Safety and Stability of Stormwater Infiltration BMPs Adjacent to Roadsides

Requested by

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Table of Contents

Executive Summary

Background

Caltrans Office of Stormwater Management Design is updating its guidance to comply with new National Pollutant Discharge Elimination System (NPDES) permit requirements. The new permit requires Caltrans to prioritize soil-based best management practices (BMPs) and to give first consideration to installing BMPs that are capable of infiltrating the amount of water from the 85th percentile 24-hour storm. This requirement must be implemented where feasible, based on other Caltrans safety and design requirements.

Installing soil amendments adjacent to roadsides presents challenges. To facilitate water infiltration, amended soils are commonly compacted to less than the 90 percent of the relative compaction specified in the Caltrans Standard Specifications, which may cause an issue with traversability of vehicles in the clear recovery zone (CRZ). District traffic safety offices have questioned the safety impacts of amending soils on slopes in the clear recovery zone adjacent to roadways that must be traversable. In particular, Caltrans was interested in the following topics:

- The bearing capacity of amended soils.
- The soil classifications or gradations that provide enough bearing support for a vehicle while also providing adequate stormwater infiltration at a certain relative compaction.
- The impact of soft shoulders on the likelihood of vehicle rollovers.
- Conditions for slopes or embankments that allow them to maintain structural integrity and not fail or slide away when saturated.

To assist with this effort, CTC & Associates conducted a review of literature and state and federal guidance, and interviewed staff at FHWA, TRB and state DOTs with experience in this area.

Definitions

The following terms are used in this Preliminary Investigation.

Bearing capacity: The load per unit area that can be safely supported by the ground. (*McGraw-Hill Dictionary of Scientific & Technical Terms*)

Bearing pressure: The load on a bearing surface divided by its area. Also known as bearing stress. (*McGraw-Hill Dictionary of Scientific & Technical Terms*)

Clear zone: The unobstructed, traversable area provided beyond the edge of the through traveled way for the recovery of errant vehicles. The clear zone includes shoulders, bike lanes, and auxiliary lanes, except those auxiliary lanes that function like through lanes. *(AASHTO Roadside Design Guide)*

> **Recovery area:** Generally synonymous with clear zone. *(AASHTO Roadside Design Guide)*

Non-recoverable slope: A slope which is considered traversable but on which the errant vehicle will continue on to the bottom. Embankment slopes between 1V:3H and 1V:4H may be considered traversable but non-recoverable if they are smooth and free of fixed objects. *(AASHTO Roadside Design Guide)*

Recoverable slope: A slope on which a motorist may, to a greater or lesser extent, retain or regain control of a vehicle. Slopes flatter than 1V:4H are generally considered recoverable. *(AASHTO Roadside Design Guide)*

Traversable slope: A slope from which a motorist will be unlikely to steer back to the roadway but may be able to slow and stop safely. Slopes between 1V:3H and 1V:4H generally fall into this category. *(AASHTO Roadside Design Guide)*

Sources: AASHTO Roadside Design Guide, 4th edition, 2011 (see Glossary, page G-1); McGraw-Hill Dictionary of Scientific & Technical Terms, version 6E, 2003.

Summary of Findings

Most of the sources that we interviewed shared Caltrans' concerns about the use of amended soils adjacent to roadsides because of the potential for the amendments to create "soft shoulders" that may have traversability and recoverability issues. For example, Oregon DOT has experienced that an amended soil adjacent to a highway shoulder almost immediately developed ruts from vehicles driving on it, and ODOT now uses geogrids for additional stabilization in similar situations. Washington State DOT, however, has successfully used vegetated filter strips and media filter drains adjacent to roadsides; the initial rutting did not lead to vehicle rollovers or other accidents. More study is needed on the extent to which stormwater infiltration BMPs adjacent to roadsides cause soft shoulders, traversability issues and crashes.

While we found general information on the bearing capacity of several types of soils (see page 13 of this Preliminary Investigation), there does not appear to be any simple guidance for determining whether specific soil conditions pose a greater risk than others of leading to reduced slope stability when the soil is saturated. Instead, we found several methods for modeling slope stability (see page 18). These complex modeling techniques account for many variables related to soil type and condition.

