Appendix E

Guide to Geotechnical Considerations Associated with Stormwater Infiltration Features in Urban Highway Design

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1 Introduction

This Guide is intended to be used to help identify the technical factors that should be considered in conducting a site-specific geotechnical evaluation of the potential impacts of stormwater infiltration, and to help guide the development of geotechnical designs that safely allow for an enhanced degree of volume reduction in the urban highway environment. This Guide is intended to be used in conjunction with the comprehensive feasibility screening process described the main body of this Guidance Manual, which includes several feasibility screening factors beyond geotechnical factors. This Guide is primarily intended for stormwater engineers to understand the potential geotechnical impacts that stormwater infiltration may have on surrounding features (i.e., after water leaves these systems). It is not intended to serve as a complete geotechnical reference.

This Guide is organized as follows:

Section 2 provides a discussion on how infiltration feasibility factors into the geotechnical investigation and design process. In other words, what types of investigations and analysis are appropriate at each design phase?

Section 3 identifies several key forms of geotechnical failure that may be associated with stormwater infiltration, including discussion of how these failure mechanisms should be assessed, analyzed, and potentially mitigated in the planning and design process.

Section 4 provides more detailed information about certain “mitigation measures” that may be incorporated into planning and/or design to help mitigate elevated risks posed by stormwater infiltration and potentially allow for greater volume reduction.

Section 5 provides a synthesis of geotechnical feasibility factors and general guidance regarding how they may influence different types of volume reduction approaches.

Section 6 provides a summary of recommended contents of project-specific reports related to investigation of geotechnical feasibility of stormwater infiltration and associated design parameters**.**

The geotechnical factors and potential mitigation measures presented in this Guide were based on the following range of stormwater BMPs:

1. Direct infiltration into roadway subgrade – designs include permeable pavement with direct infiltration and collection of runoff within the roadway shoulder and routing back beneath the roadway for infiltration;
2. Infiltration in shoulders – designs include collecting drainage from the roadway and infiltrating within permeable pavement strips or other features along roadway shoulders;
3. Compost amended slopes/filter strips adjacent to roadway – designs incorporate compost or other decompaction approaches to increase absorption and encourage subsurface infiltration as water sheet flows away from the roadway;
4. Channels, trenches, and other linear depressions parallel to roadway - designed to achieve direct and incidental infiltration, tend to be set back from the roadway at the toe of slope where space allows;
5. Basins and localized depressions – design incorporating basins or localized depressions, ranging in size from relatively small (with footprint less than 200 square feet) to larger (with

footprint on the order of 1 acre or more), located at intervals along the roadway or in open spaces such as interchanges and other wide spots in the right-of-way (ROW).

Description of specific BMPs are provided in **Appendix A**. Additional geotechnical design issues not presented in this Guide may result from design features and infiltration mechanisms other than those stated above.

2 Assessment of Infiltration Feasibility in the Geotechnical Investigation and Design Process of Roadways

2.1 Overview

2.1.1 Goals of Infiltration Assessment in Planning and Design Phases

Successful stormwater infiltration inherently results in an increase in soil moisture in subsurface soil and/or rock and a potential rise in the local and/or regional groundwater table, which in turn may have geotechnical impacts on local features. For a successful project, these potential geotechnical impacts must be identified and considered during the preliminary feasibility screening/planning phases. In infiltration will be used on a project, then these issues must be fully evaluated (including design and evaluation of mitigation measures, if appropriate) during the design phases of the BMP.

> **Preliminary feasibility screening/planning level evaluation.** At the planning phase of a project, information about the site may be limited, the proposed design features may be conceptual, and there may be an opportunity to adjust project plans to adapt to project goals, including volume reduction, if applicable. At this phase, geotechnical practitioners are typically responsible for conducting explorations of geologic conditions, performing preliminary analyses, and identifying particular aspects of design that require more detailed investigation at later phases. As part of this process, the role of a planning level infiltration feasibility assessment is to help planners reach early and tentative conclusions regarding where infiltration is likely feasible, possibly feasible if done carefully, or clearly infeasible. This determination can help guide the design process by influencing project layout, informing the selection of BMPs, and identifying more detailed studies, if needed.
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> **Design level evaluations.** When a decision has been made to use BMPs that infiltrate stormwater, additional analyses may be required to be performed or existing geotechnical analyses may require refinement. This phase may require more detailed information, particularly in the vicinity of proposed infiltration BMPs. The purpose of design level infiltration analysis is to ensure that infiltration used in a manner that is safety and reliable. The additional information and analyses at this phase could also result in a reversal of planning level findings, such as identification of issues that were not previously known or considered.

Guidance for geotechnical assessment of infiltration feasibility is provided in this document for both the planning level and design phases. General guidance for each phase is provided in the sections that follow. Guidance on assessing and accounting for specific geotechnical hazards is provided in Section 3.

2.1.2 Consideration of Total versus Incremental Risk

In standard roadways designs, there are various pathways for water to enter the road base and shoulder material in the absence of intentional infiltration (e.g., seepage through cracks and joints in the pavement, lateral drainage). As such, a certain degree of wetting of base materials is commonly anticipated in assessment of material properties and the design of the roadway. Therefore, the risk posed by stormwater infiltration should be considered to be the incremental risk posed by the addition of greater quantities of water into the subsurface. For example, where a standard design analysis includes an assumption of saturated subgrade to assess the risk of a certain form of failure, then the incremental risk posed by stormwater infiltration may be negligible.

2.2 General Guidance for Planning Level Feasibility Assessment

Potential geotechnical impacts from stormwater infiltration should be determined early in the planning phase to reduce the potential for late-stage design changes and unanticipated project costs. Fortunately, information commonly collected as part of project planning level investigations can be used as part of planning level geotechnical feasibility screening. The goal of the geotechnical assessment in the planning and feasibility phase is to identify potential geotechnical impacts and to determine which impacts may be considered fatal flaws and which impacts may be possible with design features to mitigate risks.

To identify and assess the potential geotechnical impacts, the designer should first understand the area of impact of the proposed stormwater infiltration system. The “impact area” is the area within which stormwater infiltration would have a non-negligible effect on geotechnical conditions. The extent of the impact area will depend on the type of infiltration system, volume and duration of infiltration anticipated, subsurface geology and other site-specific features. In general, the impact area can range from several feet to hundreds of feet or more and can extend beyond property boundaries and right-of-ways

To assess the area of impact, the designer may find it necessary to answer the following questions regarding the subsurface conditions:

- How deep is the water table? Is it expected to fluctuate significantly, such as due to seasonal effects or due to water level fluctuations of adjacent water bodies?
- What are the typical subsurface soil and rock conditions?
- Is the subsurface environment naturally-laid sediment or historical fill?
- What is the permeability/hydraulic conductivity of the subsurface materials?
- Is subsurface water flow controlled by percolation, flow in joints, flow in fractures, or along a confining layer?

The subsurface geology may have a significant impact on the determination of the area of impact. For example, if a high permeability sand layer is present above a deep groundwater table, the area of impact may be relatively limited because the infiltration would be generally vertical and the potential for groundwater mounding would be limited. In contrast, for conditions with lower permeability soils and a shallow groundwater table, the area of impact may be greater as the groundwater table would tend to mound to a greater degree and promote lateral migration of water. The user can consult **Appendix C** to assess these factors for specific combinations of BMP types and conditions. Other factors, such as dipping geologic strata (i.e., geologic layers that are inclined from horizontal), buried riverbeds, or jointing (i.e., directional cracks in rock layers) can have significant effects on the area of impact.

In addition to the hydrology of the subsurface, the designer must also consider other aspects of the geology and subsurface conditions to be able to access the types of potential geotechnical impacts that stormwater infiltration. The designer should be able to provide answers to the following questions, in addition to those above:

- What is the potential impact on the groundwater table from stormwater infiltration? (consult Appendix C)
- Are there expansive or collapsible soils present?
- Are there compressible or liquefiable soils present?
- Are there any slopes nearby?
- What are the potential impacts to existing structures?
- Is there a risk of inducing sinkhole development or collapse?

Further, the designer should catalog the existing infrastructure features within the potential impact area. This catalog should include utilities (present and abandoned), above- and under-ground structures, retaining walls and abutments, and hardscape and structure road subgrade features. The proximity to existing infrastructure and structures may help the designer identify early in the planning and feasibility phase areas where infiltration may be considered more favorable and areas where it has the potential to have significant geotechnical impacts.

The designer should consider potential impacts from stormwater infiltration as well as the risks associated with that impact. For example, is reduction of the factor of safety of a slope acceptable? Is potential settlement in a public park area acceptable? Is potential infiltration into subsurface structures acceptable and at what cost to repair or mitigate is the BMP worth incorporating? Are there regulations (local, state or federal) controlling the design – such as minimum factors of safety for slopes? While these questions may be more appropriately answered in the design phase, the considerations should be considered in the planning level phase.

Lastly, the BMP designer should be in communication with other design leaders on a development project to make sure the impacts of their design are considered in the early planning stages of concurrent designs. For example, if a new highway is proposed, the civil and geotechnical engineers should be aware of future planned BMPs located near slopes when determining the road alignment and designing the future cut or fill slopes.

Guidance for planning level assessment of specific geotechnical hazards is provided in Section 3.

2.3 Considerations in Design Phase Analyses

During the design phase, potential geotechnical impacts should be fully considered and evaluated, and mitigation measures should be incorporated in the BMP design, as appropriate. In this context, mitigation measures refer to design features or assumptions intended to reduce risks associated with stormwater infiltration. While rules of thumb may be useful, if applied carefully, for the planning level phase, the analyses conducted in the design phase require the involvement of a geotechnical professional familiar with the local conditions.

