system chemical alteration that has a significant impact on mineral heterogeneity was the increase of hexavalent chromium in the HB COPR.

In pure water, brownmillerite hydration begins with the formation of metastable precursor phases composed of calcium, aluminum, and water (these combined phases are referred to as 'C-A-H' in cement chemistry nomenclature). The alumina in these hydrated phases is more reactive than in the parent brownmillerite, which allows the chromate to react with the hydrated alumina to form monochromates. Based on the research shown in Appendix D, chromate is believed to promote the hydration of brownmillerite and the formation of cementing phases.

The hydration of brownmillerite plays an essential role in the formation of aluminum-bearing minerals that cement COPR particles or nodules together, which can cause lithification and expansion. Lithification occurs as the AFm phases form in the pore spaces surrounding the COPR nodules. Expansion occurs later when brownmillerite and periclase react with water inside the COPR nodules. Brownmillerite that is not converted to cementing phases is converted to hydrogarnet, which causes the COPR nodules to expand.

The process whereby an unconsolidated granular material becomes cemented and consolidated is referred to as 'lithification'. In natural systems, uncemented materials exhibit different stress-strain behavior than cemented materials. For example, sandy soil behaves differently than sandstone (i.e., a naturally lithified material composed of sand) under applied stresses. Lithification promotes expansion in HB COPR because the stresses and expansion created during hydration are readily transmitted to contiguous particles at the cemented contacts. Because the material is cemented at the particle contacts, all particles tend to act as an interconnected system. On the other hand, non-lithified GB COPR does not exhibit overall expansive behavior because: (i) much less particle expansion has taken place (i.e., the COPR still contains significant amounts of brownmillerite; and (ii) if expansion has taken place, this expansion will, in general, not be transmitted to adjacent particles because particle contacts are uncemented; instead, the expansive particles will simply tend to displace into unfilled pore space, moving past adjacent particles.

The concentrations of divalent anions, including chromate (½ CrO_4^{2-}), carbonate (½ CO_3^{2-}), and sulfate (½ SO_4^{2-}) in GB and HB COPR, result in the conditions that cause lithification of COPR. Elevated chromate concentrations have been observed in lithified COPR, particularly in the vadose zone and at the horizontal interfaces between GB and HB COPR. Elevated concentrations of sulfate have only been observed in a small area at DMT (primarily one trench in Area 1800). In addition, elevated carbonate concentrations have generally been observed in the shallow vadose zone (i.e., a few feet above the stable groundwater table), likely as a result of the intrusion of atmospheric carbon dioxide into the system. Carbon dioxide is believed to contribute to lithification of GB COPR. At DMT, the phase equilibrium system most strongly correlated to lithification and expansion is that of monochromates.

5.3.2 Fundamental Reactions in Brownmillerite Transformation

The fundamental mechanism considered to be responsible for lithification of COPR is the reaction between the divalent anions and AFm compounds produced during the hydration of brownmillerite. A symbolic (i.e., not balanced) equation for the overall alteration of brownmillerite can be written as:

$$\text{Brownmillerite} + \text{Y} \longrightarrow \text{AFm} + \text{CF}_2\text{H}_x \qquad \text{Equation 5-1}$$

where Y can represent divalent anions $\frac{1}{2}CrO_4^{2-}$, $\frac{1}{2}CO_3^{2-}$, $\frac{1}{2}SO_4^{2-}$, OH^-, or Cl^-; AFm is the monochromatic phase; and CF_2H_x is an amorphous residual iron phase, where C = CaO, A = Al_2O_3, F = Fe_2O_3, and H = H_2O, according to cement chemistry nomenclature.

In general, AFm phases tend to be aluminum-rich, although these phases can also contain a limited iron fraction present as a solid solution. Experiments using synthetic brownmillerite have shown that AFm crystals produced from hydration of synthetic brownmillerite exhibit very little iron substitution (see Appendix C). The residual iron phase tends to be amorphous, having a reasonably consistent calcium/iron ratio and an indeterminate number of water molecules.

The following general equation describes the hydration of brownmillerite:

$$\overbrace{\text{C}_4\text{AF}}^{\text{Brownmillerite}} + \overbrace{22\text{H}}^{\text{Water}} \longrightarrow \overbrace{\text{C}_4\text{AH}_{19}}^{\text{AFm}} + \overbrace{\text{FH}_3}^{\text{Ferric Hydroxide}} \qquad \text{Equation 5-2}$$

where the symbols are shown using the cement chemistry nomenclature.

Under certain conditions (described in Section 5.3.3), brownmillerite can hydrate to hydrogarnet, AFm phases, or other minerals, as described in Section 5.2.2. However, of most significance at DMT are the geochemical conditions that drive the hydration products towards a hydrogarnet phase or an AFm phase.

The reaction rate for Equation 5-2 can vary significantly. Reactivity can be slow under certain conditions or even passivated (i.e., temporarily stopped), and it can be increased under other conditions. For example, it has been shown that the formation of hydrogarnet from brownmillerite pastes can take several days or longer at ambient temperature (Meller et al., 2004). In contrast, hydration of C_3A produces hydrogarnet in only minutes. The reactivity of brownmillerite can be passivated by a number of mechanisms; for example, metastable C-A-H can passivate the brownmillerite surface and limit further dissolution and hydration (Meller et al., 2004). On the other hand, various mechanisms can increase brownmillerite reactivity, including temperature, surface disaggregation and/or grinding, and incorporation of other species that react with C-A-H.

5.3.3 Phase Equilibrium for Hydrated Minerals in COPR

The chemical reactions that are responsible for COPR lithification and expansion can be explained by equilibrium calculations and the use of phase diagrams. Establishing the phase equilibrium for the monochromate phases is particularly important because the availability, abundance, and mobility of the monochromate phases in the system determine how these reactants interact and create new mineral species.

To establish the phase equilibrium relationships for COPR, equilibrium calculations were performed for AFm and AFt phases and other hydrous calcium-aluminate compounds using equilibrium constants for the dissolution of these mineral phases at 25°C. Results for reactions between two solid phases in aqueous solution for four key components of the system including, Al^{3+}, Ca^{2+}, H_2O, and CrO_4^{2-}, are shown on Figure 5-3 as an equilibrium diagram for the monochromates (AFm), hydrogarnet, chrome- ettringite (Aft phase) AFt, and other hydrated calcium aluminate phases. This stability diagram relates the combinations of chromate concentrations and the pH of the surrounding liquid phase that are needed for certain materials to be stable. As shown on the diagram, the monochromate phase remains unstable until the chromate concentration is greater than approximately 19,000 µg/L (i.e., log of CrO^{-2} is greater than -3.5) and pH is between 11.2 and 13.4 SU. The data points plotted in this figure are from: (i) lysimeter samples (i.e., from the pore water in the vadose zone) obtained from Area 1800 (see Section 7.7), in an area where lithified COPR and surface heave have been historically observed; and (ii) site-wide groundwater-monitoring wells that are screened in COPR. The pore water concentrations of chromate and pH measured in the field are close to the values shown on Figure 5-3 at the theoretical boundary between monochromate and hydrogarnet. This trend indicates that conditions typically encountered in the vadose zone are suitable for the formation of both cementing minerals (i.e., monochromate) and expansive minerals (i.e., hydrogarnet).

5.3.4 Experimentally Supported Evidence

An extensive experimental study (see Appendix C) has been completed in conjunction with the HIMS to develop an understanding of: (i) brownmillerite hydration; and (ii) stability of the resulting monochromate phases. Experiments have produced hydrogarnet after only a few days in experiments involving synthetic brownmillerite and mechanically ground GB COPR. Similarly, an AFt phase (chrome-ettringite) containing hexavalent chromium is postulated as a reactant; however, it is suspected that this phase is either difficult to form (for kinetic reasons) or thermodynamically unstable. Nevertheless, chromium-bearing needles (having chromate-ettringite stoichiometry) have been found in experiments by scanning electron microscopy (SEM) for samples having high chromate concentrations in solution (greater than 10,000 mg/L).

To evaluate the hydration reactions and pathways for brownmillerite, experiments were conducted using a finely ground (i.e., particle size less than 38 µm) synthetic brownmillerite powder (see Appendix C). Pre-conditioning of this material with DI water at room temperature resulted in a substantial conversion of synthetic brownmillerite into thin platelets of AFm. Similarly, upon exposure to a chromate solution, the AFm phase was converted to a fully chromated form.

In experiments, the converted brownmillerite formed a lithified mass that was much harder than the material that had been pre-conditioned in DI water. Microscopic images of one of these experiments (see Figure 5-4 as an example, and Appendix C for additional details) show that brownmillerite, which initially made up most of the solid phase, was present only in small areas in the center of the material grains, or had disappeared altogether. On Figure 5-4, the large particle on the left has some remnant of the material labeled Bm (brownmillerite). The left particle also has a substantial amount of the material labeled HG (hydrogarnet). The large particle on the right is hydrogarnet after transformation. AFm-monochromates fill the pore spaces. The figure shows hydrogarnet forming around the brownmillerite, as the grains contain hydrogarnet but have the original shape of the brownmillerite particle. The cross-sectional diameter of the large grain on the left of Figure 5-4 is approximately 100 μm, which is about twice the maximum size of the unreacted brownmillerite (38 μm). It was observed that residual iron formed on the periphery of the grains. The intergranular space was completely filled with an AFm phase, which resulted in part from the reaction of this sample with the chromate solution.

5.3.5 CO_2 and Carbonate

As noted above, the transformation products in HB COPR layers are related to the position of COPR in the soil column. The greater concentrations of mineralogically-bound carbonate phases in COPR in the vadose zone and at shallower depths indicate the potential for uptake of atmospheric CO_2 into the COPR structure. Because COPR pore water is highly alkaline, CO_2 transported into the vadose zone in air is quickly absorbed by the pore water and converted to carbonate ion (CO_3^{2-}).

The average content of AFm carbonates is highest in HB COPR located in the vadose zone. This is explained by Equation 5-1, where Y represents ½CO_3^{2-} (in place of ½CrO_4^{2-} in the chromate analog) and CF_2H_x is the amorphous residual iron phase. Availability of carbonate can also favor the formation of simple carbonate minerals such as calcite ($CaCO_3$), and also more complex carbonate-bearing compounds such as the hydrotalcite group of minerals (Appendix C). X-ray diffraction (XRD) evidence indicates that calcite forms at concentrations up to 10 to 20 percent and hydrotalcites form at concentrations of about 1 to 5 percent by weight of COPR.

Lysimeter sampling of vadose zone pore water and CO_2 monitoring of vadose zone gas in Area 1800 (see Section 7.7) show seasonal variations in CO_2 levels and pH in the subsurface. Pore water pH is in the range of approximately 10.5 to 11.5 SU at peak seasonal CO_2 levels. One important observation in laboratory experiments undertaken by Battelle (Appendix C) is that very high pH values (e.g., as in lime-saturated conditions) retard brownmillerite hydration, whereas moderate acidification (i.e., pH becoming < 12 SU) was found to increase brownmillerite reaction rates. The form of brownmillerite transformation in the chromate system is also pH-dependent. As seen on Figure 5-3, the range in pH values from 10.5 to 11.5 SU is on top of the phase boundary between hydrated calcium aluminate phases (i.e., denoted as CA:10H, for which pH < 11.2 SU) and the hydrogarnet and monochromate phases.