Softer soils adjacent to roadsides do contribute to vehicle rollovers, according to FHWA staff and published research. As with soil stability, models are available to evaluate the rollover potential of specific soils. See pages 19 to 22 of this Preliminary Investigation for details on these topics.

Several suggestions and recommendations emerged from our research regarding use of amended soils adjacent to roadsides. These include:

- Consulting with geotechnical staff during the design phase to ensure that slopes or embankments will maintain stability under all conditions.
- Using geogrids to add stability to amended soils.
- Visually delineating BMPs, such as with flexible guidepost markers, to reduce the likelihood of vehicles driving over them.
- Testing other methods of improving soil stability in the first years after a BMP's construction, such as mixing compost with aggregate base course.

States' Experiences

We conducted interviews with state agencies in Washington, Oregon and Maryland, which were selected by Caltrans as agencies likely to have experience in this area.

Washington

- Washington State DOT uses amended soils in vegetated filter strips and media filter drains adjacent to the roadside. While the state has seen rutting in these BMPs due to vehicles driving on them, no accidents have occurred. Rutting is worst in the first few years of the BMP's life, after which the vegetation's root structures help to make the BMP more stable.
- Options that have been considered to address instability of soil in vegetated filter strips or media filter drains include using construction barrels or flexible guidepost markers to delineate the BMP, or using a half-and-half mix of aggregate base course and compost in the compost-amended vegetated filter strip to toughen the soil. These options have not been implemented as they have not been considered necessary.

Oregon

- A few years ago, Oregon DOT implemented amended soil outside of a freeway's gravel shoulder to infiltrate stormwater and prevent runoff from impacting fish species of concern in nearby rivers. While no rollover accidents occurred, ruts appeared in the amended soil almost immediately.
- As a result, Oregon typically uses amended soils only near the drainage line or bottom of a slope. When space limitations force amended soils to be used adjacent to driving lanes, ODOT uses geogrids to provide a relatively solid surface for vehicles that run off the road.
- Oregon's guidance prohibits installing stormwater infiltration BMPs where they could contribute to instability of the terrain. Engineers are directed to consult with geotechnical staff before implementing stormwater infiltration BMPs to ensure that slopes remain stable.

Maryland

- In Maryland, stormwater infiltration BMPs are not constructed in locations where they might be driven over.

Related Research and Resources

Soil Bearing Capacity

- The Code of Federal Regulations defines methods for determining a soil's bearing capacity, including soil tests, soil records or use of a pocket penetrometer. It also provides maximum allowable soil bearing pressures for six soil classifications, although bearing capacity for a soil composed of peat, uncompacted fill or organic clay must be determined by a registered geologist, engineer or architect.
- The American Society of Civil Engineers has published a design guide for determining the bearing capacity of soils under many types of structures, including embankments.

Stormwater Infiltration BMPs and Slope Stability

- We did not find documentation that addresses both a soil's ability to support vehicles and infiltrate stormwater. However, several sources note that infiltration can have a negative impact on a slope's stability. For example, NCHRP Report 802 notes that vegetated conveyances are typically located at least 10 feet from travel lanes. They may reduce the stability of slopes if they are located near the top or the toe, the report says, and they increase the potential for groundwater mounding (a localized rise in groundwater underneath a BMP). Dispersion techniques may lead to erosion issues if they are implemented on steep slopes, and slopes may need to be compacted to the same degree as the mainline roadway.
- Appendix E to NCHRP Report 802 details a variety of geotechnical concerns related to stormwater infiltration, including slope stability and settlement and volume change.
- Two reference books offer detailed methods for calculating the conditions necessary for slopes to maintain structural integrity. There are many variables involved, including soil type, density, grain-size distribution, pressures and soil conditions.
- Two NCHRP projects in progress are separately examining (1) limitations of stormwater infiltration techniques, and (2) slope traversability. However, neither project is expected to address the installation of stormwater infiltration BMPs adjacent to roadsides.

Impact of Soft Shoulders on Vehicle Rollovers

- Soft shoulders or slopes contribute to vehicle rollovers, according to FHWA staff and published data. Several documents present methods for modeling the behavior of vehicles on soft soils, including a 1986 FHWA report on rollover potential on embankments and a 1998 SAE technical paper on soil-tripped rollovers.