One of the first steps in the design phase should be determination if additional field and/or laboratory investigations are required (e.g., borings, test pits, laboratory or field testing) to further assess the geotechnical impacts of stormwater infiltration. As the design of infiltration systems are highly dependent on the subsurface conditions, coordination with the stormwater design team may be beneficial to limit duplicative efforts and costs.

Additional resources, such as design and as-built information regarding existing structures should be obtained, as appropriate. When representative conditions and input parameters are compiled, final design analyses and calculations can be performed to evaluate the geotechnical impacts. Design may also include evaluation of mitigation measures to reduce potential geotechnical impacts to acceptable levels, as appropriate.

Determination of acceptable risks and/or mitigation measures may involve adjacent land owners and/or utility operators, as well as coordination with other projects under planning or design in the project vicinity. Early involvement of potentially impacted parties is critical to avoid late-stage design changes and schedule delays and to reduce potential future liabilities.

2.4 Supporting Resource on Groundwater Mounding (Appendix C)

Groundwater mounding can have important influence on geotechnical evaluations. Appendix C summarizes the results of an extensive analysis of groundwater mounding performed by the research team as part of developing this Guidance Manual. Appendix C also provides screening-level design chart and an Excel-based user tool for assessment of groundwater mounding (based on the results of HYDRUS2D simulations). This is anticipated to support evaluation of several geotechnical issues described in the following chapter. For example, the tool provides information about the height and shape of the groundwater mound, zones of saturated soil, and saturation of the subgrade soils below the roadway pavement.

3 Guidance for Evaluating Specific Geotechnical Hazards Associated with Stormwater Infiltration

This section introduces the types of geotechnical conditions and/or hazards that could be impacted by stormwater infiltration. This section is not intended to cover all possible conditions and additional regional- or site-specific conditions may need to be evaluated. Each section contains (1) an overview to introduce the key concepts and technical elements that underlie the potential hazard, (2) guidance for evaluating the potential hazard as part of the planning level feasibility analysis, and (3) considerations that should be reviewed and/or analyzed by the project geotechnical practitioner as part of designing to allow safe infiltration. Where available, rules of thumb are provided for planning level feasibility analyses; however, these are not intended to replace the need for project-specific analysis and exercise of professional judgment by the project design team.

This Guide is not intended to provide geotechnical guidance on design of pavements. Designers should consider the impact of BMPs on the drainage and performance of roadway subgrade systems and may refer to NCHRP Report Nos. 499 or 583 (Hall and Correa, 2003; Hall and Crovetti, 2007) or other design references for guidance.

Section 4 provides greater information about the potential mitigation measures identified in this section, and Section 5 provides a summary of the relative risk posed by different failure mechanisms for different categories of stormwater infiltration facilities.

3.1 Utility Considerations

3.1.1 Overview

Utilities are either public or private infrastructure components that include underground pipelines and vaults (e.g., potable water, sewer, stormwater, gas or other pipelines), underground wires/conduit (e.g., telephone, cable, electrical) and above ground wiring and associated structures (e.g., electrical distribution and transmission lines). Below ground utilities are conveyed in trenches, typically located at depths of 1 to 10 feet below the ground surface and often within roadway right-of-ways. Culverts, storm drains, and sanitary sewers may exist well deeper than 10 feet where dictated by adjacent grades. This section will focus on underground utilities; impacts of stormwater infiltration on foundations for above ground structures and utilities are addressed in Sections 3.3 and 3.4.

Utility considerations are typically within the purview of a geotechnical site assessment and should be considered in assessing the feasibility of stormwater infiltration. Infiltration has the potential to damage subsurface utilities and/or underground utilities may pose geotechnical hazards in themselves when infiltrated water is introduced.

3.1.2 Planning Level Feasibility Screening Recommendations

At the planning phase, the designer should identify underground utilities (including abandoned, existing and proposed) within the area of impact. Impacts related to stormwater infiltration near underground utilities are not likely to cause a fatal flaw in the design, but the designer should be aware of the potential cost impacts to the design during the planning stage. The following paragraphs present typical impacts that stormwater infiltration may have on underground utilities.

When located within the area of impact of a stormwater infiltration facility, an underground utility trench can become a preferential pathway for the infiltrated stormwater. This can result in a larger than anticipated area of impact of stormwater infiltration that could lead to additional geotechnical or other types of impacts that were not considered. This is likely a concern if the utility trench backfill is more permeable (i.e., higher hydraulic conductivity) than the surrounding soil. The practice of bedding and shading the pipe or conduits with granular materials to reduce damage is a common practice during utility construction. If granular backfill (sand and gravel) is present, the infiltrated water may travel within and along the axis of the utility trench causing unanticipated flow patterns. This is particularly of concern when working in areas with older existing infrastructure.

Additionally, localized groundwater table fluctuations may impact the underground conduits and underground vaults or manholes. Possible localized buoyancy of pipes may damage pipes and/or result in changes in pipeline gradients that could impact the effectiveness and flow rates of pipelines designed for gravity drainage. Localized increases in water table may impact buoyant forces on sealed underground vaults that could result in uplift of the vault. Differential uplift forces may impact the integrity of utility connections, such as conduits connecting to underground vaults. Further, underground vaults or access ports such as manholes may become submerged or flooded because of the increased groundwater table. This would impact the accessibility of the vault for maintenance and repair and may impact performance of aged electrical utilities with degraded coatings.

The infiltration designer should consider the potential for aged utilities (specifically sanitary sewer or petroleum pipelines, pipes with gravel bedding that do not have cut-off wall) to impact the water quality of the stormwater that may flow in the vicinity of the trench, increase the inflow and infiltration (I&I) into sanitary sewers, and/or create preferential pathways where water could migrate longitudinally and potentially cause issues such as sinkhole formation.

3.1.3 Design Considerations and Potential Mitigation Measures

During the design stage, the impacts of stormwater infiltration on utilities should be further evaluated. Design drawings and as-built records of utilities should be obtained and reviewed, if available. Detailed design efforts may include the following:

- Determination of likelihood of preferential flow within utility corridor based on comparison of permeability of existing trench backfill with typical subsurface soil/rock permeability. This may require sampling of subsurface materials for laboratory or field testing and in complex conditions detailed modeling of flow patterns;
- Calculation of uplift loads and associated factor of safety for uplift of underground vaults and evaluation of impacts resulting from potential uplift;
- Survey assessment of as-built gravity flow lines that could be impacted by uplift and calculation of pipe flow conditions in the event of uplift; and
- Determination of impacts to leach fields based on rises in the groundwater table.

Mitigation measures to control impacts to utilities primarily consist of methods to keep the potential impact area away from underground trenches or vaults, such as cut off walls/membranes running parallel to trenches, and measures to help prevent flow within the trenches, such as cutoff walls (low permeability backfill like concrete or bentonite grout) within the trenches.

Mitigation measures to reduce impacts of uplift on underground vaults may include anchors or adding additional weight to the vault, or measures that would limit the local rise in the groundwater table, such as deep infiltration or additional drains surrounding the vaults. These potential mitigation measures discussed further in Section 4.

3.2 Slope Stability

3.2.1 Overview

Infiltration of water has the potential to increase risk of slope failure of nearby slopes and this risk should be assessed as part of both the feasibility and design stages of a project. There are many factors that impact the stability of slopes, including, but not limited to, slope inclination, soil and unit weight and seepage forces. Increases in moisture content or rising of the water table in the vicinity of a slope, which may result from stormwater infiltration, have the potential to change the soil strength and unit weight and to add seepage forces to the slope, which in turn, may reduce the factor of safety of the stability of the slope.

3.2.2 Planning Level Feasibility Screening Recommendations

The first step in a planning level or feasibility assessment for slope stability impacts from stormwater infiltration is to identify existing or planned slopes that are located within the area of impact (see Section 2.2 for discussion of area of impact). For preliminary planning purposes, the designer may consider slopes as any area with a ground inclination steeper than approximately 20 percent or 5H:1V (horizontal:vertical). Typically slopes that are greater than 4 feet should be reviewed for geotechnical impacts, however, if potential impacts from movement or failure of a shorter slope are significant, they should be reviewed as well.

The designer should understand the typical subsurface conditions in the slope areas:

- How deep is the groundwater table?
- Are there existing seeps or springs in the slope?
- Are there joints or bedding layers in the slope that could be impacted by introduction of water?
- What are the subsurface conditions near the slope?
- Is the soil/rock prone to strength loss or weakening if wetted?
- Is the area prone to landslides?

A review of existing site conditions, including available geotechnical investigations for the area and published geologic maps, may indicate whether slope stability is an existing concern. Indications of slope movement may include presence of surface cracking or scarps at or near the crest of a slope and slumping at or near the toe of a slope. A review of geotechnical reports for development in the vicinity can also provide information regarding slope stability in the region and, in particular, subsurface conditions/formations. Further, a qualified geologist or geotechnical practitioner may review aerial photographs of the area to identify existing landslide features.

When evaluating the effect of infiltration on the design of a slope, the designer working with the geotechnical engineer should consider all types of potential slope failures, including but not limited to:

- Deep seated failures – these failures are often rotational or block-like and the failure surface is typically at a depth below five feet;
- Toppling failures – these failures can result from movement along joint sets in subsurface soil or rock;
- Surficial slumping or debris slide– these failures are often in the surficial soils and often related to seepage along the slope face;
- Surficial erosion failures – these failures are often initiated by erosion of the slope surface and propagate due to over-steepened areas of erosion; and
- Creep/lateral fill extension – slopes which experience long term creep of fill soils down the slope;

Figure 1: Slope slumping failure along roadway (Wikipedia)

The stability of a slope is generally evaluated by comparing the sum of the destabilizing forces and moments on a slope to the stabilizing forces and moments:

$$\text{Factor of Safety} = \frac{\text{Stabilizing Forces and Moments}}{\text{Destabilizing Forces and Moments)}}$$

A slope that has equal stabilizing and destabilizing forces has a factor of safety of 1.0 and failure is considered imminent. Slopes with factors of safety in the range of 1.1 to 1.3 may be considered stable for short term conditions but may experience minor to significant slope movement. Long term and permanent slopes are often designed for a minimum factor of safety of 1.5. While evaluating the effect of potential infiltration of the factor of safety, the designer working with the geotechnical engineer should determine what factor of safety would be considered acceptable. The acceptable factor of safety will be dependent on the duration of the impacts of the stormwater infiltration and the whether some slope displacement would be considered acceptable. For example, for conditions where settlement sensitive developments (i.e., buildings, hardscape, or utilities) are present at the top or toe of the slope, any measureable slope movement may be considered unacceptable. Whereas in undeveloped areas with no development near the slope, minor slope creep or surface erosion that does not lead to more significant failures may be acceptable. Local or state regulations may stipulate minimum factors of safety for various slope conditions.