In summary, higher CO_2 levels can depress pH into a range that favors brownmillerite transformation. Higher concentrations of mineralogically-bound carbonate phases are observed in the vadose zone at DMT, including carbonate AFm phases in HB COPR. This observation indicates the potential for uptake of carbon dioxide into the COPR structure. The range of pH also impacts the stability of mineralogical phases in the chromate system.

5.4 Unifying Concept of Transformation, Hydration, and Expansion of COPR

5.4.1 Introduction

In order to develop a unifying concept for COPR transformation, the conditions under which COPR will transform and the factors that promote (catalyze) or restrict (passivate) COPR transformation must first be identified. In this section, each of these conditions and factors is described, as is an overall unifying concept for COPR transformation, hydration, and volumetric expansion. Potential reaction mechanisms are described first in Section 5.4.2; catalysts for the reaction are described in Section 5.4.3; conditions that restrict the reaction are described in Section 5.4.4; and, finally, the expansion of transforming COPR into pore spaces is discussed in Section 5.4.5.

5.4.2 Reaction Mechanisms

Phase relationships that are important in COPR reaction mechanisms can be graphically illustrated using ternary diagrams such as the one shown on Figure 5-5. In general, this ternary diagram is a representation of the potential reaction pathways and common end products of brownmillerite hydration, as represented by their composition in terms of CaO, Al_2O_3, and Fe_2O_3, as measured in experiments conducted on synthetic brownmillerite (which are described in detail in Appendix C). The potential phases that are represented in the ternary diagram are: brownmillerite (i.e., the starting point, shown as open circles on Figure 5-5), AFm phases, hydrogarnet, and residual iron.

The reaction mechanisms can be represented by 'tie lines' on the ternary diagram that connect phases in equilibrium with one another. For example, on Figure 5-5, a tie line passes through brownmillerite and connects the AFm phases (i.e., yellow upward triangles) with the residual iron (i.e., purple downward triangles) representing potential pathways that brownmillerite may take during transformation. According to the ternary diagram of Figure 5-5, the transformation may result in AFm phases that are aluminum-rich, although it may result in a small amount of iron as a solid solution. This trend was observed in tests on synthetic brownmillerite that exhibit very little iron substitution. The residual iron phase has an approximate composition given by CF_2H_x. Although the compound CF_2H_x is believed to be amorphous, the calcium/iron ratio is consistent over analyses of several samples. Also, while the residual iron phase is likely to be hydrated, the number of water molecules associated with calcium and iron are unknown.

5.4.3 Transformation Catalysts

COPR transformation can be catalyzed by the following:

- Particle size reduction and disaggregation;
- Geochemical exposure (i.e., pH and chromate concentration, and CO_2 or carbonate influence on pH);
- Wet-dry cycles; and
- Elevated temperature.

The following paragraphs present a brief discussion of each of these factors and their relevance to brownmillerite transformation at DMT.

Particle Size Reduction and Disaggregation

Experiments conducted separately by Battelle (Appendix C) and the University of Wisconsin-Madison (report in preparation) on samples of GB COPR that had been ground indicate that COPR is much more reactive when ground to a relatively small particle size than when it is intact. The increased reactivity is explained by the significantly larger reactive surface area per mass of COPR in the ground material and the removal of the passivating surface layers that had been encapsulating the nodules and preventing brownmillerite from reacting with the aqueous solution in the pore spaces of COPR. In experiments conducted by Battelle (Appendix C), finely-ground COPR particles were found to be susceptible to mineral alteration by water and dissolved anions. After these particles had been reacted and the resulting free alumina was converted to monochromate, the reactions abruptly stopped even though a large fraction of brownmillerite remained.

Physical observations of the degree of induration of samples tested in wet-dry cycles in a pressure plate extractor show that synthetic brownmillerite (having a grain size smaller than 37 μm) had the greatest degree of induration/hardness compared to that of coarsely-ground GB COPR and unprocessed GB COPR (see Appendix C for details). Experiments conducted by the University of Wisconsin, Madison, in a pressure plate apparatus (ASTM D 6836) show that unprocessed, unground GB COPR (greater than 200 μm in size) exhibited minimal induration (see sample Cr-10-U on the left of Figure 5-6), and that ground GB COPR (less than 100 μm in size) exhibited moderate induration.

Furthermore, ground GB COPR (data points labeled “GB P 200 - 4 Day Sat” on Figure 5-7) absorbed a relatively large amount of water in tests conducted under negative pressure (i.e., suction), indicating that the material rapidly hydrated under simulated unsaturated conditions. In comparison, unground GB COPR absorbed less water; (data points labeled “GB 2 - 6 Hr Sat” on Figure 5-7), while intact HB COPR actually expelled (data points labeled “HB- Intact” on Figure 5-7) water during the experiment. In these tests, the application of a significant drying cycle (i.e., by increasing the suction or negative pressure) on COPR samples demonstrates that water is absorbed into the microstructure of COPR. For non-reactive sand-sized material such as quartz, water typically drains from the specimen (i.e., the volumetric water content decreases with increasing suction). However, for COPR, water moves from an exterior source into the sample when suction is applied, as demonstrated by the increasing volumetric water content (Figure 5-7). This tendency is greatly increased when the GB COPR is ground to particles size of < 75 µm.

Geochemical Exposure (pH, Chromate Concentration, CO_2 and Carbonate Influence on pH)

Based on analyses of approximately 60 COPR samples, the calculated median pH of GB COPR is 12.28 SU, as compared to the median pH of 12.14 SU for HB COPR (Figure 5-8a). This indicates that pH is relatively constant during field transformation of GB COPR to HB COPR. The slightly lower pH of HB COPR may be due to the fact that HB COPR is more typically located near and/or above the groundwater table. This is in the zone of aeration where the addition of carbonic acid from atmospheric carbon dioxide can slightly decrease pH. As shown on Figure 5-3, a typical field pH range near 12 SU is optimal for the stable formation of either monochromates or hydrogarnet, depending on the concentration of chromate in the solution.

In the solid-phase, HB COPR has significantly higher concentrations of Cr(VI) (median concentration of approximately 6,200 µg/L) than GB COPR (median concentration of approximately 4,100 µg/L), as shown on Figure 5-8b. In the vadose zone, repeated wet-dry cycles can tend to increase chromate concentrations, especially during the drying cycle, when chromate becomes supersaturated in the pore space as water is removed from the system. This tendency can accelerate transformation kinetics (i.e., the rate of mineralogical reactions), especially if the drying cycle damages the passivating layers that surround unreacted brownmillerite in the COPR nodules. This hypothesis is supported by comparing results of analyses performed on COPR pore water samples collected from the vadose zone to analysis results for groundwater. While the median Cr(VI) concentration in vadose zone pore water is 35.8 mg/L, the median Cr(VI) concentration in groundwater samples is much lower, only 11.1 mg/L.

Wet-Dry Cycles

In closed systems (i.e., those without a mineralogic exchange with the outside), the greatest transformation changes occur near the water table because of the ability of these systems to transfer and accumulate compounds (Mitchell and Soga, 2005). Important mineralogical changes can take place in COPR deposits due to the presence, accumulation, and mobility of chromate and other anions in the vadose zone, where wet–dry cycles occur. At DMT, portions of the vadose zone may experience wet-dry cycles as a result of:

- Fluctuations in groundwater levels;
- Infiltration from, and exfiltration to, storm drain systems and, to a lesser extent, other subsurface utilities; and/or
- Subsurface flow from pavement underdrains (e.g., formerly those used in Area 1800).

Because a direct source of water is required to transform and hydrate brownmillerite in COPR, the availability of water is a necessary component of COPR transformation. Also, changes in the availability of water (e.g., lowering of the groundwater table or covering an area with a low-permeability cap) may lead to circumstances where GB COPR becomes either more or less reactive. Therefore, understanding the relationship between wet-dry cycles and transformation is important to understanding both COPR current conditions and future behavior.

In the subsurface at DMT, both HB and GB COPR may be encountered in thinly stratified zones above the groundwater table. The majority of HB COPR is encountered near or above the groundwater table or in areas subject to wet-dry cycles, as discussed previously in Section 3 and presented in CH2M HILL (2009a). A small percentage of HB COPR is presently encountered below the groundwater table due to placement history. In addition, some HB COPR was originally deposited above the groundwater table and subsequently excavated and redeposited in areas that are now below the groundwater table. Also, COPR deposited into the river has slowly subsided over time. This observation, combined with the observation that many shallow heave ridges are directly correlated to shallow utilities and/or drains that transmit water within the vadose zone (see example on Figure 5-9), indicates that wet-dry cycles are a potential primary catalyst for the transformation of GB COPR into HB COPR at DMT.

When COPR is saturated, the hydration of brownmillerite in the core of COPR nodules is restricted by the hydrated shell of hydrogarnet (as observed in SEM photographs; material labeled HG on Figure 5-4) and an amorphous rind of iron-rich precipitates that surrounds the brownmillerite core. These hydrated minerals and precipitates strongly retard the penetration of water into the core of the nodules, preventing hydration of the brownmillerite core. This phenomenon is referred to as "shrinking unreacted core" (SUC) theory and is a well-known model within the materials processing and mining engineering communities (Hinsenveld and Bishop, 1994; Levenspiel, 1999; Gbor and Jia, 2004). For unreacted cores of brownmillerite, the factor that limits the reaction rate is liquid diffusion through the 'inert' or 'ash' layer of the hydrated minerals and/or the surface precipitates.

For unsaturated conditions, the shell of hydrogarnets and precipitate is subject to shrink/swell and fatigue cycles, which allows micro-cracks (i.e., a few µm deep) to develop in this shell to provide pathways for water to reach the brownmillerite core. This phenomenon can become particularly pronounced if the nodules undergo repeated wet-dry cycles. As shown on a dry SEM mount of partially reacted synthetic brownmillerite (left large particle on Figure 5-4), shrinkage cracks are located throughout the COPR nodules. When rewetted, this system of shrinkage-related microporosity can allow the penetration of water into the unreacted brownmillerite core and promote further brownmillerite hydration. This observation supports the SUC model described in the previous paragraph. Additional observations have been made at the field-level at DMT that support the SUC model, including:

- COPR proximity to the groundwater table and wet-dry cycles have a strong observational correlation to COPR lateral transitioning from GB to HB COPR and layering of the GB/HB COPR system; and
- The thickest continuous sequence of HB COPR layers at the site is located near the current groundwater table.