Gaps in Findings

- There does not appear to be simple guidance for determining whether specific soil conditions will lead to reduced slope stability or an increase in vehicle rollovers; more research is needed. See "Next Steps" below for more detail on potential future research directions.
- The documentation we identified generally addresses either a soil's ability to infiltrate stormwater or a soil's stability and impact on vehicle rollovers, not both.
- The literature lacks definitions based on quantitatve or qualitative criteria for terms such as "soft shoulder."

Next Steps

Moving forward, Caltrans may wish to consider:

1. Following up with Oregon DOT for more information about geotextiles' capacity to stabilize amended soils adjacent to roadsides.
2. Contacting Washington State DOT to learn more about that agency's experiences with media filter drains and vegetated filter strips, especially to understand any factors that may help prevent rollovers.

3. Working with geotechnical staff or other qualified personnel to evaluate slope stability considering all variables of soil type, compaction and saturation level.
4. Exploring visual delineation of BMPs.
5. Conducting research on the potential of stormwater infiltration BMPs to cause soil stability issues that pose a safety hazard. Potential research topics identified include:

   Quantifying the problem

   - Quantifying the extent to which water infiltration causes soil stability issues.
   - Identifying additional studies or tests needed to better define limits for stormwater infiltration BMPs adjacent to roadsides. Areas of study could include:
     - Defining what constitutes a "soft shoulder," including quantifiable parameters of soil properties.
     - Establishing the depth of rutting that presents a safety concern.
   - Assessing whether stormwater infiltration BMPs cause soft shoulders that have vehicle traversability and recoverability issues, and whether rutting in these BMPs leads to an increase in crashes.
   - Identifying soil gradations that can be used for stormwater BMPs adjacent to roadsides to minimize soil stability concerns.
   - Determining an adequate distance away from the shoulder (but still within the clear recovery zone) where soil amendments could be utilized.

   Developing and testing design criteria

   - Developing design criteria for earthen stormwater infiltration BMPs in protected and nonprotected areas of the roadside. These criteria should:
     - Balance the need to infiltrate water, provide stable slopes, and reduce the potential for causing vehicle traversability issues.
     - Consider traffic safety as well as parameters such as amendment type and depth, compaction, bearing pressure and slope steepness.
   - Developing specifications and construction guidance to build BMPs that maximize infiltration without causing traffic or stability issues, and then conducting a comprehensive study to determine whether the new standards cause traffic issues. (Current standard specifications are based solely on maximizing stability, reducing compaction and adding void space to increase infiltration and stormwater treatment.)
     - Developing designs to give a maximum expected compaction depth to which a soft shoulder is allowed.

Detailed Findings

Consultation with Experts

CTC interviewed staff at FHWA, TRB and three state agencies—Oregon, Washington and Maryland—about the safety impacts of soft shoulders. These conversations are summarized below.

FHWA

Interviewees: Ken Kochevar, Safety Program Manager, California Division, 916-498-5853, Ken.Kochevar@dot.gov.

Frank Julian, Safety Engineer, FHWA Resource Center, Safety and Design Team, 404-562-3689, frank.julian@dot.gov.

Frank Julian of the FHWA Resource Center discussed the impact of soft shoulders on vehicle rollovers. "Softer shoulders or slopes are contributors to vehicle rollovers," he said. "Soil furrowing and tripping have come up frequently in many discussions on rollovers over the years. Softer soils are not as likely to be a big issue when a vehicle is tracking, but the problem comes when the vehicle is in a yaw and the soft material allows the tires to dig in, and that induces tripping and rollover." (*Yaw* is one of three axes that can define vehicular rotation, and refers to spinning around a vertical axis. The others are *roll,* or flipping around an axis that runs from the front of the vehicle to the back, and *pitch,* or flipping end-over-end around an axis that runs horizontally through the side of the vehicle.)

Julian noted that according to a 1986 FHWA report, *Rollover Potential of Vehicles on Embankments, Sideslopes and Other Roadside Features*, about half of vehicles that leave the pavement are in yaw, although anti-lock brakes and electronic stability control have reduced the yaw rate to about 40 percent since the publication of that report. (See http://www.mchenrysoftware.com/Rollover Potential of Vehicles.pdf, and see page 18 of this Preliminary Investigation for more details.)