Once an understanding of existing conditions is gained, the designer should evaluate, possibly in conjunction with a geotechnical practitioner, whether an increase in moisture content, seepage forces and/or rising of the water table may reduce the stability of the slope by:

- Softening of clay resulting in lower shear strengths and a reduction in the stabilizing forces/moments;
- Increasing soil unit weight thereby increasing the destabilizing forces/moments;
- Increasing potential for ice formation within joints/cracks resulting in increased destabilizing forces/moments;
- Increasing seepage forces within the slope, particularly seepage moving parallel to the slope face which increase destabilizing forces/moments; and
- Raising the groundwater table at the toe of the slope reduces the stabilizing forces/moments.

Several tools are available to provide simplified solutions for stability of a slope. All simplified methods should be used with caution as they do not take into account site specific conditions or alternative mechanisms of failure. Simplified chart solutions for slope stability of homogenous slopes have been developed for use as a preliminary planning tool (Taylor, 1934; and Michalowski, 2002). Chart solutions for slopes with cohesive soil (clays and silts) as well as submerged slopes are available in design manuals such as NAVFAC (1986).

Local stormwater design manuals may provide rule of thumb guidance for maximum slopes suitable for infiltration systems and setbacks from slopes. For example, WADOE (2012) recommends a setback of at least 50 feet from slopes that are greater than 15 percent slope, while LACDPW (2011) recommends setbacks of at least 5 feet or half the height of the slope for any slope. Clearly, rules of thumb have not converged in all areas, and setback recommendations found in local guidance should be supplemented by site-specific information and professional judgment.

3.2.3 Design Considerations and Potential Mitigation Measures

In the design stage, detailed analyses of the infiltration impacts on slope stability should be performed by the geotechnical engineer as part of overall slope stability calculations. These analyses will likely include two-dimensional modeling with programs such as SLIDE (Rocscience, 2012) or SLOPE/W (Geo-Slope, 2012). To perform these analyses, the geotechnical professional needs a thorough understanding of the topography, subsurface conditions (soil stratigraphy, strength, and unit weight) and groundwater conditions. Additionally, the stormwater designer may need to provide the geotechnical practitioner with an estimate of the expected peak and long-term infiltration volumes.

The results of the detailed stability analyses should be evaluated with respect to allowable risks (see discussion in 3.2.2) and regulatory guidelines. Various federal, state and local agencies require minimum factors of safety as part of the grading permit approval process. If an acceptable factor of safety is not achieved considering the anticipated level of infiltration, mitigation measures may be considered. The most direct mitigation for slope stability is to limit the potential for water in the slope by providing a minimum setback from the top of the slope. Other options include encouraging deeper infiltration into the slope that extends below the depth of the calculated failure surface. Methods for encouraging deeper infiltration include french drains, dry wells, or wick drains. The effects of the deeper infiltration should be modeled for their impacts to the slope.

Other methods to increase slope stability may include overexcavating soft or weak layers in the slope subsurface that impact stability, decreasing the inclination of the slope, providing drainage, adding a soil buttress to the toe of the slope or inclusion of soil/rock anchors or tiebacks. Surficial stability may be increased by planting vegetation with a significant root mass at depth. These measures may allow infiltration to be accommodated while maintaining an acceptable factor of safety; however, they may add considerably to project costs.

3.2.4 Consideration of Existing versus Proposed Slopes

It is common for roadway projects to create new slopes via project grading activities or work near slopes that have been previously constructed by earlier projects. Three general categories of slopes are typically found in the highway environment: (1) natural slopes formed by natural topography that are not created or substantially modified by the roadway project or prior projects, (2) cut or fill slopes created by grading activities as part of a previous project, and (3) proposed cut or fill slopes that will be created by the excavation or placement of fill as part of roadway project. While slope stability analysis is necessary for each of these categories, investigation and analysis methods may differ.

Natural and existing slopes. For natural slopes and existing constructed slopes that will not be substantially modified, field exploration can establish baseline information about these slopes. In the absence of infiltration, a slope stability analysis may still be conducted to verify that slopes are stable, or a more approximate method may be used if it is clear that the slope is currently stable and will not be modified by the project. The addition of infiltration in the vicinity of these slopes may warrant a more detailed analysis than would otherwise be done. Additionally, modification of these slopes to accommodate infiltration may expand the project footprint and increase costs considerable and therefore may not be feasible.

Proposed slopes. For slopes that are proposed as part of the project, slope stability calculations are generally performed based on the project plans, the existing geologic characteristics, and characteristics of the anticipated fill material. For these slopes, the consideration of potential infiltration impacts may be incorporated as part of the design of the slopes in terms of a change in the design inputs, such as change in moisture content, unit weight (bulk density) or strength, and/or modification of other parameters. For fill slopes, the question of infiltration feasibility should be answered in terms of how much additional design cost would be required to maintain a stable slope with stormwater infiltration versus the case where only incidental infiltration is assumed. Guide #1 (Appendix C) provides more guidance on infiltration into fill areas, including challenges associated with estimating infiltration rates, as well as reduction in infiltration capacity as a result of compaction.

For all types of slopes, the potential for surficial erosion should be considered in drainage design. If slopes are allowed to erode, either from lack of surface stabilization or from unstabilized drainage pathways, this can increase the potential for slope instabilities by creating weak spots in the slope face. However, this factor is inherent in all drainage design, regardless of whether stormwater infiltration is proposed or not.

3.3 Settlement and Volume Change

3.3.1 Overview

Settlement refers to the condition when soils decrease in volume. Heave refers to expansion of soils or increase in volume. Upon considering the impacts of an infiltration design, the designer should identify areas where soil settlement or heave is likely and whether these conditions would be unfavorable to existing or proposed features within the area of impact. Changes in volume, and particularly differential changes in volume, can result in the following impacts:

- Damage to pavement structures, sidewalks, and other rigid structures;
- Changes in surface drainage patterns;
- Reduction of structural integrity and/or serviceability of structures or retaining walls; and
- Impacts to utility gravity drainage and utility connections.

There are several different mechanisms that can induce volume change due to water infiltration that the designer should be aware of, including:

- Hydrocollapse and calcareous soils;
- Expansive soils;
- Frost heave;
- Consolidation;
- Dispersive soils and piping; and
- Liquefaction.

The following sections discuss these various mechanisms. Many of these forms of failure may already be evaluated in a standard roadway design process to evaluate the suitability of soils for subgrade and determine subgrade strength properties. Soils subject to volume change are typically not used in road base material or are remediated as part of construction. However, unremediated soils subject to volume change may still exist outside of the mainline roadway section, in areas where infiltration facilities are planned. Therefore, these forms of failure remain important for infiltration feasibility assessment.

3.3.2 Hydrocollapse and Calcareous Soils

Overview

Collapsible soils are typically loose and cemented soil and soils with low moisture content that may experience a large and sudden reduction in volume upon wetting. Calcareous soils are soils that have significant components of calcium carbonate or other salts (e.g., gypsum, calcite, halite). Calcareous soils are typically sedimentary and were deposited in a shallow marine environment. Grains of sand or clay are cemented together by the calcium carbonate. For both collapsible and calcareous soil, the introduction of moisture can dissolve or soften the cementation or structure of the soil, causing rapid and possibly extensive settlement.

Planning Level Feasibility Screening Recommendations

Impacts from soil collapse may include damage to hardscapes, utilities and foundations as well as changes in site drainage patterns that may lead to additional impacts. Early in the planning phase, the designer should identify potentially collapsible and calcareous soils as well as potentially impacted features, as settlement impacts can be significant, and mitigations typically require intrusive actions that may not be feasible or cost-effective.

Collapsible soils tend to be geologically young and are often found in alluvial (water deposited), aeolian (wind deposited), and colluvial (gravity deposited) deposits. In addition, residual soils formed by extensive weathering of parent materials, such as weathered granite, can be loose collapsible soils. These soils are common in the upper 10 to 15 feet of the ground surface but can extend to depths greater than 100 feet. Calcareous soils are typically sedimentary and were deposited in a shallow marine environment. Grains of sand or clay are cemented together by the calcium carbonate or other salts.

If collapsible soils are present within the area of impact, a preliminary estimate of anticipated settlement should be performed based on available information such as existing geotechnical reports and typical soil behavior in the area.

Design Considerations and Potential Mitigation Measures

If collapsible soils may be left intact within areas where settlement would be considered undesirable, undisturbed samples of the soils may be taken and tested for collapse potential, with a test such as ASTM D4546 (ASTM, 2012a) to estimate the magnitude of the potential settlement. The vertical and lateral extent of the potentially collapsible soils should be investigated so a thorough understanding of the potential impacts of the introduction of water into the subsurface may be evaluated.