Elevated Temperature

Experiments conducted by Battelle (Appendix C) at room temperature produced slower reaction rates of synthetic brownmillerite than those produced in experiments conducted at 60°C. In experiments conducted at room temperature using relatively low concentrations of chromate, first chrome-ettringite formed, and this was followed by the conversion to the more thermodynamically stable monochromate form. When reacted with lower concentrations of chromate but elevated temperature (i.e., 60°C), brownmillerite reacted to form a monochromate product of approximately 97 percent in composition (by weight) in just 28 days. The elevated temperature in these tests promoted rapid leaching of aluminum and calcium from the brownmillerite and the rapid formation of AFm compounds in the chromate-containing pore fluid. In field conditions, elevated temperatures are not likely, especially for long-term conditions and where COPR is below the groundwater table, because water is effective at transporting excess heat from earth materials. However, it is possible that the COPR in the vadose zone experienced elevated temperatures shortly after the COPR was placed due to the exothermic lime hydration reactions that occurred.

5.4.4 Passivation and Retardation of Hydration Reactions

As discussed in Section 5.2.2, at the time of its deposition at DMT, COPR was composed primarily of the minerals brownmillerite, periclase, and portlandite. Also, as discussed in Section 5.3.4, experiments performed on synthetic brownmillerite show that brownmillerite transforms primarily to hydrogarnet when exposed to DI water and primarily to monochromate when exposed to a chromate solution. In experiments described in Appendix C, when a Cr(VI) source (0.2 percent by mass) is added to synthetic brownmillerite, the thermodynamic tendency is for monochromates (a known cementing component of COPR) to form, over time, as brownmillerite. However, even in the carefully controlled conditions of these laboratory experiments (i.e., synthetically pure brownmillerite, optimum pH, small grain size, continuous mixing, and high liquid/solid ratio), the transformation of brownmillerite into monochromates takes months to complete. In the field, the conversion rate of brownmillerite to transformation products is constrained by the variability of COPR and the environmental conditions across the site.

As mentioned in Section 3, it was estimated that approximately 1,700,000 yd^3 of GB COPR and 700,000 yd^3 of HB COPR exist at DMT (CH2M HILL, 2009a). Over 70 percent of COPR is GB COPR. The significantly larger quantity of GB COPR indicates that, decades after being disposed at DMT, high concentrations of brownmillerite in GB COPR is still predominant and widespread. Therefore, it is concluded that mechanisms exist at DMT that do not promote the transformation of GB to HB COPR, especially for the COPR that is not subject to repeated wet-dry cycles or is located below the permanent groundwater table.

The passivation and retardation that has been observed in COPR at DMT follows the model of wet-dry reaction inhibition in aluminous cements developed by Emanuelson and Hansen (1997). In this model, it is rationalized that inhibition of cement hydration in sulfate-rich systems is due to the formation of a non-porous surface layer that protects the ferrite cement clinker (i.e., brownmillerite). Sulfate systems (sulfate is another divalent cation) are a geochemical analog to chromate systems. Furthermore, in this model, to prevent the transfer of water and other components from the solution phase to the cement, an amorphous material must be in intimate contact with a fine-grained AFt phase (chrome-ettringite). Emanuelson and Hansen (1997) hypothesized that crystallization of small sulfate ettringite needles desiccates the amorphous layer, which becomes compact and essentially water-proof (Figure 5-11a).

In the COPR nodules, experiments (described in Appendix C) have shown that, in the presence of high concentrations of dissolved-phase Cr(VI), in the range occurring in the vadose zone, and under strongly basic conditions, brownmillerite reacts to form chrome-ettringite on the nodule surfaces (see Figure 5-11b). As discussed by Emanuelson and Hansen's (1997) investigation of cements, the fine needles and compact amorphous layer on COPR nodules create a shell that inhibits further reaction (see Figure 5-4).

5.4.5 Ability of COPR to Accommodate Expansion Within Pore Spaces

The analysis of the volume (or mass) proportions of the solid, liquid, and gas phases of GB and HB COPR can be used to estimate the ability of COPR to accommodate expansion within the pore space between particles. The geotechnical phase diagram shown on Figure 5-12 can be used to calculate the average porosity (i.e., the ratio of voids volume to total volume, as a percentage) of a sample. The phase diagram shown on Figure 5-12 indicates that the average porosity of GB and HB COPR are similar. This suggests that the available space between particles remains approximately the same after GB COPR transforms to HB COPR. Therefore, because HB COPR has a lower specific gravity than GB COPR (as discussed in Section 3) and the porosities are similar, HB COPR is expected to have a lower unit weight than GB COPR. In analyzing the typical phase diagram for GB and HB COPR, the following conclusions relative to expansion theory and movement mechanisms are provided:

- The average porosities of GB and HB COPR are similar, indicating that the transformation of GB COPR to HB COPR does not reduce the pore volume of COPR; and
- The volumetric expansion of COPR minerals in lithified HB COPR cannot be accommodated within the available pore space between COPR nodules because the grain contacts are cemented.

Geotechnical phase diagrams (Figure 5-12) indicate that GB COPR has significant available pore space to accommodate expansion; however, cementation of the structure can prevent the available pore space from accommodating expansion in HB COPR.

The stability field for the formation of cementitious monochromates requires more than approximately 6×10^{-4} Mol (M) of chromate in solution (see Figure 5-3). However, because the median chromate concentration of monochromates below the groundwater table is only 5.2×10^{-5} M (i.e., approximately one order of magnitude lower than that necessary for stability for this phase), monochromates are not thermodynamically stable below the water table. In contrast, the median chromate concentration in COPR pore water in the vadose zone is 3.1×10^{-4} M as measured in Area 1800 by MRCE (CH2M HILL, 2009b), with multiple measurements above the chromate equilibrium line, indicating that monochromates would be expected to form in the vadose zone. This is consistent with observed conditions at the site.

5.5 Expansion Magnitude and Rates

Geotechnical investigations have shown that the average specific gravity of the solids in the GB and HB COPR are 3.10 and 2.79, respectively (CH2M HILL, 2009a), or equivalently an approximately 10 percent decrease from GB to HB COPR. Considering that the porosity of GB and HB COPR are about the same, the decrease in specific gravity indicates that the volumetric expansion potential associated with the full conversion of the original GB COPR to HB COPR is also approximately 10 percent at the grain scale. The volume expansion at the grain scale occurs with similar magnitudes in all directions; a trend referred to as isotropic volumetric expansion. The volumetric expansion is calculated as the sum of three linear expansion values occurring in three orthogonal directions. As a result, if the conditions are similar in all three directions, the linear expansion potential in any single direction is on the order of 3 percent. However, if expansion is prevented at the macro-scale in one direction, the linear expansion in the other directions may increase while the volumetric expansion is the same. This tendency has been observed at DMT.

In addition to the reaction tests described above, laboratory tests were performed on 10 in. long bars of COPR mixed with a mortar submerged in water to evaluate the rate and magnitude of expansion under those conditions (results are provided in Appendix C). The bars (referred to as ‘mortar bars’) were composed of ground GB or HB COPR mixed with a mortar consisting of a small amount of Portland cement, which served as a binder. The mortar bars were submerged in water baths at various temperatures in an autoclave. During the tests, all COPR expanded in the submerged condition over time.

Although the mortar bars were submerged in water, these specimens expanded because the COPR particles were locked into a cemented system akin to lithified HB COPR. The cemented system did not allow the micro-scale expansion to occur into the available pore matrix in the bars because the particles were fixed by the cement binder. Therefore, any expansion of COPR due to hydration resulted in an overall expansion of the mortar bars. Had the cement binder not been present, hydration products of GB COPR would have simply filled the pore spaces without causing net expansion of the bars. Thus, the cement binder acted similarly to the cementing matrix that gives HB COPR its lithified nature. In these tests, HB COPR also was partly disaggregated, such that some of the mineral cementation was destroyed. However, the tests involving GB and HB COPR both included a cement binder. Therefore, it was not entirely unexpected that they would expand, because the same unhydrated minerals (brownmillerite and periclase) are present in both types of COPR.

As discussed earlier, grinding of COPR particles causes the loss of the passivation layer and can reactivate COPR expansion. The maximum linear expansion rate was measured at about 0.1 percent per year in the mortar bar experiments. This rate is comparable to the linear strain rate of approximately 0.15 percent per year measured in inclinometer arrays installed near free edges in Area 1501 (see Section 7).

The rate of mortar bar expansion was most likely affected by the mild grinding performed to disaggregate the COPR particles before the expansion experiments. Grinding exposed new mineral surfaces and caused this COPR to become more reactive.

In summary, the mortar bar experiments provided suitable conditions for expansion because of the application of cement, which bound COPR grains together, and the disaggregation of COPR, which increased the exposed surfaces for the transformation of brownmillerite. The mortar bar experiments are an analogy that provided an estimate of the rate and magnitude of potential linear expansion of HB COPR. However, these tests do not represent actual physical and chemical conditions of COPR below the water table at DMT.

5.6 Summary

The major points related to COPR transformation and potential expansion are summarized below.

- COPR undergoes mineralogical changes due to the presence, accumulation, and mobility of chromate and other anions in the vadose zone, and due to the environmental conditions to which COPR is exposed.
- In the absence of ionic species in solution (other than hydroxide), brownmillerite reacts with water to produce an AFm phase, which later transforms to the thermodynamically stable hydrogarnet. The conversion of brownmillerite to hydrogarnet causes expansion in COPR at the grain level without producing any cementation.
- When high concentrations of dissolved phase Cr(VI) are present, brownmillerite also reacts to produce an AFt phase (chrome-ettringite), which is thermodynamically unstable and later converts to the more thermodynamically stable monochromates. These

monochromates cement individual COPR grains producing lithification at the macro-scale of the COPR mass. This process finalizes in the conversion of GB COPR to HB COPR.

- Wet-dry cycles in the vadose zone tend to both increase the concentration of the dissolved phase of Cr(VI) and disrupt passivation layers on COPR grains. These cycles contribute to the transformation of GB to HB COPR and subsequent lithification and expansion.
- Some conditions at DMT prevent, passivate, and retard the transformation of GB COPR to HB COPR, especially for COPR below the groundwater table.
- Particle size is an important variable in COPR transformation. Fine particulates of brownmillerite produced from disaggregation are more susceptible than coarse particles to mineral alteration by water and dissolved ions.
- The production of chrome-ettringite and AFm phases around COPR nodules creates a passivating layer that inhibits further brownmillerite reaction (similar to the well-known dormant state of cement systems). Once a passivating layer is in place around the nodules of GB COPR, the chemical reactions inside the nodules operate as if no chromate were present in the system. If water becomes available to the interior of these nodules, brownmillerite is converted to hydrogarnet, which is responsible for expansion at the grain scale. Even in a saturated system, passivating layers retard the solid-phase movement of water to the brownmillerite core, resulting in long-term (i.e., decades to possibly centuries) stability of brownmillerite.
- Decades after COPR placement at DMT, over 70 percent of COPR is unlithified GB material. Therefore, apparently, conditions exist at DMT that preclude GB COPR transformation into HB COPR, particularly below the groundwater table.
- The volumetric expansion that may be expected as GB COPR transforms to HB COPR is approximately a maximum of 10 percent at the grain level. Volumetric expansion is isotropic, and tends to manifest with the same linear expansion magnitude in each of three orthogonal directions. The linear expansion potential in any single direction therefore is expected to be on the order of three percent at the grain scale (i.e., 10 percent of volumetric expansion is made up of the sum of 3.3 percent of linear expansion in each of three directions).