The friction of the soil is also a factor in vehicle rollover, Julian said: Lower friction would likely reduce rollovers. As a result, a wet or lubricated—but hard—soil would be beneficial to reducing vehicle rollovers.

Julian recommended several resources on this topic, which are summarized later in this report (see pages 13 and 19):

- NCHRP Project 17-55, "Guidelines for Slope Traversability," completion expected in March 2016.
  http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3177
- "Characteristics of Soil-Tripped Rollovers," SAE International conference paper, 1998.
  Citation at http://papers.sae.org/980022/
- "An Examination of Furrow Tripping and Vehicle Rollovers," *Proceedings of the Canadian Multidisciplinary Road Safety Conference IV,* 1985.
  Citation at https://www.worldcat.org/title/an-examination-of-furrow-tripping-and-vehicle-rollovers/oclc/173447551

Julian also suggested that porous pavements (both concrete and asphalt) could be used in paved shoulders to help reduce water runoff.

TRB

Interviewee: William C. Rogers, Senior Program Officer, National Cooperative Freight Research Program, 202-334-1621, WRogers@nas.edu.

Rogers is the TRB staff member responsible for NCHRP Project 25-51, "Limitations of the Infiltration Approach to Stormwater Management in the Highway Environment." He said that this project is intended to provide guidance in situations where DOTs have no other option but to use infiltration techniques, but where there are site concerns like a high water table that could lead to groundwater contamination. The project is expected to receive funding soon; its anticipated duration is 30 months. See http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3891.

In general, Rogers suggested that there may not be much data available on the safety impacts of soft shoulders because many run-off-the-road incidents do not get reported if the vehicle is able to recover and continue on its way.

He also recommended several references, which are summarized beginning on page 14 of this report:

- NCHRP Report 802, *Volume Reduction of Highway Runoff in Urban Areas: Guidance Manual*, 2015.
  http://www.trb.org/main/blurbs/172415.aspx
- NCHRP Report 728, *Guidelines for Evaluating and Selecting Modifications to Existing Roadway Drainage Infrastructure to Improve Water Quality in Ultra-Urban Areas,* 2012.
  http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_728.pdf
- *Urban Stormwater Management in the United States*, National Research Council, 2008.
  http://www.epa.gov/npdes/pubs/nrc_stormwaterreport.pdf

Oregon DOT

Interviewee: William B. Fletcher, Water Resources Program Leader, 503-986-3509, William.B.Fletcher@odot.state.or.us.

Fletcher described an Oregon project involving amended soils adjacent to a highway shoulder. A few years ago, ODOT widened the shoulder on I-5 south of Portland. There were environmental concerns related to the impact of runoff from widened paved shoulders on fish species of concern in nearby rivers, so ODOT implemented amended soil outside of a gravel shoulder. Almost immediately, large numbers of ruts appeared on the amended soil. No rollover accidents occurred, but Fletcher suggested that was due to luck.

In response, ODOT developed internal guidance that may eventually be added to the state hydraulics manual. Under this guidance, amended soils should be used near the drainage line or the bottom of a slope, rather than adjacent to the driving lanes, if there is enough space to do so. When there isn't enough space, ODOT uses geogrids to provide a solid surface for vehicles that run off the road to drive on and limit the extent to which those vehicles will sink into the soil.

ODOT also utilizes geogrids with media filter drains—a linear treatment also called a bioslope that runs parallel to the road. ODOT's media filter drain design consists of a narrow vegetated strip; drain rock and a mix of sand, pearlite and other materials to remove dissolved metals; and an underdrain to capture and discharge stormwater.

Fletcher noted that ODOT's guidance directs engineers who are considering using infiltration BMPs to consult with geotechnical staff to ensure that slopes will remain stable. In general, state guidance prohibits stormwater infiltration when it could contribute to geographic instability.

Fletcher said that Oregon has not investigated soil classifications or gradations that would support a vehicle while also infiltrating stormwater. The state also does not have guidance or specifications related to load-bearing capacity of embankments or roadside slopes when saturated.