Options for mitigation of risks associated with collapsible and calcareous soils include prewetting of the soil prior to construction of settlement sensitive features, moisture conditioning and recompaction of the collapsible soils to break down the sensitive soil structure and treatment with chemical grouting (e.g., sodium silicate or calcium chloride solutions) to encourage cementation that is not significantly affected by water, or compaction grouting. To the detriment of infiltration feasibility, treatment may result in a significant reduction in soil permeability.

3.3.3 Expansive Soils

Overview

The designer should consider the presence of potentially expansive soils in and around structures and improvements when considering infiltration in design. Expansive soils are soils that experience volume changes with changes in moisture content. In particular, increases in moisture content result in expansion or swelling and decreases in moisture content result in shrinkage and cracking. The forces imparted by expansive soils can be large, causing significant differential movement/heave in hardscapes and structures. It is estimated that damage to pavements caused by expansive soils each year in the United States exceeds $1 billion (USDOT FHWA, 2012). Expansive soils can generate pressures in excess of 20,000 pounds per square foot and swell to more than 10 times their initial volume (Colorado Geological Survey, 2012).

Planning Level Feasibility Screening Recommendations

The first step for the designer is to evaluate if expansive soils are present within the area of impact of stormwater infiltration facilities. In accordance with the International Building Code (IBC), (2012), expansive soils are typically defined as soils that:

- Have a plasticity index of 15 or greater, determined in accordance with ASTM D4318 (ASTM, 2012a);
- More than 10 percent of the soil particles pass a No. 200 sieve (75 mm), determined in accordance with ASTM D422 (ASTM, 2012a); and
- More than 10 percent of the particles are less than 5 mm in size, determined in accordance with ASTM D422 (ASTM 2012a); or
- Expansive index greater than 20, determined in accordance with ASTM D4829 (ASTM, 2012a) or AASHTO T 258.

Expansive soils usually contain the clay minerals montmorillonite (smectite) and/or kaolin and are typically clayey or have significant components of clay. Visual cracking in the soils or areas of extended ponded water are indications of the presence of expansive soil.

Because of the presence of clay, expansive soils tend to have relatively low hydraulic conductivity and are not ideal for vertical infiltration of stormwater. The designer should consider the potential of lateral moisture migration and its effect on expansive soils. The magnitude of the expansion/shrinkage will depend on the mineralogy of the clay, chemistry of the water, and changes in moisture content.

Expansive soils exist throughout the United States but tend to be a more significant issue in the western states. Regional maps identifying areas of expansive soils have been prepared by NOAA and may be suitable for initial screening activities (NOAA, 1978). The designer should review any geologic data available in and near the project area for the presence of clays soils with significant clay fractions. The NRCS Web Soil Survey (http://websoilsurvey.sc.egov.usda.gov) may be useful to understand if expansive soils exist in the vicinity of the projects area, however this dataset should be confirmed with local observations, as it is not intended to be accurate at the site scale.

Figure 2: Desiccation cracking upon drying indicates likely presence of expansive soil conditions (http://www.geology.ar.gov/images/mudcracks.jpg)

If expansive soil is present within the limit of impact, the designer should determine if features such as structures or hardscapes are present that may be damaged by the potential expansive and desiccation of these soils. The designer should also consider that deep foundations and retaining walls may be impacted by expansive soils at depth.

Design Considerations and Potential Mitigation Measures

If, during the planning level design, the designer identifies expansive soils within the area of impact that may cause undesirable impacts, the extent of the soils should be mapped and identified within the field. Laboratory testing, such as ASTM D4829 (Standard Test Method for Expansion Index of Soils), can be performed to determine the potential swelling pressure imparted by wetting of a site-specific soil. This can be useful in evaluating potential for swelling of expansive soils at various confining pressures.

Removal and replacement of potentially expansive soils can be one of the most effective methods to reduce swell hazards. However, this method may only be economical if the expansive soils are limited in area and/or thickness and their overexcavation will not impact existing improvements. Another possible mitigation measure includes limiting contact of infiltrated water with expansive soils. Methods for limiting contact could be installation of membrane barriers (such as asphalt membranes or geomembranes) to limit lateral moisture migration into zones with expansive soils or installation of drainage systems near foundations to limit the variation in moisture conditions. Prewetting of expansive soils prior to construction has seen limited success; however, this option only applies to areas where no existing features are in place that can be impacted by potential swell.

One of the most commonly used methods to stabilize expansive clays is admixing with a chemical such as lime (calcium oxide or calcium hydroxide). Lime treatment can be performed during construction where the expansive soil is mixed directly with lime (typically 2 to 6 percent by weight of soil) or post-treatment, where the lime is introduced by pressure injection, drilling or irrigation trenches. Lime treatment chemically decreases the expansion potential while also reducing the hydraulic conductivity of the soil.

If infiltration is proposed in areas with expansive soils, existing foundations and retaining walls should be analyzed for potential impacts from soil expansion. Horizontal swelling along a retaining wall can add significant destabilizing forces (see Section 3.4) that should be addressed. If unacceptable movements are predicted, foundations and walls may be able to be retroactively strengthened to limit damage from expansive forces.

3.3.4 Frost Heave/Thaw

Overview

Upward displacement of soil resulting from formation of ice in the subsurface, called frost heave, has the potential to cause significant damage to pavements, utilities, lightly loaded structures and the proposed BMP. In addition, the cyclic nature of frost heave/thaw cycles has the potential to substantially deteriorate roadway and subgrade layers leading to eventual damage and/or failure of roadways. Frost heave is considered a hazard when the following three conditions are met:

- Water is present in the subsurface;
- Frost susceptible soils are present; and
- Weather is cold enough to freeze.

Upon freezing, water increases in volume by approximately 9 percent. This increase, while not insignificant, is not the primary mechanism of frost heave. When temperatures drop below freezing, ice lenses form in the subsurface. When capillary forces are great enough, which is commonly the case in fine grained soils (silts and fine sands), moisture is drawn to the ice lenses which increase in volume, causing upward heave of the overlying soil. Heaving can often exceed several inches or more. Frost effects on foundations, which tend to result in permanent vertical displacements, tend to be smaller in magnitude than on pavements and hardscapes, but can result in significant cumulative damage over many seasons.

Figure 3: Formation of subsurface ice lenses and resulting frost heave. (source: Wikipedia)

Planning Level Feasibility Screening Recommendations

Because the primary mechanism for frost heave is growth of ice lenses from capillarity, only soils with significant capillarity, such as soils with loam, silt, and clay components, are typically considered frost susceptible. Further, the growth of the ice lenses occurs by movement of water in the subsurface toward the ice lenses; soils with very low permeability may not allow significant water movement during the freezing conditions to experience significant capillarity. Silts are typically considered to be the most susceptible to frost heave; however, low plasticity clays, and silty or clayey sands and gravels also have potential for frost heave.

The first step for a designer is to determine if there is potential for frost heave within the area of impact by identifying if both frost weather conditions and frost susceptible soil type(s) are present. By nature of capillarity, the types of soils that are most susceptible to frost heave do not tend to provide the most desirable conditions to promote infiltration. For example, high permeability soils tend to be coarser grained with low capillarity and low potential for frost heave.

If the three criteria for frost heave are present (freezing weather conditions, frost susceptible soil, and a source of water), the designer should then determine the frost depth is in the vicinity of the project. Frost depth can be obtained from local building codes and can be estimated based on plots provided by NOAA (1978). The designer should also determine what features are located within the frost zone that may be negatively impacted by frost heave driven by an increase in subsurface water. If potential frost heave hazards are identified, the designer should evaluate potential impacts and mitigations as early in the design phase as possible, as effects from frost heave can be significant.

Design Considerations and Potential Mitigation Measures

If potential for frost heave is identified, detailed subsurface information and foundation design of all potentially impacted features should be obtained to evaluate which feature components are located within the frost zone and whether mitigation measures can be sufficiently incorporated.

On of the most effective ways to control frost heave is to design grades to limit the access of water to frost susceptible soils (i.e., the source of water is below the capillary range of the frost susceptible soils). This can be achieved by grading (e.g., providing a large elevation change between hardscapes and drainage features) or by designing for deep infiltration (infiltration wells).

For features that have not yet been constructed, frost heave damage can be limited by placing foundations at elevations below the frost depth or removal of isolated areas of frost susceptible soils (e.g., silt pockets). Additional measures such as providing good drainage around foundations limits the potential for formation of ice lenses below and around foundations.

To limit damage to hardscapes, layers of granular soil can be placed at or near the frost depth to provide a capillary break and limit the source of water for ice lens formation. Alternatively, for fill embankments not yet constructed, frost susceptible soils may be placed and compacted at depth, beneath the frost line to limit potential for frost heave.

3.3.5 Consolidation

Overview

Consolidation settlement occurs when loading causes water from the pore space between saturated soil particles to be squeezed out, resulting in soil volume reduction. Consolidation is typically induced by an increase in overburden or loading of the subsurface soil. This additional loading can be caused by placement of fill, construction of a structure, or by increases in the bulk density (resulting from an increase in moisture content) of the overlying soil stratum. Soils that are most susceptible to consolidation settlement are typically soft silts and clays.

Planning Level Feasibility Screening Recommendations

To determine if consolidation settlement may be a potential risk, the designer should determine if saturated soft sediments exist within the area of impact. This can be determined by review of available boring logs and geotechnical reports performed in the area. The designer should also evaluate if significant changes in moisture content of subsurface soils and/or whether there may be significant long-term changes in the groundwater table. Both of which could impact consolidation settlement. The rate of consolidation settlement is dependent on the hydraulic conductivity of the soil, which for silts and clays, tends to be quite low. Hence, consolidation settlement is not typically observed for interim or intermittent conditions. However, long term changes in moisture content or groundwater table elevation resulting from increased infiltration may result in long term settlement.