SECTION 6

6 Analysis and Assessment of Heave Mitigation Measures

6.1 Introduction

This section presents the results of an engineering analysis and assessment of various specialized measures that have been used at DMT to mitigate and manage the effects of COPR movement and heave on DMT infrastructure. Section 6.2 provides an overview of the approaches that can be followed for mitigating and managing the effects of COPR heave and movement. Section 6.3 describes the use of cover systems as a measure to mitigate the effects of COPR heave and movement. Section 6.4 describes the use of SRTs as a means to absorb COPR lateral movements in the subsurface. Section 6.5 describes the use of surcharge loading to provide vertical resistance against COPR heave. Section 6.6 provides conclusions regarding the constructability, durability, and implementability of these measures.

6.2 Overview of Mitigation of COPR Movement and Heave

In general, the mitigation of the effects due to COPR movement and heave can be undertaken using various approaches. These approaches involve:

(i) The use of pavement systems to resist, accommodate, and manage heave;

(ii) The use of SRTs to absorb subsurface lateral movements; and

(iii) The application of vertical stress (e.g., using a surcharge restraint) to reduce heave.

Some of these approaches can also incorporate engineering controls to prevent the infiltration of surface water into the COPR fill and reduce the potential for wet-dry cycles, which was identified as a factor in COPR transformation.

Approaches to mitigating the impacts of COPR movement and heave can be implemented individually or in combination in different areas, depending on existing conditions, including land use, heave rate, and the condition of surfaces and structures. In general, these approaches can be put into practice through a maintenance program that is based on the findings of a formal monitoring program. Several monitoring systems that have been effectively established at DMT are described in Section 7.

The focus of this section is on those measures and technologies that have been field-demonstrated at DMT to be effective in mitigating the impact of COPR movement and heave, including: special cover systems, SRTs, and vertical stress controls, as discussed in the following paragraphs. An evaluation of a broader set of remedy alternatives for DMT will be conducted as part of the CMAA pursuant to Section III.B.8 of the CD.

6.3 Cover System Evaluations

6.3.1 Introduction

This section presents the results of an evaluation of the response of various types of cover systems at DMT to COPR heave. The evaluation includes an assessment of whether these systems are viable in terms of constructability and maintainability, as well as an assessment of whether or not sufficiently reliable methods exist to monitor the performance of these systems. All of the cover systems amassed in this section include pavement as the uppermost component to support vehicular traffic and/or cargo storage activities of the MPA. Several types of pavements, including both conventional and special types of paved surfaces, have been used at DMT for this purpose. Conventional pavements have been used over most of the terminal. Special pavements have been used in pilot studies conducted over relatively smaller areas to evaluate the feasibility of these systems for managing pavement response to COPR heave. Special pavements include roller-compacted concrete (RCC), MatCon™, ABC, and modified conventional pavements. RCC pavement has been installed in Area 1702 and the other special pavements have been installed in the study pilot area in Area 1800.

An evaluation of conventional pavements is presented in Section 6.3.2. An evaluation of RCC pavement is presented in Section 6.3.3. The evaluation of special pavements installed in Area 1800 is contained in Sections 6.3.4 through 6.3.7.

6.3.2 Conventional Pavement Systems

The most common type of pavement surface installed over the COPR fill area of DMT is conventional asphalt pavement. Although concrete pavement was used in some parts of Area 1800, most of this pavement has been milled, cracked, and seated. The thickness of conventional asphalt pavement was typically up to 8 in. (Figure 6-1, section a) when originally applied. Today, the asphalt pavement is generally thicker due to subsequent repaving that has been required in the course of routine maintenance activities. In some areas, the cover surface consists of the proprietary system TLA®, which is an asphalt concrete. In this pavement type, the cover generally consists of a 4 in. thick layer of asphalt concrete, which is underlain by an 8 in. thick base layer of dense coarse aggregate and a 6 in. thick subbase layer of granular material.

In general, the historical performance of conventional pavements has been good at many areas of DMT but problematic in areas of significant COPR heave. In most areas of the terminal, where COPR heave has not been significant, conventional asphalt pavements have performed well. Asphalt pavement systems subjected to significant COPR heave undergo cracking and loss of trafficability. Examples are Area 1800 and Areas 1501 and 1602 (when the latter areas consisted of an engineered cell). In these areas, conventional asphalt pavements experienced damage and needed to be repaired or replaced. Moreover, these pavements tend to crack under heave conditions, leading to increased surface water infiltration.

Conventional concrete pavements are not well-suited to accommodate COPR heave because they are brittle and tend to crack when subjected to heave. Conventional concrete pavements tend to be especially vulnerable along construction joints that do not overlap. In general, rigid pavements can not accommodate ground distortions caused by heave.

6.3.3 Roller-Compacted Concrete Pavement

A RCC pavement section was installed in Area 1702 in 1998 (MPA, 1998). This pavement section includes a top surface of Hot Mixed Asphalt (HMA) up to 2 in. thick. The top layer is underlain by three 6 in. thick layers of RCC, which is underlain by a granular subbase having a minimum thickness of 6 in. (Figure 6-1, section b). Joints in the concrete panels are strategically staggered to control and prevent surface water infiltration. In the RCC pavement section, some of the underlying COPR was removed so that the top elevation of the relatively thick section of RCC would match pre-existing grades. The thickness of COPR under portions of the RCC varies between approximately 5 and 15 ft (see Figure 4-6). In this HIMS report, the RCC is referred to as a 'special pavement' to differentiate it from conventional pavement.

Overall, the RCC pavement has maintained a high level of serviceability throughout 10 years of use, as observed during the baseline inspection (CH2M HILL, 2007f) and verified during a recent inspection conducted in March 2009 by CH2M HILL and Geosyntec. In 2007, most of the features observed in the pavement were cracks, not heave features. Some depressions and relatively small ridges have been observed in the recent inspection. The successful performance of this system is attributed to the intrinsic strength of RCC, the increased weight of the pavement section resulting by replacing fill/COPR with RCC thus producing a surcharge, and the reduced amount of surface water infiltration.

6.3.4 Special Pavements Tested in Area 1800 Pilot

In 2007, a pavement pilot test area was created to evaluate and compare the performance of: (i) modified conventional asphalt pavements; (ii) ABC pavement; and (iii) low-permeability MatCon™ pavement. The pilot study area extended mainly in Area 1800 (therefore, the pilot test is usually referred to as the Area 1800 Pilot Study) and in portions of Areas 1602 and 1702. The ABC system extended over 1 acre (ac.), MatCon™ pavement over 1.8 ac., and the modified conventional asphalt pavement over 4.4 ac. In this HIMS report, the ABC and MatCon™ systems are also referred to as 'special pavements'.

The scope of work for the Area 1800 Pilot Test Study:

- Installing pavements and evaluate construction procedures in areas of significant historic heave;
- Installing a shallow drainage system within the ABC pavement section as an alternative to using a conventional pipe drainage system and evaluating performance;
- Installing SRTs at selected locations; and
- Installing inclinometers to monitor COPR horizontal movement and asses through inclinometer monitoring effectiveness in absorbing COPR lateral expansion.

The scope also included installing instrumentation in the subsurface to monitor groundwater, soil moisture, pH, CO_2, and temperature in the vadose zone that may affect the COPR transformation (see Section 5). In addition, the work included implementing: (i) long-term monitoring of COPR heave and lateral movement; (ii) inspection of pavement conditions; and (iii) maintenance requirements of the various pilot pavement systems. A more detailed description of monitoring of pavement systems at DMT is presented in Section 7.

Surface inspections within the pilot area included observations of general pavement conditions, ponding conditions after rainfall events, evidence and degree of rutting, presence of reflective cracking, surface settlement or heave, and identification of any requirements for maintenance. Although these observation/monitoring aspects do not constitute a set of standardized criteria typical of pavements in roads, together they can provide strong evidence over the long term of whether these pavement systems are behaving adequately and are effective in resisting or accommodating COPR heave and its effects. The assessment of each of the pavement types included in the pilot test area is presented in following subsections.

6.3.5 MatCon™

MatCon™ pavement is a specialized, low-permeability asphalt pavement that is constructed of a proprietary binder supplied by Wilder Construction Company, of Everett, Washington. This product has been used for various settings, including environmental applications where a low-permeability pavement is required to provide an impervious cover over environmentally-sensitive fill material while providing suitable bearing resistance for traffic loading. In this HIMS report, MatCon™ is referred to as 'special pavement'.

The nominal permeability of the MatCon™ pavement is reported to be 1×10^{-8} cm/sec. The MatCon™ system has a significantly higher resistance to traffic and fatigue tire pressures when compared to conventional asphalt pavement systems and can accommodate nominal traffic tire pressures up to about 100 pounds per square inch (psi). Due to this feature, MatCon™ can result in thinner (i.e., by a few inches) pavement sections than conventional asphalt pavement for a comparable load resistance. Thinner sections can result in a smaller volume of the existing underlying materials that need to be removed to preserve grades. The depth of milling and excavation of existing material that is typically required to install MatCon™ and to preserve grades does not reach the top of the COPR fill for most locations. MatCon™ pavements reportedly have a relatively long service life in most applications, on the order of 10 to 15 years. In addition, due the composition of its binder, MatCon™ has been reported to be more resilient, crack resistant, and flexible (i.e., ability to accommodate deformation without cracking), than conventional asphalt pavements (e.g., EPA, 2003, and Carson et al., 2001). The MatCon™ materials were placed at the site in a single 4-in. lift over a prepared base (Figure 6-1, section c).

During inspections (see Section 7) the MatCon™ area was noted to be in very good condition. No cracks or surface heave features were observed in this area. Depressions observed at the beginning of the monitoring period remained stable. Some pavement relief (potentially heave conditions) was observed along the southern and eastern portions of the modified conventional asphalt pavement sections. In a March 2009 inspection conducted by CH2M HILL and Geosyntec, the conditions of these features were observed to have been similar to the conditions reported for the previous inspection, suggesting that these features tend to manifest at the beginning of the pavement use and may not necessarily be related to heaving of COPR. Surface abrasion resistance of this surface is similar to that of conventional pavement. Although this system provides better control of infiltrating surface water, compared to conventional pavements, some data may suggest that limited surface water infiltration may have occurred (CH2M HILL, 2008b and 2009b). Overall, MatCon™ does not appear to have been subject to significant effects resulting from COPR expansion since placement.