ODOT has one related in-progress research project:

- "Appropriate Width of Filter Strips for Natural Dispersion of Stormwater in Western Oregon," Project SPR 758, expected completion in fall 2015.
  http://www.oregon.gov/ODOT/TD/TP_RES/pages/activeprojects.aspx#SPR_758
  This project seeks to establish an equation for determining the width of dispersion areas adjacent to roadsides needed to infiltrate the required design storm.

Washington State DOT

Interviewee: Alex Nguyen, P.E., Hydraulics and Stormwater Office, 206-440-4537, Nguyeal@wsdot.wa.gov.

WSDOT has used amended soils in vegetated filter strips on embankments adjacent to roadsides, Nguyen said. The DOT adds a layer of compost, tills it down to a foot thick, and tamps it down but leaves it uncompacted. The DOT also scarifies the interface between the compost layer and the embankment to help water move from the amended compost layer into the subsoil.

Nguyen said that the state has seen rutting in these vegetated filter strips, but this rutting has not led to any more serious incidents. Rutting occurs primarily in the first few years after installation of the BMP. "In a few years, that area really thickens up with vegetation as its root structure takes hold," Nguyen said. Roots do not impair the BMP's ability to infiltrate water, however, because the roots create holes through which water can travel to the subsoil.

While there have been no accidents related to vegetated filter strips, Nguyen said that he has considered installing construction barrels or flexible guidepost markers to delineate the BMP if any issues were to arise. As this has not been necessary, Nguyen was unsure what impact it would have, but he considered it a possible method of alerting drivers to the presence of a BMP to avoid driving over it.

Another potential mitigation method that the state has considered is using a half-and-half mix of aggregate base course and compost in the compost-amended vegetated filter strip, which would toughen the BMP during its early years. As with the use of delineation tools, this approach would only be considered if problems arose.

WSDOT has also implemented media filter drains, which consist of a leveled spread of crushed surfacing, followed by a 3-foot grass strip with compost in it, followed by a 2- to 4-foot strip of media filter mix. The state has seven configurations of media filter drains, three of which are adjacent to the roadway. The drain used to be built by excavating a foot down and constructing on top of the excavation, but after several large trucks drove on this type of drain and created ruts, the state began using existing soil and simply adding 3 inches of compost on top of it, which has resolved issues. Both media filter drains and compost-amended vegetated filter strips are detailed in the state's Highway Runoff Manual and Standard Specifications for Road, Bridge, and Municipal Construction (see below).

Nguyen said that geotechnical staff is consulted during the BMP design. He noted that the proper design requires both the amount of water that needs to be infiltrated and the infiltration rate of the soil. Determining the infiltration rate requires testing the soil and understanding the level of the groundwater table. "Both are important to know to determine if there's capacity for water to go down or if it will just go out," Nguyen said. "If the water goes out at the toe of the BMP, you've lost some stormwater volume but not all of it."

Additionally, Nguyen said that compost-amended soils do not work well on steep slopes. Amended soils typically start sloughing off of slopes steeper than 2:1. In general, most stormwater management BMPs have a maximum slope of 3:1, and compost-amended vegetated filter strips have a maximum slope of 4:1 without a barrier or guardrail. Additionally, on high-speed highways, slopes that are 3:1 or steeper are considered nondrivable and require some form of barrier.

While the state permits media filter drains and compost-amended vegetated filter strips adjacent to roadways, Nguyen said WSDOT prefers to locate BMPs at the bottom of slopes for safety purposes whenever possible.

WSDOT guidance documents:

- Highway Runoff Manual, April 2014. http://www.wsdot.wa.gov/Publications/Manuals/M31-16.htm
- Standard Specifications for Road, Bridge, and Municipal Construction, 2014. http://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/2014Amended2015-04-06.pdf

Maryland Department of the Environment

Interviewee: Amanda Malcolm, P.E., Acting Chief, Sediment and Stormwater Plan Review Division, 410-537-3551, amanda.malcolm@maryland.gov.