The magnitude of the settlement will be dependent on the thickness and compressibility of the compressible layer and degree and duration of the subsurface moisture content variations. Minor changes in soil unit weight are not anticipated to induce significant consolidation settlement. To illustrate this point, a long-term 5 percent increase in moisture content of a 10-foot-thick soil layer overlying a 20-foot-thick, saturated, soft clay layer may result in settlement on the order of 1 to 2 inches. This example was computed using some standard soil parameters. The reader is cautioned that there is considerable variation in the properties of fine-grained soil which correspondingly leads to large variations in settlement.

Typically for design, differential settlement has more negative impacts than uniform settlement. Differential settlements greater than approximately 0.1% to 0.4% (depending on structure type) are typically considered undesirable for structures (Day, 2010 [Table 7.2]). The designer should determine if localized infiltration has the potential to induce differential settlement greater than allowable levels. Standard soils text books such as Holtz et al. (2010) can provide typical values for consolidation ratios and initial void ratios that can be utilized in one-dimensional consolidation equations for preliminary estimation of settlement.

Design Considerations and Potential Mitigation Measures

If there is potential for unacceptable settlements resulting from consolidation, undisturbed soil samples should be taken within the compressible soil layer for testing in accordance with ASTM D2435 (ASTM, 2012a) or similar to determine existing soil conditions (e.g., void ratio, preconsolidation ratio, compressibility index). Alternatively, correlations to typical soil parameters (such as Atterberg Limits, ASTM D4813) may be used in lieu of additional testing. Further, the location of potential drainage layers (e.g., higher permeable layers to which the excess moisture can flow) should be estimated based on subsurface investigations (e.g., test pits, boring logs, cone penetrometer tests) to estimate the duration of the anticipated settlement, if appropriate. With an understanding of the subsurface strata, material parameters, and loading conditions, a geotechnical practitioner can then predict the anticipated settlement, differential settlement and duration of settlement.

If total or differential settlements are greater than allowable tolerances, the designer may consider reducing the potential infiltration volume per unit area to reduce the impact on the soil unit weight or and/or groundwater table. This may be accomplished by reducing diversion of stormwater into the infiltration system or increasing the infiltration area of the system or a combination of the two. If the settlement sensitive features have not been constructed yet, several options exist to limit future damage from settlement. Future foundations can be designed to accommodate the potential settlement by, for example, using a mat or raft type foundation that is not as sensitive to differential settlement. Another approach is to preload the compressible soil prior to construction of the settlement sensitive structure. However, effectiveness of preloading may be reduced if the preloading is performed prior to anticipated changes in groundwater levels

3.3.6 *Dispersive Soils and Piping*

Overview

Piping can be described as subsurface erosion and typically occurs in dispersive soils or fine grained cohesionless soils (e.g., silts or fine-grained sands) which are overlain by at least slightly cohesive soils.

Planning Level Feasibility Screening Recommendations

Internal piping is a phenomenon when subsurface movement of water induces soil particle migration. Piping has the potential to result in subsurface voids in the form of pipes or fissures, which can lead to surface settlement and/or collapse. One of the most commonly known large-scale manifestations of piping is when underground utility pipelines break, causing rapid, uncontrolled movement of water and subsurface erosion or scour, resulting in development of a ‘sinkhole’ or collapse of the overlying soils into the resulting void space. Development of piping can also occur over a longer time scale – for example, subsurface pumping of water through a silt layer could result in significant and progressive fines migration, development of subsurface pipes/fissures and possible settlement. Fine-grained cohesionless soils such as silts and very fine sands, and dispersive soils are considered the most susceptible to piping.

Figure 4: Road damage from a sinkhole in Colorado. Photo by Jon White. (http://geosurvey.state.co.us/hazards/Collapsible%20Soils/Pages/DispersiveSoils.aspx)

Dispersive soils contain clay particles that typically have a higher content of dissolved pore water sodium and upon wetting, disperse into solution. Dispersive soils cannot be identified by standard index properties. Common tests to identify dispersive soils are the pinhole test (ASTM D4647) and the double hydrometer test (ASTM D4221).

To determine if the project may be impacted by piping, the planner should determine if soils susceptible to piping are likely present and should evaluate subsurface water gradients. Piping typically occurs where subsurface water gradients are moderate to significant and can mobilize movement of soil particles. While the factor of safety with respect to piping by subsurface erosion cannot be evaluated with practical means (Terzaghi, Peck and Mesri 1996), risks for development of piping failures can typically be reduced by providing proper filtration design in areas of subsurface gradients and by attention to detail in the design of areas of water collection and diversion.

Design Considerations and Potential Mitigation Measures

Careful design and control of subsurface flow is critical to preventing piping failures. In areas of soil transitions where subsurface flow is anticipated, a designer may include filter fabric(s) or soil filter(s) to reduce particle migration. Additionally, methods to decrease subsurface gradients may be utilized – such as increasing the flow path. Dispersive soils can be treated with lime to reduce their potential for particle suspension. The designer may also incorporate features such as anti-seep collars around piping inlets to control unanticipated flows and reduce the potential for subsurface scour.

3.3.7 Liquefaction

Overview

Liquefaction is a process by which saturated sediments temporarily lose strength and act like a fluid when exposed to rapid, cyclical loading conditions, such as an earthquake. This loss of strength can result in loss in foundation support, lateral spreading (see Figure 5), floating of underground buried tanks and utilities, slope failures, surface subsidence and cracking, and development of sand boils.

For liquefaction to occur, the soil should typically be:

- Saturated;
- Loose to medium dense sandy soil and fine-grained soil with a plasticity index (PI) less than 12 Bray and Sancio, 2006); and
- In a region with potential to experience rapid loading conditions (i.e., earthquakes).

The potential for stormwater infiltration to increase the risk of liquefaction hazards exists if the proposed design would increase the water table to elevations that include liquefaction susceptible soils. A change in moisture content of soils, below saturation, does not present a risk of liquefaction.

Planning Level Feasibility Screening Recommendations

Figure 5: Roadway damaged from lateral spreading in 1989 Loma Prieta earthquake (from Nakata et al., 1990)

During the feasibility evaluation of potential stormwater infiltration sites, the designer should evaluate if the potential sites are located within liquefaction susceptible zones. As discussed above, this can be evaluated be determining if the three general criteria for liquefaction are present. The United States Geological Survey (USGS) provides resources and maps that designate liquefaction susceptibility or potential in various subregions of the United States, however, comprehensive maps of all areas are not currently available. Other sources for liquefaction susceptibility maps may be local planning agencies.

By reviewing available subsurface data, the designer may determine if sandy or silty soils are present below or near the groundwater table. Standard Penetration Tests (SPTs) performed during sampling of subsurface soils provide a general indication of the density of in-situ soils; typically, sandy or silty soils with a corrected SPT blow count ($N_{1\text{-}60}$) greater than 30 are not typically liquefiable. Further, surface evidence of soil liquefaction typically only results from liquefaction of soils in the upper 15 meters (50 feet) from the ground surface (Idriss and Boulanger, 2008).

The designer should also evaluate if the proposed infiltration system has the likelihood of increasing the ground water table in the area. This will be dependent on the type of infiltration approach proposed, duration and volume of infiltration, and local geologic conditions (see Section 2.2).

More information regarding liquefaction can be found in Idriss and Boulanger (2008) or Kramer (1996).

Design Considerations and Potential Mitigation Measures

If the preliminary feasibility assessment indicates increased liquefaction potential at a site as a result of stormwater infiltration, the project geotechnical professional should perform a liquefaction analysis for the proposed conditions and project seismic design criteria. This analysis will assess the risks for liquefaction and potential for lateral spreading resulting from the proposed design. The geotechnical professional will assess the proposed groundwater level, design maximum ground acceleration, and soil conditions (unit weight, density, and soil type). At this point, the project team should evaluate whether the increased risks resulting from the infiltration system are considered acceptable based on the return period for the potential liquefaction-triggering earthquake, and the consequences of liquefaction.

Liquefaction susceptibility can be mitigated by densification or removal of loose sediments, or by infiltrating into deeper soil horizons that are less susceptible to liquefaction. Methods used to densify existing soils include overexcavation and recompaction, jet grouting, deep dynamic compaction (DDC), injection grouting, or stone columns. These approaches may reduce the hydraulic conductivity of the soils. Alternatively, infiltration systems can potentially be designed with drainage trenches or barriers to avoid saturation of liquefiable soils.

3.4 Retaining Walls and Foundations

3.4.1 Overview

Retaining walls, including basement walls and bridge abutments, are common features within or in close proximity to urban roadways. These structures are designed to withstand the forces of the earth they are retaining and other surface loading conditions such as nearby structures. Foundations include shallow foundations (spread and strip footings, mats) and deep foundations (piles, piers) and are designed to support overburden and design loads. All types of retaining walls and foundations can be impacted by increased water infiltration into the subsurface as a result of potential increases in lateral pressures and potential reductions in soil strength.

3.4.2 Planning Level Feasibility Screening Recommendations

Many urban highways are located in areas of dense development with frequent overpass structures, bridge abutments, and retaining walls, as well as buildings in close proximity to the right of way. Designers should identify foundations and retaining walls within the area of impact of stormwater facilities. For preliminary screening purposes, a horizontal setback equal to one to two times the depth of the foundation or the height of a retaining wall may be assumed to identify soils that may affect the foundation/wall.