6.3.6 Articulated Block Cover Pavement

ABC pavement is a system of articulated blocks specially designed to accommodate heave of the ground in general and to allow the temporary removal of blocks for easy regrading of the underlying base in the event of substantial ground vertical movements. The main components of the ABC pavement system are illustrated on Figure 6-1, section d. In this HIMS report, ABC pavement is referred to as ‘special pavement’. The ABC pavement system used at the site consisted of the following components (listed from top to bottom):

- 6-in. thick layer of articulated concrete blocks (or ‘pavers’);
- Leveling layer of coarse stone;
- 18-in. thick layer of gravel;
- Network of low-profile subsurface geosynthetic drain pipes;
- Upper geotextile cushion layer;
- 80-mil thick linear low-density polyethylene (LLDPE) geomembrane;
- Lower geotextile cushion layer; and
- Subgrade (i.e., existing pavement).

The ABC pavement system described above is designed to provide: (i) a low-permeability layer (i.e., geomembrane) to minimize storm water infiltration into the subgrade; (ii) a containment system (i.e., geomembrane) that can separate the pavement system from COPR; (iii) a drainage system (i.e., pavers and highly permeable subbase) to convey surface water from the site; and (iv) a flexible pavement that can accommodate future COPR heave and be easily maintained. This system was first tested during a proof of concept (POC) demonstration (CH2M HILL, 2007d). The system was then tested further in the Area 1800 pilot study.

In this system, the concrete blocks are separate elements connected with steel cables. As such, the blocks permit storm water infiltration and accommodate COPR heave. The coarse layer of stone can support the loading of port vehicles and transmit a relatively large quantity of storm water to the drainage network following a rain event.

Panels of concrete blocks (or “mats”) can be lifted and allow the rapid repair and regrading of heave features in case they develop. ABC pavement can accommodate heave until pavement leveling is needed (Figure 6-2). Heave features are repaired by lifting the concrete block mats, removing the heaved portion of the coarse stone layer, and replacing the concrete block mats. The vertical magnitude of heave that may be repaired without exposing the geomembrane is controlled by the original thickness of coarse stone that was placed. The LLDPE geomembrane used in the ABC magnitude pavement was selected because of its flexibility and ability to accommodate COPR heave. The coarse stone layer and pipe network convey water around reverse slope heave features. The thickness of stone fill and concrete blocks can also accommodate and thus reduce the surface expression of heave.

Extensive programs of laboratory testing and model testing were performed for this system (CH2M HILL, 2007d). The tests demonstrated that the 80-mil thick LLDPE geomembrane can withstand an elongation greater than 200 percent without rupture. Model tests supported the conclusion that the geomembrane and non-woven geotextile exhibit adequate performance for this application. In addition, the selected geomembrane and protective layers have adequate resistance to puncture. Various concrete blocks were observed to be cracked at contact with adjacent blocks as a result of excessive distortion of blocks and localized rutting. The compression strength of the concrete selected for the POC demonstration (i.e., 4,000 psi) appeared to be too low for DMT operation conditions (CH2M HILL, 2007d). However, when the concrete strength was increased to 8,000 psi in the Area 1800 pilot test, the concrete composite strength was found to be adequate (CH2M HILL, 2008a). In addition, the ABC pavement system was observed to be free-draining. No punctures or tears were observed in the geomembrane after exhumation of the field test area. No damage to the drainage pipe was observed in the section that was exhumed.

The ABC pavement system can be designed to resist the loads of operations at DMT and to prevent surface water infiltration to the subsurface. The system could result in a lower groundwater table pavement system due to the increased and faster infiltration in ABC pavements. The overall condition of the ABC pavement with a compressive strength of 8,000 psi during the pilot test has been good. Minor movement of blocks and limited chipping at the edges of some blocks was reported during inspections; however, rutting, surface heave, and broken blocks were not observed. Some blocks exhibited a few cracks. However, during a January 2009 inspection (CH2M HILL, 2009b), the magnitude of grades was observed to remain stable. A small bulge (5 ft in diameter, 2 to 3 in. high) and a small depression were observed. Future observations and monitoring will help establish if the observed pavement relief is related to COPR heave.

6.3.7 Modified Conventional Asphalt

The modified conventional asphalt pavement was noted to be in very good condition. No cracking was observed during inspection. Light-track wear was observed in a few locations. During the early inspections, a 5-ft diameter depression with standing water was observed in this area. In addition, an approximately 10-ft long and 2-in. high heave ridge was observed near a corner of the area where this system was installed. Future observations and monitoring will help establish if the observed pavement relief is related to COPR heave.

6.3.8 Summary

Experience at DMT has shown that the RCC pavement is viable under the conditions found in Area 1702. The Area 1800 pilot test and previous ABC POC testing have demonstrated that: (i) these special pavement systems are viable; (ii) materials required for the pavement system are readily available; and (iii) technologies can be easily implemented without any significant constructability impediments. MatCon™ has been effective and durable as pavement and has provided a low-permeability barrier to infiltration. ABC pavement was also found to be effective as it allows for expedient maintenance and repairs. It is expected that the durability of modified conventional asphalt would be comparable to or exceed that of conventional pavements. Since the installation of these pavement systems, no significant COPR heave has been observed in the pilot test area. Monitoring of the long-term effectiveness of these systems is underway (Section 7).

6.4 Strain Relief Trenches

6.4.1 Introduction

This section presents an evaluation of the performance of SRTs at the site, and provides a synthesis of key design concepts of SRTs.

6.4.2 Description of SRTs

SRTs are trenches filled with soft, compressible backfill material that can accommodate COPR lateral movement while protecting nearby underground structures. The concept of a SRT is illustrated on Figure 6-3. Unlike trenches with conventional soil backfill, SRTs include specially designed backfills that can displace or compress and thereby accommodate COPR lateral expansion. To allow SRT backfill to displace, relief ports must be provided as part of SRT design. In general, after a SRT is installed, expanding COPR tends to move toward this location because the SRT provides effectively a free-edge condition (see Section 3). SRTs absorb lateral displacement and protect buried structures from expanding COPR.

6.4.3 Historic Perspective of SRTs

Two methods have been used at DMT for SRT construction: a continuous trench method and a secant column method. In the continuous trench method, the trench was installed by conventional slurry trench techniques to produce a continuous trench of constant width. The trench was backfilled with a semi-fluid, soft COPR/clay mixture. In the secant column SRT method, 'columns' of soft material were installed by first drilling into COPR overlapping holes (i.e., secant columns) following a primary-secondary pattern, and by mixing in-situ clay slurry with peat granules to create a soft backfill. The continuity of the secant columns is achieved by careful layout and is verified by close observation of the drilling work. The secant column method has several advantages over the trench method. Secant columns occupy a smaller construction area. The in-situ mixing of secant columns reduces exposure to COPR and generates a significantly smaller amount of excavation cuttings. Additional information related to SRTs is provided in Appendix G.

SRTs have been used at the site in three locations: (i) Area 1501; (ii) Area 1800; and (iii) Area 1602, as described below.

- *Area 1501.* In 2004, a SRT was installed using the continuous trench method parallel to, and 4 ft offset from, a damaged storm water pipe in this area. The SRT was approximately 185 ft long, 2 ft wide, and 17 ft deep, extending beyond the damaged pipe section and deeper than the COPR stratum. The SRT was backfilled with a slurry consisting of bentonite, COPR spoils, and Styrofoam pellets. Immediately after the excavation of the SRT was completed, the pipe compression total ceased and the decreased diameter affected by compression rebounded approximately 3 in. (of the 12 in. of total compression). Since the installation of the SRT, no additional compression has been detected in the pipe. Additional details on the performance of this SRT as assessed using inclinometers can be found in Lazarte and Bonaparte (2008).

- *Area 1800.* Three SRTs were installed in Area 1800 along the alignment of existing heave ridges to protect the pavement systems and other subsurface features (e.g., drainage pipes and electrical duct banks) at this location. The basis for installing SRTs along existing heave ridges was that the ridges represent lines of natural strain relief. The SRTs were

12 ft deep and were backfilled using a mixture of native soil/COPR that was injected with organic peat (i.e., Dakota Peat), bentonite, and water. The SRTs were constructed with the secant column method using augured columns 24 in. in diameter. The SRTs were capped with a reinforced concrete slab that covered a continuous horizontal relief port. The relief port has inspection openings installed through the slab every 40 ft to allow visual inspections or instrumentation analysis of the SRT, if needed.

- *Area 1602.* A SRT was also installed using the secant column method to mitigate the effects of COPR expansion on a sound wall located at the southeast corner of Area 1602. In the winter of 2007–2008, the precast concrete panels of the sound wall, which is founded on shallow spread footings, were observed to be displacing from each other, especially at one corner of the wall alignment. As a remedial measure, a SRT was installed along the access road, which is a few feet from the second wall and at a location that approximately coincides with the edge of COPR in this area. The SRT was created with a series of short secant columns that did not extend below the bottom of the COPR layer. The road surface, curb, and gutter were reconstructed and adjacent panels were connected with steel cables. Monitoring of inclinometers near this SRT is ongoing and the sound wall and adjacent features have performed well since the SRT was installed.

6.4.4 Evaluation of SRTs

Extensometer and inclinometer monitoring results (which are presented in Section 7 of this report) indicate that, the SRT in Area 1501 is effectively absorbing ground movements and relieving high compressive stresses that had previously been applied to the concrete storm water pipe. Inclinometer results show a significant displacement component parallel to the SRT, likely due to the decreased lateral confinement near a slope at the edge of Area 1501 (i.e., a free-edge condition). Extensometer results confirm that COPR movement is continuing, but not impacting the pipe. After the SRT was installed, additional compression of the pipe was negligible.

Observations to date suggest that these systems are effectively accommodating COPR lateral displacement and are helping to control heave. SRTs can also redirect expansion to the location where they are built. SRTs should in general extend to the bottom of the COPR to provide protection.

It has been demonstrated that SRTs can absorb COPR lateral expansion and protect nearby underground structures. These systems have been demonstrated to be viable, the materials are readily available, and the two construction technologies tested can be easily implemented with no significant constructability impediments. Since their installation, SRTs have been effective in mitigating COPR lateral displacement. Monitoring of the long-term effectiveness of this system is underway.

6.5 Vertical Stress Control

The principle behind vertical stress control (also referred to as surcharge restraint) is that placing earth fill over COPR provides resistance to heave. The placed fill also provides containment and encapsulation of underlying COPR. A potential consequence of surcharge loading is that the lateral displacement of COPR may tend to increase because, while vertical expansion is deterred, the total volumetric expansion (i.e., sum of individual components in the vertical direction and two orthogonal horizontal directions) remains the same. Although surcharge loading appears to be effective in controlling heave, it may not be effective in controlling the lateral manifestation of COPR expansion toward free edges.