Malcolm said that Maryland prefers to infiltrate stormwater in designated stormwater facilities that may be alongside the shoulder, but never in the shoulder itself. "We would never want to put it in a place where it could be driven over," she said. She suggested contacting the Maryland State Highway Administration (SHA) for more details about soil amendments, as the agency was one of the first NPDES permittees. (Staff at Maryland SHA were not available for an interview during the time frame of this Preliminary Investigation.)

State Guidance

Oregon DOT

Hydraulics Design Manual, Oregon DOT, 2014.
http://www.oregon.gov/ODOT/HWY/GEOENVIRONMENTAL/pages/hyd_manual_info.aspx
Chapter 14 of the manual provides general technical guidance for several stormwater control facilities, with further detail in appendices. Appendix C addresses media filtration facilities, including bioslopes and other BMPs “where stormwater flows through soil, amended soil, compost or a special mix of materials” to absorb dissolved pollutants. According to this appendix, “Bioslopes are recommended for highway application because of their minimal right-of-way requirements and maintenance schedule.” They consist of a vegetated filter strip upstream of the bioslope; a treatment zone that includes a mixture of aggregate, dolomite, gypsum and pearlite to remove pollutants; and a subsurface drain to allow runoff outflow. Bioslopes may not be considered where sheet flow cannot be maintained, where slopes are steeper than 4:1, where unstable slopes are present, or where shallow groundwater is present.

According to Section 14.9.6.2, the soils on a site “determine whether infiltration-based BMPs are feasible or not.” Hydrologic class A and B soils (with high or moderate infiltration rates when thoroughly wetted) support infiltration BMPs, class C soils permit a small amount of infiltration, and class D soils (primarily clay soils with high swelling potential or soils with a permanent high water table) are not suitable for infiltration. Additionally, “Soil amendments can improve the pollutant removal characteristics of soils while maintaining acceptable permeability. They can also improve permeability in tight soils, but only in the layer with the amendment, so the amendment will support media filtration but not infiltration.”

BMP siting criteria are described in Section 14.9.8. Geotechnical requirements include that embankments must be designed to safely impound stormwater runoff, long-term permeability of surrounding soil must be verified, and retaining walls must be designed according to the ODOT Geotechnical Design Manual.

Washington State DOT

Highway Runoff Manual, April 2014.
http://www.wsdot.wa.gov/Publications/Manuals/M31-16.htm
Chapter 4 (page 4-29) advises that infiltration facilities should be located 20 feet downslope and 100 feet upslope from building foundations, and 50 feet or more behind the top of slopes that are steeper than 15 percent. It also advises that designers should “Request a geotechnical report for the project that would evaluate structural site stability impacts due to extended subgrade saturation and/or head loading of the permeable layer, including the potential impacts to downgradient properties (especially on hills with known side-hill seeps.)”

Design Manual, July 2014.
http://www.wsdot.wa.gov/Publications/Manuals/M22-01.htm
Chapter 610 provides guidance on conducting a soil investigation. Geotechnical investigation is conducted by the WSDOT Geotechnical Office, and requires data such as soil borings, testing and geometric data. Known unstable slopes adjacent to the transportation network may be stabilized to prevent landslides or rockfall.

Geosynthetics—including geotextiles, geogrids, geonets, geomembranes, or geocomposites—can be used to stabilize soils and are described in Chapter 630. Before implementation, designers should ask whether the geosynthetic is truly needed, identify the properties that will ensure that it functions as intended, determine where it should be located, and determine maintenance needs.

Regarding soft soils, the guide states that "Soil stabilization geotextile is used in roadway applications if the subgrade is too soft and wet to be prepared and compacted as required in the [WSDOT] Standard Specifications [for Road, Bridge, and Municipal Construction]."

Washington State DOT Standard Specifications for Road, Bridge, and Municipal Construction, 2014.
http://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/2014Amended2015-04-06.pdf
Section 2.03 addresses embankment construction. The preferred construction method (described in 2-03.3(14)C) requires the top 2 feet of material to be compacted to 95 percent of maximum density, while material below the top 2 feet should be compacted to 90 percent of maximum density. Two other methods are permissible if special provisions require them. One requires 95 percent compaction of each layer throughout the embankment; the other requires compaction "by routing loaded haul equipment over its entire width."