Increases in moisture content of subsurface soil and increases in the elevation of the groundwater table have the potential to reduce the factor of safety of these features. Similar to the calculation of factor of safety for slope stability, the factor of safety of a foundation or retaining wall is determined by comparing the stabilizing forces and moments to the destabilizing forces and moments. A factor of safety of 1.0 corresponds to a wall or foundation where failure is imminent. Typical minimum factors of safety for walls and foundations vary based on the failure mechanism but may range from 1.5 to greater than 3.0. The designer should understand the primary mechanisms in which increased infiltration can impact foundation or wall stability:

- Addition of water may reduce the strength of clay soils (clay softening), decreasing the stabilizing forces/moments;
- Addition of water increases the unit weight of soil being retained, increasing the destabilizing forces/moments and potentially causing infiltration into subsurface structures; and
- Rise in the groundwater table increases hydrostatic pressure on a wall or foundation, increasing destabilizing forces/moments, possibly decreasing the stabilizing forces of the soil (by reducing effective stresses), and potentially causing infiltration into subsurface structures;

If reductions in stabilizing forces/moments and/or increases in destabilizing forces/moments for a wall or foundation are potentially significant, a thorough investigation of the impact to the specific design of a feature is warranted. This may require an understanding of the design loads on the feature and as-built conditions (including dimensions, soil backfill conditions, concrete reinforcement, anchors or tie-backs, if applicable for retaining walls). Reductions in factor of safety can result in movement of foundations and retaining walls, and if great enough, failure. Movement can result in differential settlements which can impact the serviceability of structures and hardscapes. For example, if foundations on one side of an abutment were embedded in clay which was softened by significant increases in infiltration, settlement on one side of the abutment may occur. This would result in differential settlement that could result in cracking of structural elements and overall decrease in the structural integrity and/or serviceability of the structure.

Guidance for simplified calculation of foundation bearing capacity and retaining walls are provided in textbooks such as Bowles (2001) or circulars from the Federal Highway Administration (FHWA, 1996, 2002) that may be utilized to gain a general understanding of how changes to moisture conditions and groundwater tables may impact foundation and retaining wall stability. Stormwater planners and designers should contact a geotechnical practitioner to understand site specific issues and potential soil strength impacts.

3.4.3 Design Considerations and Potential Mitigation Measures

If reductions in stabilizing forces/moments and/or increases in destabilizing forces/moments for a wall or foundation are potentially significant, a thorough investigation of the impact to the specific design of a feature is warranted by a geotechnical and, if appropriate, a structural practitioner. This may require an understanding of the design loads on the feature and as-built conditions (including dimensions, soil backfill conditions, drainage features, concrete reinforcement, and anchors, struts or tie-backs, if applicable for retaining walls).

The primary mitigation measure to reduce the impact of subsurface infiltration on foundations and retaining walls is to limit the area of impact away from the feature. This can be accomplished by design features with appropriate setbacks and/or by providing drainage behind retaining walls and near foundations to limit subsurface water in the vicinity of the feature. Drains can be incorporated to design of existing future features or retroactively constructed. Additional measures include addition of struts, anchors, soil nails, or tie backs for retaining walls to increase the resisting forces of the wall. Foundations can be stiffened to accommodate differential settlement or foundation subgrades can be strengthened with procedures such as jet grouting to increase bearing strength and reduce potential settlements.

3.5 Pavement Impacts

3.5.1 Overview

One of the most prevalent causes of damage to pavements is insufficient drainage and/or excessive moisture in the pavement section and subgrade. Excess moisture commonly results in pavement damage such as rutting, bumps, depressions, potholes, fatigue cracking, roughness, etc. Many of the mechanisms for this damage have been discussed in the Section 3.3 (e.g., settlement and volume change resulting from issues such as hydrocollapse, expansive soils, consolidation, dispersive soils, and frost heave). Additional mechanisms for pavement damage resulting from excessive moisture include subgrade softening, variability in pavement properties, and fines migration.

3.5.2 Planning Level Feasibility Screening Recommendations

Pavement design in accordance with NCHRP 1-37A (NCHRP, 2004) is dependent on infiltration and drainage system design inputs, including volume and rate of infiltration, drainage system quality, and drainage path length. BMP designers should incorporate pavement engineers on the design team to evaluate the potential impacts on nearby roadways early in the project. In the case of retrofitted sites, introduction of moisture in the subgrade may significantly reduce the serviceability of the pavement. For new roadways, anticipated increases in moisture may require thicker pavement sections as well as additional drainage features. The designer should determine if the BMP has the potential to impact moisture conditions within the pavement section:

- Are existing roadways in the area exhibiting signs of moisture-related damage?
- Will the BMP increase the demand on edge drains in the roadway shoulders beyond acceptable levels?
- Will the BMP increase moisture conditions beneath the pavement, with lateral flow or increases in groundwater elevation?
- Will the ponded levels in the BMP result in backwater into the pavement drainage layers?
- Are pavement section materials, including base, subbase and subgrade sensitive to moisture variations?
- Will increased moisture within the pavement section increase the potential of fines migration into or within the pavement section?

One of the primary design factors for pavement design is modulus or stiffness of the pavement system components. Increases in moisture can significantly reduce this modulus, particularly in soils with considerable fines (silt and clay particles), resulting in loss of pavement support. Studies indicate that modulus reductions in unbound aggregate base and subbase as well saturated fine-grained subgrades can be more than 50% (FHWA, 2006; AASTHO, 1993). Localized changes in moisture conditions can result in non-uniform subgrade conditions, which is a common cause for pavement damage such as roughness or fatigue cracking. Movement of water through the subbase/base and subgrade with improper filtration systems (such as soil or geotextile filters) can result in clogging of drainage systems and development of voids and localized loss of foundation support.

3.5.3 Design Considerations and Potential Mitigation Measures

When infiltration is being proposed in the vicinity of pavement, but not directly into pavement, the most efficient way of limiting moisture impacts on pavement systems is to reduce the likelihood of moisture migration into the pavement section. Water typically enters the pavement system by 1) capillarity and groundwater, 2) migration from roadway shoulders, and 3) infiltration through the pavement section, typically through cracks and joints. Mitigating the potential impacts for increased moisture can be achieved by controlling these sources of water, with enhanced roadway maintenance (sealing of cracks and joints) and increased drainage systems, both along the shoulder and within the pavement sections. Drainage systems should include edge drains to collect and remove drainage from the pavement system and to limit migration of water from the shoulder to the pavement section. Pavement engineers should also consider the use of free-draining base layers (with separator layers), interceptor drains (to limit run-on), and underdrains (to control groundwater and capillarity). More information on impacts on pavement design can be found in numerous publications by NCHRP (2004), AASHTO (1998) or FHWA (2006).

However, in some cases (such as permeable shoulders), infiltration into the pavement section is part of the design. In this case, the primary mitigation methods available to designers include utilizing materials that are less sensitive to moisture variability (such as coarse-grained materials with limited fines or cement treated materials) and/or developing pavement designs that are resilient to elevated moisture conditions (e.g., by increasing the depth of the base layers or using asphalt treated permeable base layer).

In some cases, the additional depth of base layer needed for hydrologic design purposes can provide the additional strength needed to compensate for elevated moisture conditions in the subgrade material.

4 Potential Mitigation Measures for Elevated Design Risk

Once a designer has identified the potential geotechnical impacts from an infiltration design, a range of possible mitigation measures can be considered to reduce the impact to acceptable levels. When considering potential mitigation measures, factors include:

- Technical feasibility – can the risk be adequately mitigated within the constraints of the site?
- Cost – Does the cost of mitigating potential impacts add considerably to the cost of the project? Is this cost increase justified by the increased level of runoff volume reduction that can be achieved?
- Public perception and affected parties **-** Is the area that would be used to mitigate a risk (i.e., for example, building soil buttress to mitigate slope stability risk) owned by another party? Does the project have access to this area? Is there perception of risk that cannot be mitigated?

Several types of approaches can be incorporated into a design to reduce the potential for geotechnical impacts from an infiltration design. These mitigations generally involve one of the following strategies: a) limiting the area of impact of the infiltration design, b) removing or reducing the geotechnical risk factor, or c) modification in the design of potentially impacted features.

4.1 Limit Area of Impact / Effective Site Design

By limiting the area of impact of an infiltration design, the increased moisture and/or effect on the groundwater table is limited and therefore, the geotechnical impacts are limited. For example, if a mitigation measure is incorporated to keep the infiltrated water away from a utility trench, the potential for flow in the trench is substantially removed. Mitigation options to reduce the impact include:

- Cut off walls/curtains;
- Subsurface drains;
- Setbacks from sensitive features; and
- Targeted infiltration locations.

A cut off wall or curtain is a relatively low permeable barrier that limits the amount of vertical or horizontal flow of groundwater. A cut off wall could take many forms depending on the application and the nearby sensitive feature. For example, a geomembrane (low permeability synthetic membrane barrier) may be placed in a trench upstream of a sensitive utility corridor. The geomembrane would likely be extended below the depth of the utility corridor and would encourage vertical infiltration below the depth of the utility trench and limit horizontal migration of water into the utility trench. An alternative may include excavation of portions of the utility trench backfill on regular intervals and backfilling with low permeable material (e.g., concrete, grout or clay) to limit flow along the trench. More costly options such as deeper slurry walls or sheet pile walls can be utilized. This type of barrier approach may also be suitable to limit lateral moisture movement toward collapsible or expansive soils or areas where frost heave may cause unacceptable soil movement.

Additional drainage features may provide another method to reduce the potential for infiltrated water to impact sensitive features. For example, a subsurface drain could be installed upgradient of a retaining wall or slope that would intercept subsurface moisture and direct it away from the sensitive feature.

Setbacks can be incorporated into site design and the selection of locations for infiltration systems such that the potential for impacts are reduced. For example, an option would be to limit infiltration to areas a minimum specified distance from the crest of a slope or from an underground structure/vault, foundation or retaining wall. This would reduce the amount of infiltration in the vicinity of the sensitive feature and therefore reduce the potential impacts. The setback distance will depend on the quantity and duration of infiltration and design considerations for the sensitive feature. When infiltration can be considered early in the process of laying out the project, it may be possible to identify key areas for infiltration that observe necessary setbacks so drainage can then be routed to these suitable areas. Site design approaches to mitigate infiltration risks are generally more applicable for new projects than for lane-addition projects and retrofits.