To mitigate the damage to pavement due to COPR heave in Areas 1501 and 1602, a 6- to 7-ft thick layer of surcharge fill was placed over the existing pavement section. This surcharge fill provided an effective restraint against COPR heave. Pavements in these areas have performed well since the installation of the surcharge fill. No upthrust heave ridges have been observed in these areas during recent inspections, except for a small ridge observed in Area 1602 in 2009 that was not surcharged. One of the key factors in achieving adequate performance of surcharge file is the thickness that is required to control COPR heave. Overall, the experience in Areas 1501 and 1602 indicates that the surcharge fill can be effective in controlling COPR heave.

6.6 Conclusions

The findings of the technology evaluation demonstrate that various engineering measures are available for preventing or mitigating damage resulting from COPR lateral movement and heave. Pilot testing and previous site experience provide evidence that multiple mitigation measures can be used to effectively manage COPR movement and heave. These mitigation measures can be used individually or customized in combination based on: (i) the magnitude and nature of COPR lateral movement and heave at a specific location; (ii) the behavior of these remedies and the infrastructure revealed through monitoring; and (iii) the specific nature of the infrastructure to be maintained or protected. The assessment of technologies to mitigate damage resulting from COPR movement also demonstrates that all of the field-tested techniques are viable, can be easily constructed, and can be implemented without significantly impacting port operations or creating a significant environmental or public health issue.

SECTION 7

7 COPR Monitoring and Maintenance Programs

7.1 Overview

This section presents a description and assessment of the COPR monitoring and maintenance programs that have been implemented at DMT. These programs are intended to monitor the response to COPR movement and heave of pavement systems and other site infrastructure and to provide maintenance to pavements and other infrastructure, as may be needed. The monitoring programs were developed to obtain observations and measurements needed to make an evaluation of: (i) whether COPR lateral displacement and heave can be monitored; (ii) maintenance can be implemented in a safe and efficient manner; and (iii) any potential environmental impacts associated with COPR movement and heave can be prevented or mitigated.

Section 7.2 provides a historical perspective of pavement repairs and a brief description of the current maintenance tasks that are being conducted to address the requirements of the CD. Section 7.3 contains a description of the programs conducted to monitor pavement systems and provides a discussion of the main observations and results from monitoring programs to date. Section 7.4 presents a discussion of inclinometer monitoring that has been performed at the site. Section 7.5 provides a discussion of extensometer monitoring that has been performed at DMT. Section 7.6 presents a description of topographic surveys conducted to monitor COPR heave across the DMT site. Section 7.7 presents the results of monitoring of quantities other than ground movement that are relevant to the behavior of COPR or to the performance of pavement surfaces at DMT. Finally, in Section 7.8, a summary is presented of the use of monitoring and maintenance approaches for mitigating and effectively managing issues resulting from COPR movement and heave at DMT.

7.2 Maintenance Programs

7.2.1 Historic Perspective

Maintenance and repair of pavement surfaces that have been damaged by COPR heave at DMT have been performed by MPA since the 1970s. The purpose of the maintenance and repair operations has been to restore the functionality of these surfaces. For example, significant repairs of pavements were made in Areas 1600, 1601, 1700, and 1701 in the late 1970s as a result of historic COPR heave. These areas coincide with the locations of the earliest manifestations of heave at the site. In 1999, surface heave manifestations in Area 1702 were repaired and the area was repaved using RCC. In 2001, damaged pavement in Areas 1501 and 1602 was repaired by placing a surcharge fill over the existing engineered cell in these areas and then paving on top of the fill. In 2002, a large area of pavement in Area 1400 was repaired. Overall, pavement maintenance and repair have been performed in a manner that has successfully presented the functionality of pavements at DMT for approximately 30 years.

7.2.2 Current Maintenance Program

The approach to pavement maintenance at DMT has been enhanced since approximately 2006, in the framework of the CD requirements. As required by the CD, a plan for conducting site-wide inspection of surface covers and for maintenance was developed, as presented in the document titled "*Surface Cover Inspection and Maintenance Plan*" (CH2M HILL, 2007g). The plan presents a methodology for performing inspections and maintenance of surface covers over COPR at DMT, as well as a schedule for performing inspections and maintenance. As part of the scope of the plan, a baseline set of observations was made in 2008 of all paved surfaces at DMT. In addition, areas requiring maintenance and/or repairs were identified during the initial inspection of pavement surfaces. The primary focus of the baseline inspections was on cracks, heave ridges, potholes, breakage areas, and other defects. The data and observations observed in the baseline of inspection serve as a reference against which future observations will be compared. This plan also calls for semi-annual inspections on a site-wide basis following a systematic methodology. Two surface inspections have been conducted since the plan was first implemented in June 2008.

After the baseline inspection was completed and areas requiring maintenance/repair were identified, a planned sequence of pavement repairs was initiated in late 2008. Repairs to more significant or time-sensitive areas were prioritized. Figure 7-1 presents a plan view of the repairs that will be completed through the end of 2009. The planned maintenance activities involve repairs to cracks and potholes in various locations, as well as milling and pavement replacement in other locations, particularly where large heave ridges have been observed. In all, approximately 45 locations of relatively large size have been identified for repair or maintenance (Figure 7-1). Numerous other smaller areas have been identified for maintenance or have already been repaired but are not shown on Figure 7-1. A significant number of the planned repairs have been completed. For example, since 2008, over four linear miles of cracks have been repaired, potholes have been filled, and areas have been repaved. In addition, one of the larger areas identified for pavement replacement (i.e., a 1.5-acre area in Area 1400) has been repaved. During this work, disruptions to port operations have been minimized.

Overall, the baseline inspections, routine repairs, and repairs identified during the baseline inspection have enhanced the functional performance and the degree of environmental protection of the cover systems at DMT.

7.3 Monitoring of Cover Systems

7.3.1 Historic Perspective

Pavements have historically been monitored at DMT to assess the effects of COPR heave on pavement performance. After pavement disruption was first observed at DMT, MPA initiated efforts to determine the nature of the pavement distress and to identify measures to mitigate damage to paved surfaces. In this section, a historic perspective of the impacts of COPR to pavement performance is provided. This perspective is relevant to the HIMS because it provides valuable background information on the long-term performance of certain mitigation measures and the viability of these measures for controlling heave.

Century (1980) conducted a survey of distressed pavement as part of a site investigation in Areas 1400, 1500, 1600, 1601, 1700, and 1701. A copy of Century's report is included in Appendix A. Century observed that pavements exhibited general heave up to 4 in. high over a relatively large area. This feature type coincides with the manifestation of general heave described in Section 3 of this report. In addition, linear heave features (e.g., ridges) up to approximately 10 in. high were observed in some areas. General heave was observed to be not particularly detrimental to pavement surfaces, as it was noted that differential vertical movement had not occurred in these areas. On the other hand, ridges were concluded to be particularly detrimental to pavement integrity. In addition to heave of pavements, a small component of horizontal movement was reported at some locations, as evidenced by offset traffic lines painted on the pavement. Concrete slab pavements exhibited vertical movement of up to 3 in. in some locations. Pavements over utilities tended to exhibit the largest heave, which in some locations was as great as 1 ft. This observation is consistent with the trend noted in Section 3 of this report, that the larger heave features observed tend to occur over utility alignments. In other locations, no heave was observed over utility duct banks. Some of the utility trenches inspected by Century were noted to have been backfilled with COPR. Along the COPR-backfilled trenches, heave features were relatively larger than in other locations. Based on the discussion of COPR expansion mechanisms presented in Section 5 of this report, the cause for these large heave features can be attributed to: (i) reactivation of COPR transformation due to disaggregation and associated loss of passivation that most likely took place during trench backfill; and (ii) increased water content in the COPR backfill where the trench served as a water conduit. No apparent correlation was observed between magnitude of heave and traffic patterns, utility location, or others factors.

PCS-Law (1991) performed a site-wide evaluation of pavement conditions, as well as a series of NDTs on pavement surfaces. A copy of PCS-Law's report is included in Appendix A. Using topographic survey data, PCS-Law quantified heave magnitudes and estimated heave rates. The visual survey results indicated that most pavement distress was uncorrelated to traffic loads, was correlated with COPR heave, and tended to increase to the northeast of DMT, where the thickness of fill over COPR was smaller. NDT results confirmed that the observed distress was unrelated to any pavement structural deficiencies or to the materials used to construct the pavements. Similar to trends noted previously, it was observed that pavement distress is more significant along the alignment of underground utility lines. In addition, utility corridors that allowed surface water to infiltrate into the ground correlated with more significant heave, and deeper utility conduits tended to correlate with more intense pavement distress.

7.3.2 Current Pavement Monitoring – Area 1800

Pavement monitoring is currently being conducted in the Area 1800 pilot study zone (CH2M HILL, 2008c). As discussed in Section 6, three different types of specialized pavement systems were installed in December 2007, over a relatively small area (i.e., 7.2 ac.) to evaluate whether these pavements could accommodate COPR heave better than conventional pavements. The pavement types that are being used in Area 1800 include MatCon™ pavement, ABC pavement, and modified conventional asphalt pavement. Components, features, and pilot test performance of these specialized pavement systems are presented in Section 6 of this HIMS report. The viability and effectiveness of these systems was also discussed in Section 6. In this section, observations related to ongoing monitoring of these systems are described.

Following construction of the pilot area in December 2007, pavement surfaces in the Area 1800 test location were inspected in May 2008, June 2008, December 2008, and March 2009. The inspections were performed to evaluate general pavement conditions and to observe evidence of ponding after rainfall events, rutting, reflective cracking, settlement, and heave. The inspections were also intended to identify any need for maintenance for the pavement systems or any situation that required more frequent monitoring. The primary observations from the inspections of each of these systems are provided below.

MatCon™. Since the end of construction in December 2007, this area has been used for parking of heavy equipment (i.e., front-end loaders and tracked excavators). The MatCon™ area was noted during the inspections to be, in general, in very good condition. During the first inspection, it was found that the surface had 10 depressions, ranging from 6 in. to 20 ft in diameter, that contained some standing water; each of the depressions was shallow and the MatCon™ material at each depression was not damaged. In addition, some surface abrasion was observed, apparently caused by the tracks of the excavators and the buckets of front-end loaders that had been parked at this location. No cracks or surface heave features were observed in this area. In the June 2008 inspection, the depressions containing ponded water were again noted. Minor potential heave conditions were observed along the southern and eastern portions of the modified conventional asphalt pavement sections. During the December 2008 inspection, these features were observed to have remained stable, suggesting that these features arose from construction and subgrade conditions and may not necessarily be related to heaving of COPR; similar trends were observed in March 2009. Monitoring will be continued to further evaluate pavement conditions. One small area was identified to be in need of some repair, although the feature was not related to heave. The observations made to date indicate that the effects of COPR expansion on this pavement type have been small. To date, no pavement damage caused by COPR expansion has been observed in this area.