Embankment moisture content should be adjusted during compaction to ensure a firm, stable embankment. Under the preferred construction method, moisture content must not exceed 3 percent above the optimum content.

Related Research and Resources

This section summarizes published research and guidance related to the vehicle safety impacts of roadside soil amendments. These resources address three topics:

- Soil bearing capacity.
- Stormwater infiltration BMPs and slope stability.
- Impact of soft shoulders on vehicle rollovers.

Soil Bearing Capacity

We did not identify any sources that provide bearing capacities specifically for amended soils. The following references offer general guidance on soil bearing capacities, as well as methods for determining a specific soil's bearing capacity.

Code of Federal Regulations: 24 CFR 3285.202—Soil Classifications and Bearing Capacity
https://www.law.cornell.edu/cfr/text/24/3285.202
The Code of Federal Regulations defines six soil classifications. The following table (adapted from the code) gives bearing capacities that may be used for these classifications when the capacity cannot be determined by test or soil records.

Soil classification number	Soil description	Allowable soil bearing pressure
1	Rock or hard pan	4,000 pounds per square foot
2	Sandy gravel; gravel; dense and/or cemented sands; coarse gravel/cobbles; preloaded silts, clays and coral	2,000 pounds per square foot
3	Sand; silty sand; clayey sand; silty gravel; medium dense coarse sands; sandy gravel; very stiff silt; sand clays	1,500 pounds per square foot
4A	Loose to medium dense sands; firm to stiff clays and silts; alluvial fills	1,000 pounds per square foot
4B	Loose sands; firm clays; alluvial fills	1,000 pounds per square foot
5	Uncompacted fill; peat; organic clays	See note*

* Note: When a soil is composed of peat, organic clay or uncompacted fill, or if it appears to have unusual conditions, the maximum allowable soil bearing capacity must be determined by a registered geologist, engineer or architect.

Other methods for determining soil bearing capacities include soil tests in accordance with generally accepted engineering practice, soil records, or a pocket penetrometer (a device that measures compressive soil strength). Additionally, if these methods cannot be used, an allowable pressure of 1,500 pounds per square foot may be used, unless site-specific information requires lower values based on soil type.

Bearing Capacity of Soils, American Society of Civil Engineers, Technical Engineering and Design Guide No. 7, 1994.
http://www.asce.org/templates/publications-book-detail.aspx?id=7812
This guide includes extensive tables and formulas related to soil bearing capacities. An excerpt from the book's description:

> This U.S. Army Corps of Engineers engineering manual provides all the essential guidelines needed to determine allowable and ultimate bearing capacity of soils under shallow and deep foundations. Comprehensive in scope, the guide covers topics ranging from determining the length, number, and diameter of drilled shafts to in situ modeling of bearing pressures in shallow foundations. The principles presented are applicable to numerous types of structures, including buildings, houses, towers, storage tanks, fills, embankments, and dams.
>
> The first chapter presents definitions, failure modes, and factors that influence bearing capacity. The next chapter discusses nonload related design considerations such as frost action and soil erosion. Chapter 3 explores laboratory and in situ methods of determining soil parameters required. The last two chapters present an analysis of the bearing capacity of shallow foundations and deep foundations, respectively.

Stormwater Infiltration BMPs and Slope Stability

This section summarizes published research and guidance that addresses stormwater infiltration BMPs and slope stability. In general, state and federal guidelines related to soil hydraulics focus on a soil's ability to infiltrate stormwater rather than its ability to support vehicles. Several sources offer detailed guidance on calculating the conditions necessary for slopes to maintain structural integrity.

National Research and Guidance

"Limitations of the Infiltration Approach to Stormwater Management in the Highway Environment," NCHRP Project 25-51, in progress.
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3891.
This project is intended to provide guidance to DOTs at sites where infiltration techniques are the best option (or where they are required) but where there are site concerns such as a high water table that could lead to groundwater contamination. The project is expected to be funded soon and is anticipated to last 30 months.

"Guidelines for Slope Traversability," NCHRP Project 17-55, completion anticipated in March 2016.
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3177.
This project aims to develop guidelines for what constitutes recoverable, traversable and critical sideslope conditions, considering the characteristics of passenger vehicles in today's environment. Mark S. Bush, the TRB staff liaison for the project, said that the project will make some reference to soil types, soil friction and other factors, but it will focus on the impacts of different vehicle types as described in the AASHTO Manual for Assessing Safety Hardware.