In cases where increases in moisture near the ground surface or at specific depths may result in an unsatisfactory impact, the designer may encourage infiltration at deeper or at specific depths by installing features such as french drains, wick drains or dry wells. These types of features provide preferential vertical drainage paths that allow water to reach deeper soil layers. This may be an option to reduce the potential for frost heave by limiting a source of water near the surface for ice lens growth or to reduce potential surficial stability issues. In addition, by providing surface grading that directs flows away from structures, infiltration zones can be targeted that may reduce impacts on nearby structures.

4.2 Remove or Reduce the Geotechnical Risk Factor

By removing or reducing the geotechnical risk factor, the potential for negative impacts from an infiltration type design are inherently reduced. In particular, this category of mitigation measure reduces the potential impacts by removing the geotechnical component that may cause the impact, such as:

- Prewetting or moisture conditioning and recompaction of collapsible soils;
- Removal and replacement of expansive soils;
- Lime treatment of expansive soils;
- Removal of frost susceptible soil to reduce risk of frost heave;
- Densification of potentially liquefiable soils;
- Overexcavation of soft of weak soil layers beneath foundations and slopes; and
- Utilization of bound materials (e.g., cement treated) in pavement section.

Many of these approaches may already be conducted as part of a conventional project to account for incidental infiltration that may occur. In considering the effectiveness of these practices for improving infiltration feasibility, consideration should also be given to negative impacts on infiltration rates that may result. For example, it does not make sense to recompact collapsible soils to allow for stormwater infiltration if the result would be a reduction in infiltration rate to the point where achievable infiltration does not meet project goals.

4.3 Design of Features to Incorporate Infiltration

By either retroactively or proactively designing structures or other features to accommodate increased infiltration, undesirable geotechnical impacts can be minimized. Retroactive approaches would apply to existing structures, slopes, utilities, retaining walls, and other features that were previously constructed without consideration of stormwater infiltration and would be potentially influenced by the addition of stormwater infiltration. Proactive approaches would apply to the design of features that are to be constructed.

Retroactively, mitigation designs may include features such as:

- Waterproofing of subsurface structures to limit seepage/infiltration;
- Addition of tie-back anchors, soil nails, or struts to provide additional support to counteract hydrostatic forces on retaining walls;
- Adding anchors or additional weight to counteract buoyant forces on subsurface utilities or vaults;
- Constructing drainage behind retaining walls to reduce hydrostatic forces on the wall;
- Increase capacity of drainage systems along roadway shoulders to reduce potential migration of water to pavement system;
- Modify slope inclination, add soil buttresses, rock anchors/tie-backs or drainage features to increase slope stability; and
- Increase deep rooted vegetation on surficial slopes to reduce potential of surficial slope failures.

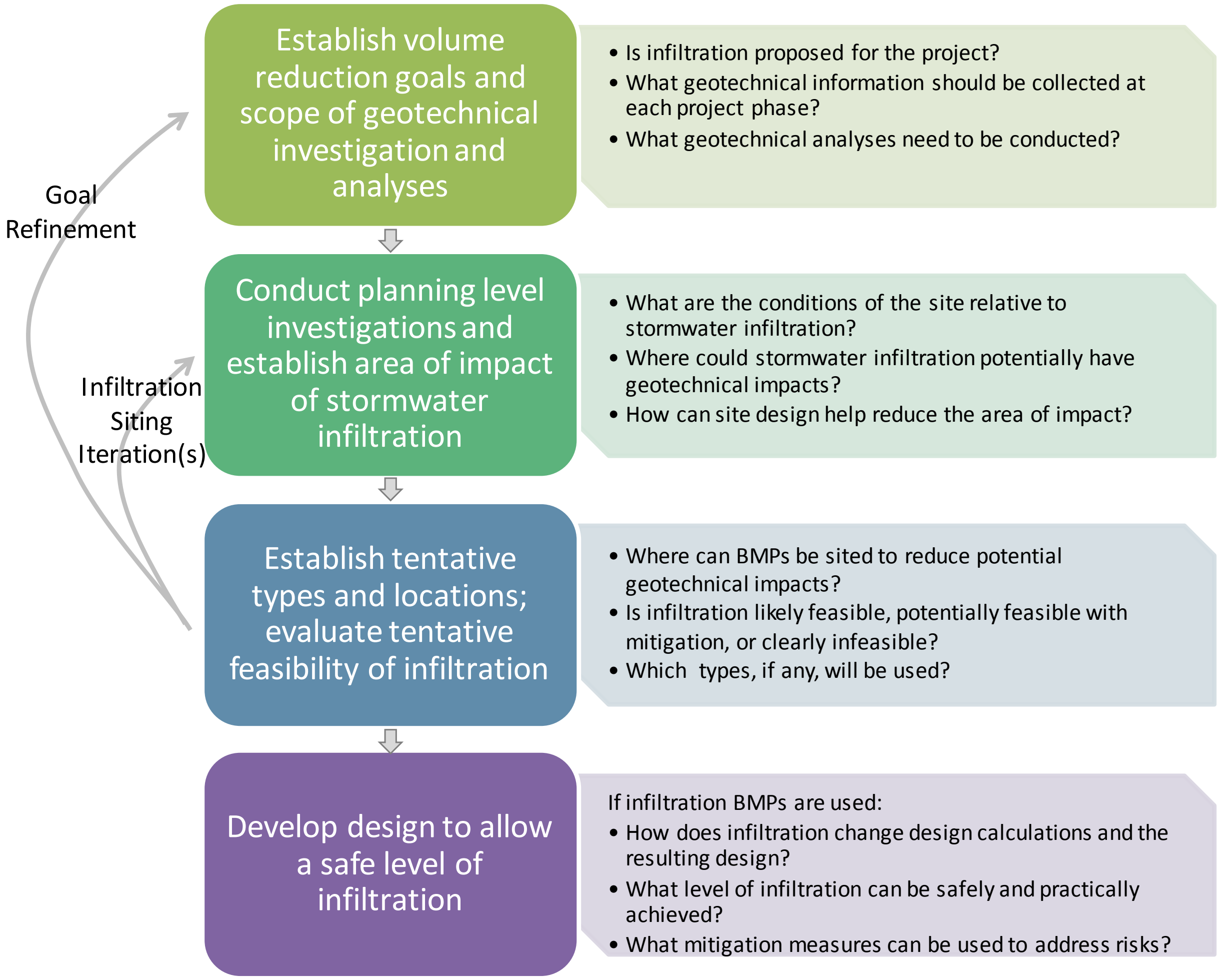
Proactively, structures or features that may be designed concurrently or after the infiltration design may include the following in their design:

- Preloading areas of soft sediments to induce consolidation settlements in advance of settlement sensitive structure construction;
- Assuming increased moisture content or modified groundwater conditions in design of slopes, retaining walls and foundations;
- Setting structure foundations below the frost line;
- Providing a capillary break beneath frost susceptible soils;
- Providing significant vertical separation of drainage features from frost susceptible soils;
- Placement of frost susceptible soils at depth in fill embankment;
- Providing redundant drainage features;
- Accommodating potential for differential settlement resulting from fluctuating moisture conditions in the subsurface by stiffening foundations and walls;
- Designing pavement section to account for elevated moisture, and
- Utilization of bound materials (e.g., asphalt treated permeable base, cement treated materials) in pavement section.

The feasibility of these approaches is expected to vary greatly on a site-by-site basis and should be evaluated using "what if" scenarios based on site-specific information. Not all mitigation measures may be physically or economically feasible.

5 Summary of Implications for Volume Reduction Design

Achieving volume reduction via infiltration of stormwater inherently introduces a greater quantity of water into the subsurface geology than would otherwise occur. This has ramifications at each phase of project design. Figure 6 below summarizes a general sequence for incorporating stormwater infiltration into project design and identifies key questions that may need to be answered at each project phase. Because additional information is obtained through this process, it may be necessary to iterate between steps for goal refinement (i.e., what can be safely and practicably achieved) and site design (i.e., where should infiltration be sited).



Establish volume reduction goals and scope of geotechnical investigation and analyses

- Is infiltration proposed for the project?
- What geotechnical information should be collected at each project phase?
- What geotechnical analyses need to be conducted?

Conduct planning level investigations and establish area of impact of stormwater infiltration

- What are the conditions of the site relative to stormwater infiltration?
- Where could stormwater infiltration potentially have geotechnical impacts?
- How can site design help reduce the area of impact?

Establish tentative types and locations; evaluate tentative feasibility of infiltration

- Where can BMPs be sited to reduce potential geotechnical impacts?
- Is infiltration likely feasible, potentially feasible with mitigation, or clearly infeasible?
- Which types, if any, will be used?

Develop design to allow a safe level of infiltration

If infiltration BMPs are used:
- How does infiltration change design calculations and the resulting design?
- What level of infiltration can be safely and practically achieved?
- What mitigation measures can be used to address risks?

Figure 6. Example Approach for Including Stormwater Infiltration in the Geotechnical Design Process

Table 1 provides a summary of the indicators of elevated risk and potential design implications associated with each category of geotechnical hazard identified in Section 3. Table 2 provides summary of potential opportunities and constraints for specific categories of BMPs related to geotechnical considerations. The guidance in these tables is intended to provide a brief summary and synthesis of the information presented in Section 3 and 4 and is not intended to replace the need for sound engineering judgment based on project-specific data.