ABC. Since the end of construction in December 2007, this area has been used for parking of tracked, heavy equipment and automobiles. The overall observed condition of the ABC pavement has been very good. Minor movement of blocks and limited chipping at the edges of some blocks was reported during inspections; however, no rutting, surface heave, or broken blocks were observed. Some blocks exhibited a few cracks. During the December 2008 inspection, block damage was not reported to have increased beyond the level of damage observed earlier. In some areas, a few localized depressions at the blocks and horizontal slippage between the blocks and the substrate were noted. Some blocks located at the edge of this area showed some spalling, apparently as a result of tracked equipment entering or exiting the ABC pavement area. A 5-ft diameter, 2 to 3 in. high bulge and a 3 ft diameter, 2 in. deep depression, both which had been caused during construction, were observed to remain stable, with no indication of deteriorating conditions over time. In general, the observations made to date indicate no visual evidence of COPR heave in this pavement area. Monitoring of the durability of the concrete blocks must continue to assess the long-term performance of this system.

Modified Conventional Asphalt. This area has been used primarily for parking automobiles, as observed during the inspections; therefore, the loading over this area has been lighter than in the other two areas. The modified conventional asphalt pavement was noted to be in very good condition. No cracking was observed during the inspections. Light-track wear was observed in a few locations. During early inspections, a 5-ft diameter depression with standing water was observed. In addition, an approximately 10 ft long and 2 in. high heave ridge was observed near a corner of this area. The observations made to date indicate that the effects of the observed COPR heave on this pavement type have been negligible.

The observations made during the monitoring of these pavement systems suggest that the special pavement systems are performing well under typical port use. Because the modified conventional asphalt pavement section was only subjected to light loads, the performance of this system under heavy loads is still unknown. The number and magnitude of the pavement defects observed at the beginning of the monitoring period have remained stable and are believed to have arisen mostly during construction. This program has shown that pavement monitoring can be effectively implemented at DMT.

7.4 Inclinometer Monitoring

7.4.1 Historic Perspective

Inclinometers have been used at DMT to quantify the magnitude and rate of COPR lateral movement. In particular, inclinometers have been used to monitor lateral ground movement near features, including buried utilities, SRTs, and natural free edge conditions. Inclinometers have been used in three different time periods, in 1980, 2005 to 2006, and 2007 to present.

Century Engineering (1980) used an inclinometer during a field trench investigation. Readings obtained from this inclinometer were compared with the convergence movement of the trench walls. This inclinometer was monitored for a relatively short time (approximately three months) and most likely captured both stress relief due to the trench excavation and very little COPR lateral expansion. Because of the short duration of use, this monitoring is not believed to be a reliable indicator of COPR movement and therefore will not be further discussed in this section.

In 2004, nine inclinometers were used to measure the response of COPR adjacent to the 185 ft long SRT built in Area 1501, which was described in Section 6 of this HIMS report. The inclinometers were installed in COPR in the near-field adjacent to the SRT. These inclinometers were monitored on a monthly basis for approximately 20 months, except for a period between early 2005 and late 2006 when readings were not obtained. Inclinometer monitoring began approximately three months after the SRT was installed; therefore, displacements that may have occurred shortly after excavation was completed were not measured by the inclinometers. By the end of the 20-month monitoring period, the functionality of four inclinometers had been lost because COPR lateral displacement apparently deformed these inclinometers and rendered them inoperable. Additional discussion of the Area 1501 inclinometer monitoring program can be found in Lazarte and Bonaparte (2008).

Forty-two inclinometers were installed during 2006 and 2007 across the site as part of the COPR investigation (see Appendix E). Several inclinometers were installed as multiple-instrument arrays in Areas 1501 to evaluate displacement adjacent to the Area 1501 SRT and the edge of the Area 1501 engineered cell. The remaining inclinometers were installed across the interior of the site relatively far from free edges to provide data on trends of ground displacement. After an initial period when the inclinometers were monitored on an approximately monthly monitoring frequency, these inclinometers have been monitored quarterly.

7.4.2 Results of Inclinometer Monitoring

The results of inclinometer monitoring conducted at the site from 2004 through the first quarter of 2009 are presented in Appendix E. The results of these monitoring events are described in Appendix E of this report and are summarized briefly below.

2004-2006 Monitoring

Monitoring at Area 1501 (Figure 7-2) between 2004 and 2006, provides evidence that: (i) the apparent displacement strain (i.e., the ratio of measured horizontal displacement to the distance between adjacent inclinometers) in an array is relatively uniform along the array, with the largest displacements occurring at inclinometers closest to the SRT; (ii) the COPR layer and the surcharge fill above it moved toward the SRT mostly as a block; (iii) a narrow (i.e., 3 to 5 ft) zone of shear was observed between the COPR layer that is moving and the underlying natural deposits, which had negligible displacement because they are below the zone of intense shear; (iv) displacement patterns and annual displacement rates were consistent over the monitoring period, suggesting a more or less constant lateral expansion of COPR with a moderate seasonal variation; (v) displacement rates near the SRT varied between 1 to 2 in./year (Figures 7-3 through 7-4); and (vi) the displacement direction toward the SRT.

2007-Present Monitoring

Monitoring results of inclinometers installed near the COPR edge (i.e., adjacent to the SRT and at the perimeter of Area 1501) show trends that are consistent with the 2004-2006 monitoring described above. The maximum inclinometer displacement in Area 1501 occurs within the COPR layer and this magnitude is also observed at the ground surface, as COPR and the above fill move as a block. No cracking of surface pavement has been observed in this area. The largest cumulative displacement of all inclinometers was observed in inclinometer INC-1501-E, which is located near a free edge and the SRT. Displacements in interior inclinometers (i.e., those relatively far from free edges) have been significantly smaller, near the range of precision of the inclinometer device over the monitored time period. The direction of movements at interior inclinometers is either stable or tends to oscillate within the degree of instrument precision, with no predominant direction of movement. Inclinometers near free-edge have exhibited relatively constant displacement rates since their installation. A seasonal variation in displacement rates can be as large as ± 50 percent but are typically much smaller in the Area 1501 inclinometers, with higher rates tending to occur during summer months and lower rates during the winter. The rate of displacement tends to decrease with distance from free edges. The average edge displacement rate during this monitoring period was approximately 1.8 in./yr. Generally, for interior inclinometers, the average displacement rate is approximately 0.1 to 0.2 in./yr., after equilibrium conditions are achieved when installation is completed (Figure 7-5).

The zone of influence, which is defined as the area where the lateral movement of COPR tends to be directed toward the free-edge or the SRT (as described in Appendix E), is estimated to be approximately 120 to 170 ft in Area 1501. For inclinometer Arrays 1 and 2 in Area 1501, the calculated average strain rates are 0.13 to 0.15 percent/yr. Inclinometers installed near the Area 1602 SRT and existing sound wall at the southeastern corner of Area 1602 have shown that movements are in a direction toward the sound wall and SRT.

7.5 Extensometer Monitoring

7.5.1 Introduction

Tape extensometers have been used to monitor the magnitude and rate of change of horizontal distance between fixed points on structures at DMT. The tape extensometer can provide reliable distance measurement to an accuracy of a few thousandths of an inch, allowing small movement trends to be detected and quantified over a relatively short time period. At DMT, tape extensometers have been used to measure the distance between structural columns of Consolidation Shed 11 and to monitor the change in diameter of the reinforced concrete storm drain pipe located in Area 1501 adjacent to the SRT described earlier. The monitoring of these features is described in the following two subsections. Additional information of extensometer monitoring is contained in Appendix F.

7.5.2. Extensometer Monitoring of Shed 11

MRCE used extensometers to measure the change in distance between columns of Consolidation Shed 11 in Area 1100. Shed 11 is approximately 650 ft long and 100 ft wide, with 20 ft wide loading docks located outside of the shed structure and extending along the north and south sides of the building. The Shed 11 roof is supported on 27 rigid steel frames spaced at 25 ft intervals (Figure 7-6). The end columns of the frames are supported on piles. At each frame column there is a tie-rod that extends below the building floor and connects to the column on the other long side of the building. Tie-rods are designed to prevent spread of the piles.

Monitoring data obtained from extensometers was used to estimate changes in column spacing or separation (i.e., along the side walls and along the frames, in a cross-shed direction) between October 2007 and October 2008 (Figure 7-7). Tape extensometer data is presented in Appendix F, which shows total displacements from baseline readings. Using the type of data presented on Figure 7-7, it was found that for the north and south walls of Shed 11, movement parallel to the walls ranged from a maximum convergence of 0.12 in. to a maximum spreading of 0.13 in. On average, the measured spreading approximately balanced the convergence along the walls. The cross-shed direction movement ranged from a maximum convergence of 0.18 in. to a maximum spreading of 0.26 in., and averaged as a spreading of 0.15 in. These rates are comparable to displacement rates of interior inclinometers.

Observations of the loading dock slabs indicate that the loading docks on both sides of the building are moving away from the Shed 11 walls. Displacement from gaps in the slab was calculated to be on the order of 0.3 in./yr.

Tape extensometer readings obtained over one year indicate that small column movements took place parallel to the longitudinal axis of the shed but some movement occurred transverse to the shed longitudinal axis. Average cross-shed movements indicate an overall spreading with an average rate of 0.16 in./yr. Cross-shed readings at Column Lines 3, 4, 9, 10, 13, 15, 17, 18, and 20, indicate increased spreading for all measurement intervals as a result of ground displacement. Average rates of spreading at these columns range from 0.14 to 0.25 in./yr.

The extensometer measurements of Shed 11 indicate that the horizontal movement of COPR in this area is occurring at a rate that is consistent with the movement of COPR in other interior locations of the site.

7.5.3 Extensometer Monitoring of 15th Street Storm Drain

The 8-ft diameter, twin, reinforced concrete pipes known as the 15th Street storm drain were constructed in the 1980s with COPR fill of Area 1501. In 2001, the south pipe was observed to be deforming inwards at the springline; while no deformation was observed in the north pipe. In June 2002, monitoring of compression (i.e., diameter shortening) in the south pipe was initiated using a tape extensometer at the springline along a 180 ft long pipe section. The monitoring was continued over a time period of 16 months. The monitoring is described in MRCE (2004). Over this period, the south pipe compressed up to 1.7 in. (Figure 7-8) and longitudinal cracking was observed in the pipe. At the start of the monitoring period, the compression rate of the pipe was calculated to be approximately 2 in. /year. After approximately four months, compression of the pipe progressed at a slower rate, approximately 1.2 in./yr, possibly due to stress relaxation in the COPR layer following pipe cracking or seasonal fluctuation in the COPR expansion rate. In contrast, the diameter of the north pipe compressed by less than 0.1 in. over the same period. After the installation of the SRT at this location, the compression of the south pipe decreased substantially over a few months, indicating that the stresses on this pipe had been effectively relaxed (MRCE, 2004).

Extensometer monitoring of the storm drain pipes (see Appendix F) has provided valuable information to evaluate the rate of deformation resulting from COPR lateral movement and also the ability of SRTs to absorb lateral ground displacement to protect the pipes. The monitoring detected that the displacement rate was sufficiently slow to allow for SRT construction to protect the pipe from continued deformation and to allow pipe repairs before the pipe functionality was unsatisfactory.