Table 1. Summary of Geotechnical Considerations

Geotechnical Hazard Category	Example Indicators of Elevated Risk[1]	Example Design Implications[1]
Utility Considerations	• Presence of utilities in ROW • Historic infrastructure • Underground vaults below groundwater table • Permeable backfill in trenches	• For existing and proposed utilities: Allow adequate setbacks or otherwise control area of impact and/or limit flow within utility corridors with cut-off walls, • For proposed utilities: Design utilities to allow for infiltration, if needed.
Slope Stability	• Presence of slopes greater than 20 percent (5V:1H), or otherwise potentially affected • Highway sections on embankment • Soil strength is sensitive to water content • Instability observed in adjacent areas	• Avoid infiltration near slopes • Provide features, such as cutoff walls or drainage systems, to control lateral migration near slopes, if needed • For proposed slopes, may be possible to allow for infiltration in design assumptions; incidental infiltration may already be assumed in standard calculations
Settlement and Volume Change		
Hydrocollapse and calcareous soils	• Younger alluvial, aeolian or colluvial soils • Soils with calcium carbonate cementation • History of hydrocollapse/calcareous soils in area	• Investigation and remediation typically part of standard highway design within the roadway footprint • Remedial options, including prewetting or compaction may reduce infiltration rates
Expansive soils	• Typically associated with certain types of clays	• Investigation and remediation typically part of standard highway design • Ability to remediate with removal and/or lime treatment may depend on depth and extent of expansive soils
Frost heave	Each of the following present: • Water content near surface, • Frost susceptible soils (soils with high capillarity and adequate permeability (typically silts and loams) • Freezing weather conditions	• Investigation and remediation typically part of standard highway design • May be limited by setting infiltration surface well below ground surface
Consolidation	• Saturated soft sediments, and • Potential for significant increase in weight of surface layer or elevation of groundwater	• Design to allow settlement • Distributed infiltration more evenly to result in lower increase in weight per unit area

Geotechnical Hazard Category	**Example Indicators of Elevated Risk[1]**	**Example Design Implications[1]**
Dispersive Soils and Piping	• Moderate to high subsurface gradients • Dispersive soils or fine grained cohesionless soils	• Design filtration systems to reduce subsurface erosion • Reduce subsurface gradients • Lime treatment of dispersive soils
Liquefaction	• Saturated, loose to medium dense sandy and silty soils, and • Rapid cyclical loadings (earthquakes)	• Design to eliminate one or more of the three key risk factors • Design to balance consequence of failure versus probability of earthquake
Retaining Walls and Foundations	• Presence of retaining walls or foundations within influence area • Finer grained soils with bearing strength sensitive to moisture content • Potential for significant increase in weight of surface layer or elevation of groundwater	• Avoid infiltration near retaining walls and foundations • Provide features, such as cutoff walls or drains, to control lateral migration, if needed • For proposed features, may be possible to allow for infiltration in design assumptions; incidental infiltration may already be assumed in standard calculations
Pavement Impacts	• Moisture sensitive base, subbase, or subgrade materials • Insufficient drainage systems to limit water contact with pavement system • Poorly draining base or subbase	• Increased pavement section thickness to accommodate reduced subgrade modulus • Design of free draining base, subbase layers • Increased maintenance requirements • Inclusion of filter in pavement design to limit fines migration

1 – Examples provided to identify typical indicators of risk and possible design implications. Additional risk factors and design implications may be present based on site specific conditions. More information regarding risk indicators, design implications and potential mitigation measures is provided in Section 3.

Table 2. Summary of Potential Opportunities and Constraints for Specific Categories of BMPs

Category of BMP	Characteristic Properties	Example Opportunities and Constraints related to Geotechnical Issues1	
		Opportunities	**Constraints**
Direct infiltration into roadway subgrade	• Broad footprint; may only receive direct rainfall or equivalent • Road subgrade has important structural considerations, particularly for flexible pavement design	• Broad footprint may allow infiltration in relatively dense soils • Standard roadway designs typically account for wetting of subgrade • Rigid pavement design (i.e., concrete) less sensitive to strength of subgrade	• Utilities in ROW • Settlement and volume change could damage roadway • Reduction in strength of subgrade material may render infeasible or require higher construction costs
Infiltration in shoulders	• Outside of main travel lanes; significantly less loading • Smaller footprint; more concentrated zone of infiltration	• Designed to accommodate less loading or no loading • Well-distributed inflow • Can have moderate to high tributary area ratio[2] • Linear configuration less susceptible to groundwater mounding than basin configurations • Underdrain with outlet can control amount of water infiltrated	• Typically, shoulder should be compacted to same degree as mainline roadway • Potential for water to migrate laterally into mainline subgrade rock or nearby development • Settlement or volume change could lead to damage to roadway • Potential reduction in slope stability for embankment or depressed sections
Compost amended slopes/filter strips adjacent to roadway	• Allows incidental infiltration over relatively broad area; also provides ET • Typically coupled with vegetated conveyance at toe of filter strip	• Drainage over shoulder is a typical design feature • Compost amended results in relatively limited increase in infiltration compared to standard design • Higher proportion of losses to ET than other BMPs	• May lead to erosion issues if applied on slopes that are too steep • Slopes may need to be compacted to same degree as mainline roadway • In some cases, settling or volume change could damage roadway.

Category of BMP	Characteristic Properties	Example Opportunities and Constraints related to Geotechnical Issues1	
		Opportunities	Constraints
Channels, trenches, and other linear depressions offset parallel to roadway	• Tends to be located 10 or more feet from travel lanes • Typically, effective water storage depth is between 6 inches and 36 inches. • Loading ratio may be higher than other BMPs • May be fully or partially infiltrated	• Channels with positive grade are common drainage features; have relatively limited increase in risk • Due to horizontal separation, features have less potential to damage roadway • Some settlement may be tolerable	• Greater potential for impacts out of ROW due to proximity to ROW line. • Greater potential for mounding due to concentration of infiltrating footprint. • Higher infiltration rates are typically needed to support centralized facilities compared to more distributed facilities. • May reduce stability of slopes if located near top or toe.
Basins and localized depressions	• Typically located in more centralized locations • Loading ratio may be higher than other BMPs • Typically, effective water storage depth is between 12 inches and 60 inches	• Centralized areas, such as wide spots in ROW or interchanges may allow ample setbacks from foundations, slopes, and structural fill • May be possible to preserve natural soil infiltration rates through construction • Impacts of potential settlement may be minor	• Broad footprints and deeper ponding depths may result in substantial groundwater mounding and lateral water migration in some cases which may impact settlement, slope stability and nearby foundations or retaining walls. • Due to more concentrated flows from large tributary area, greater setbacks may be needed than would be applied for more distributed systems • Higher infiltration rates are typically needed to support centralized facilities compared to more distributed facilities.

1 – Examples provided to identify typical opportunities and constraints of the infiltration design feature. Additional opportunities and constraints may be present based on site specific conditions. More information regarding risk indicators, design implications and potential mitigation measures is provided in Section 3.

2 – Loading ratio refers to is the ratio of the tributary area to the infiltrating surface area. A higher loading ratio indicates greater concentration of water to the infiltration BMP.

6 Recommended Contents of Geotechnical Infiltration Feasibility and Design Reports

Project teams can develop a "Geotechnical Infiltration Feasibility and Design Report" or equivalent to summarize the geotechnical feasibility of stormwater infiltration and associated design parameters. This report should build incorporate assessments of infiltration rate (Appendix B), groundwater mounding (Appendix C), and potential water balance issues (Appendix D). In practice, project teams may address these three issues as part of the same site investigation and reporting effort. Project teams may also elect to prepare a preliminary infiltration feasibility report (addressing feasibility screening questions with greater dependence on desktop analyses) and a final infiltration design report (confirming feasibility/infeasibility and addressing design-level issues).

The exact contents of report(s) may vary as a function of project type, site conditions and associated conditions of the concern, regulatory context, and agency preference. However, the key underlying questions are generally similar:

Feasibility screening:

- Where within the project site do conditions potentially allow infiltration to be used?
- To what degree are infiltration BMPs potentially feasible in these areas? What class of infiltration BMPs is most likely to be feasible (i.e., full infiltration, maximized partial infiltration, incidental infiltration, or no infiltration)?
- What remaining issues need to be investigated/assessed to confirm feasibility?

Design analysis.

- Are preliminary feasibility findings confirmed?
- For locations where infiltration BMPs are proposed, what design infiltration rates should be used?
- What design elements (i.e., modified design parameters, mitigation measures) are recommended to be included in designs to safely allow infiltration to occur in these locations?
- Is there a need for contingency/backup plans involving construction-phase testing to determine the appropriate design alternative? (such as if the project grading plan does not allow adequate testing before earthwork has occurred)

The report should address each of these questions, as appropriate for site conditions and the phase of the project. Potential elements of the report that may be relevant to address these questions include, but are not limited to:

- Location and area of influence of stormwater infiltration systems
- Depth to the seasonally high groundwater table; expected fluctuation in the groundwater table
- Typical subsurface soil or rock conditions, including bore logs and/or results of other investigations
- Permeability/hydraulic conductivity of the subsurface materials, including results of testing, as appropriate (See Appendix B)

- Estimated groundwater mounding and soil moisture impacts from stormwater infiltration (Appendix C)
- Controlling factors in subsurface water flow (e.g., percolation, flow in joints, or along a limiting layer or aquitard)
- Recommended design infiltration rates and factors of safety, considering the results of infiltration testing, assessment of controlling subsurface factors, assessment of groundwater mounding, and other factors presented in Appendix B and C.
- Presence of expansive, collapsible, compressible or liquefiable soils
- Presence of slopes and structures and evaluation of stability under stormwater infiltration conditions, including mitigation measures (e.g., setbacks, isolation systems, drains), if appropriate
- Recommended pavement design parameters, such as the modulus of resilience of subgrade soils in presence of infiltration systems
- Analysis of primary and continency design alternatives, construction or post-construction testing requirements, and thresholds that would trigger continencies, as applicable.

Various other elements may be appropriate to include in the report, at the discretion of the responsible geotechnical engineer.

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