7.6 Topographic Surveys

Certain areas of the site that have been under construction or have been part of pilot studies have been surveyed more frequently, as dictated by construction and study needs. These include Areas 1501, 1602, 1800, and Shed 11. In addition, survey pin systems have recently been installed to monitor surface movement around the area referred to as the Ports of America Building, in portions of Area 1501, and along the perimeter access road to Area 1501. Baseline data for these pin systems were established in December 2007.

Information on ground surface elevations in Area 1800 was obtained from as-built drawings of this area, which were completed in 1974. Surveys were conducted in 2003 and 2004 in areas of significant COPR heave. The 2003 survey had a relatively high density of survey points but was limited to a relatively small area. On the other hand, the 2004 survey covered a broader area but with fewer survey points. Comparing the topographical data of 1974 and 2003, contours of heave were obtained for this area (Figure 7-9). The height of the maximum heave ridge identified through the surveys was approximately 1.7 ft, over a period of 29 years, as shown in cross-section AA (Figure 7-10).

Century (1980) reports the results of a ground survey conducted in various areas (i.e., Areas 1400, 1500, 1600, 1601, 1700, and 1701) of DMT. Century (1980) compared the ground elevations obtained from the 1980 survey to those measured in an as-built survey 6 years earlier (for Areas 1400 and 1500) and 4 years earlier (Areas 1600 through 1701) (Figures 7-11 and 7-12a,b,c). The location and magnitude of heave in relation to damaged pavement areas is shown on Figure 7-11. The magnitude of heave along selected cross sections in these areas is shown on Figures 7-12a,b,c. In these figures, the negative values of heave were attributed to erroneous data in some locations in the original construction surveys (Century, 1980).

7.7 Other Monitoring

Near Surface Trench Drain (NSTD) in Area 1800

The NSTD is used to monitor the ability of the drainage system of the ABC pavement to provide collect and drain infiltration. The system consists of two drainage channels located along the southern edge of the ABC pavement section and is designed to allow measurement of stormflow. One drain is used to measure discharge from the coarse gravel fill under the ABC pavement, and the other drain is used to measure surface runoff from the ABC pavement. Water from both channels is conveyed to the existing storm drain system at the site. Monitoring has been conducted for a period of approximately one year to identify patterns under both low-flow and high-flow conditions. Monitoring reports for this area (CH2M HILL, 2008b) indicate that most of the volume of rain falling on the ABC pavement is absorbed through the open joints around the ABC blocks. Subsurface water is released to the atmosphere by evaporation, infiltrates through the stone layer, and then dissipates gradually into the underlying drainage system. Monitoring of the drainage system indicates that the system is performing as designed to collect and detain storm water flows. These results support the notion that the construction of small diameter shallow storm drains is feasible at these locations.

Geochemical Environmental Monitoring in Area 1800

Several instruments were installed in the subsurface of the Area 1800 pilot study area to monitor changes in the geochemical environment as a result of the construction of cover systems in the pilot area. Three clusters of instruments were installed to monitor changes of some key indicators (e.g., groundwater as levels and moisture content in the vadose zone) below the MatCon™ and ABC pavement compared to values at a control location without surface cover. Instruments included piezometers, barometric pressure/temperature sensors, moisture sensors, carbon dioxide (CO_2) sensors, and lysimeters (located in the vadose zone) for pore water sampling for pH measurement (Figure 7-13). Environment and geochemical monitoring data obtained in Area 1800 after one year of monitoring was presented by MRCE in CH2M HILL (2009b).

Groundwater level and moisture content findings are summarized in CH2M HILL (2009b). Findings indicate that the elevation of the perched water table dropped beneath the MatCon™ cover, and adequate storm water infiltration was noted at each storm event. The low-profile drain system of the ABC cover dissipated the perched water table, and the shallow, vadose-zone moisture sensor showed gradual drying while the mid-depth sensor showed gradual wetting, possibly due to the rise of the capillary fringe as a result of the ABC membrane preventing evaporation. After one year of monitoring, the perched water table below the MatCon™ cover was about 1 ft lower than the perched water table below the control location. Water levels below the ABC cover are observed to be at the static water table, about 4 ft lower than the water level below the MatCon™ surface and 5 ft below the control location.

CO_2 measurements show a seasonal fluctuation in atmospheric carbon dioxide within the vadose zone at the test area location, averaging about 225 parts per million (ppm) during winter months and about 450 ppm during summer months. Below the ABC cover, the shallow CO_2 sensor measured no CO_2 during winter months in the beginning of monitoring and about

25 ppm during the summer, no CO_2 after the summer. Below the control location, the shallow CO_2 sensor measured no CO_2 during winter months and about 50 ppm, with spikes as high as 240 ppm after storms, during the summer. A CO_2 content of zero ppm was measured in the deepest sensors at all locations.

Pore water pH was measured in samples recovered from lysimeters in the vadose zone periodically. Generally, pore water pH ranged from 10.5 to 13.5. The pore water pH tended to be lower when atmospheric and subsurface CO_2 were high (summer months), and was higher when atmospheric and subsurface CO_2 were low (winter months). The pH values measured in the vadose zone pore water were generally lower below the control location than below the MatCon™ and ABC pavements.

In general, subsurface temperatures fluctuated seasonally between 57 and 69°F (14 and 21°C) near the base of the COPR layer and between 39 and 77°F (4 and 25°C) above the shallow COPR layer. Warmer temperatures correspond to summer months. The deeper sensor indicated a slight time lag in this deep location as compared to atmospheric changes, which varied from 16 and 108°F (-9 and 42°C) during the same period.

Barometric pressure was measured in the atmosphere and in the ground using sealed pressure transducers to observe the difference and time lag between atmospheric and in-ground barometric pressures. In-ground barometric pressure was generally within +/- 0.01 psi (+/- 0.03 in Hg) of the atmospheric pressure over an atmospheric pressure range of 14.4 to 15.1 psi (29 to 31 in Hg). The largest difference between in-ground and atmospheric pressure was observed at a shallow barometer below the ABC membrane.

Inclinometer monitoring below the MatCon™ and ABC pavement areas is ongoing. Inclinometers are located near the SRTs. Inclinometer measurement of ground movement and direction are being used to establish whether a correlation exists between ground displacement rates measured with inclinometers and the geochemical environments monitored in this area.

7.8 Summary

The monitoring programs described above have provided critical information and data to help evaluate the performance of pavement surfaces, ground movement (both vertical and horizontal), movement of structures as affected by COPR movement, and other quantities related to the performance of the DMT infrastructure and the geochemical environment present at the site. In all cases of monitoring of COPR expansion and heave, it has been shown that COPR heave and lateral displacements occur at a very low rate. Lateral movement of COPR has been monitored to be very small at interior inclinometers (i.e., most of the COPR fill area). A faster rate of movement is only taking place under edge conditions. Heave appears to be taking place at low rates in all of DMT. It is expected that the heave trends observed at the site will become more apparent and possibly differentiated in various site areas after a few events in the programmed semiannual site surveys. The methodologies used in these programs have been effectively applied and have measured stable trends. The results presented herein also demonstrate that COPR expansion, its manifestations, and the effects of COPR expansion on the infrastructure can be quantified using systematic monitoring programs.

SECTION 8

8 Conclusions

This report summarizes the results of the Heave Investigation and Minimization Study (HIMS) that was performed to satisfy the requirements of Section III.B.6 of the 5 April 2006 CD for DMT. The HIMS has been undertaken pursuant to the HIMS Work Plan and demonstrates that the factors that cause mineralogical transformation and volumetric expansion of COPR are well understood, and that the mechanisms of COPR lateral movement and heave have been defined through field investigations, monitoring, laboratory studies, and pilot programs. As such, the HIMS meets the requirements stipulated in the CD. The main findings and conclusions of the HIMS are summarized below.

- *Extent and Nature of COPR at DMT are Well Defined.* The results of field investigations and studies described in Section 4 of this report have been used to define the depth and lateral extent of COPR and the relative distribution of GB COPR and HB COPR at the site. In addition, an extensive program of field and laboratory testing was conducted to characterize the chemical, mineralogical, and geomechanical properties of COPR. This information is used in Section 4 to develop a detailed conceptual site model describing the thickness, extent, chemical and mineralogical characteristics, and geomechanical properties of COPR.

- *Transformation and Expansion Mechanisms are Well Understood.* The field investigations, monitoring, field and laboratory testing, and pilot programs performed during the HIMS have provided information to develop a thorough understanding of COPR mineralogical transformation and volumetric expansion, which is presented in Section 5. The investigation and study results described in the HIMS demonstrate that the transformation and expansion of COPR are primarily a function of the occurrence of wet-dry cycles in the vadose zone, the location of COPR relative to the groundwater table, specific geochemical conditions of the COPR pore water in the vadose zone, differences in geomechanical behavior between non-lithified GB COPR and lithified HB COPR, COPR particle size, and presence/absence of passivation effects. A validated and unifying conceptual model has been developed for the lithification and expansion of COPR at DMT to demonstrate that the mechanisms causing COPR transformation and expansion at DMT are well understood.

- *COPR Movement and Heave Magnitudes and Rates are Well Understood.* The results from the displacement monitoring of COPR at the site are used in Section 7 of this report to define the magnitudes and rates of COPR movement (lateral) and heave (vertical) at DMT. This information, together with the understanding of COPR transformation and expansion presented in Section 5 and the site conceptual model presented in Section 4, demonstrates that COPR movement and heave can be classified, quantified, monitored, and modeled.

- *COPR Movement at DMT is Not a Significant Environmental or Public Health Issue.* It is demonstrated that heave manifestations do not result in the exposure of COPR at the surface and appropriate protocols are in place to protect workers and others from exposure during any excavations into COPR.

- *Effective Engineering Measures Exist to Prevent or Mitigate Impacts Associated with COPR Movement and Heave*. In Section 6, it is shown that special pavements, SRTs, and surcharge loads have been effectively used at DMT to prevent or mitigate damage where required due to excessive COPR movement and heave. These engineering measures can be used individually or in combination to address the specific COPR movement and heave behavior that was revealed through monitoring for the specific infrastructure features to be maintained or protected.
- *COPR Monitoring and Maintenance Programs Have Successfully Managed Heave.* As described in Section 7, monitoring and maintenance programs have been implemented at DMT over many years. Results from these programs have shown that COPR movement and heave occur slowly and can be detected before significant levels of damage occur to pavements or structures. The studies also show that monitoring and maintenance programs conducted at DMT have been effective in preventing heave-related COPR exposure at the ground surface.

In summary, the information and findings presented in this HIMS report are extensive and sufficient to support the conclusion that COPR movement and heave can be monitored, that the rates of such movements and heave are sufficiently slow to provide ample time to respond to the monitoring results, that damaging effects of these movements and heave can be monitored, prevented, or mitigated using engineering controls, and that COPR movement and heave do not pose a threat to the environment and human health.

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