Volume Reduction of Highway Runoff in Urban Areas: Guidance Manual, NCHRP Report 802, 2015.
http://www.trb.org/main/blurbs/172415.aspx
This manual provides guidance for reducing the volume of stormwater runoff in a wide range of urban highway environments. It provides recommendations for specific project types, site conditions and climate zones. Relevant sections of the report include:

- Table 14 (see page 74) summarizes geotechnical impacts related to various classifications of stormwater VRAs. According to this table, vegetated conveyances are typically located at least 10 feet from travel lanes. They may reduce the stability of slopes if they are located near the top or the toe, and they increase the potential for groundwater mounding. (Mounding is when groundwater rises in a localized area underneath a BMP; this can cause damage to structures above it, or reduce the effectiveness of infiltration at removing pollutants.) Dispersion techniques may lead to erosion issues if they are implemented on steep slopes, and slopes may need to be compacted to the same degree as the mainline roadway.
- Chapter 2 describes a step-by-step approach for incorporating stormwater infiltration into project development for an urban highway project. This chapter provides an example process that covers project planning, site investigation and project design.
- Chapter 3 characterizes the urban highway environment as it relates to stormwater volume reduction approaches (VRAs). Included in this chapter is a section related to how highway safety standards—including geometric design standards, vegetation and landscaping standards, and drainage standards—affect stormwater infiltration.
- Table 2 (see page 25) addresses the role of several aspects of the physical setting on VRAs. In particular, it states that "Compaction of fine-grained soils may be necessary for structural stability but may greatly reduce the infiltrating capacity of soils."
- Section 3.4.7 addresses geotechnical issues related to stormwater infiltration. In particular, infiltration can lead to settlement and volume changes and slope instability. The report recommends that if infiltration is considered, "A geotechnical investigation should be performed for the infiltration facility to identify potential geotechnical issues and geological hazards that may result from infiltration and potential mitigation measures to reduce risks to acceptable levels." Appendix E (which is available as a separate document, *NCHRP Web-Only Document 209*; see below) provides guidance for evaluating potential geotechnical issues at the planning and design phases.
- Specific stormwater VRAs are described in Chapter 4. Table 5 (see page 50) lists "soil amendments in landscaped areas" as a BMP that has potential for consideration in an urban highway environment, and one that has significant potential for reducing stormwater volumes.
- Table 7 (see page 52) provides the results of a 2012 survey of states that measured the relative frequency of stormwater control measures and their effectiveness at reducing stormwater volume. In this survey, compost-amended slopes were moderately common. Respondents rated compost-amended slopes as having the potential to significantly reduce stormwater volume, but said other processes should also be provided.
- Section 4.1.3 describes emerging stormwater VRAs, including media filter drains developed by Washington State DOT. WSDOT's Highway Runoff Manual (see page 10 of this Preliminary Investigation) contains design criteria for these BMPs.

Volume Reduction of Highway Runoff in Urban Areas: Final Report and *NCHRP Report 802* Appendices C through F, NCHRP Web-Only Document 209, 2014.
http://www.trb.org/main/blurbs/172417.aspx
This document contains several of the appendices for *NCHRP Report 802*. Appendix E reviews geotechnical considerations related to stormwater infiltration features. Slope stability and settlement and volume change are both potential hazards that are noted.

Slope Stability

Slope stability is described in Section 3.2: "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." (See page E-7.) Factors that affect slope stability include the slope inclination, soil and unit weight, and seepage forces; increases in moisture content or a rising water table may change the soil strength and unit weight, which can reduce stability.

The guide recommends that designers first identify existing or planned slopes in the area of impact. They should understand subsurface conditions, including whether there are existing seeps or springs in the slope or joints or bedding layers that water could affect, as well as whether the soil is susceptible to a loss of strength if it becomes wet. Reviewing geotechnical investigations for the area and published geologic maps may indicate whether slope stability is a concern. A geologist or geotechnical practitioner may identify existing landslide-prone features by reviewing aerial photographs of the area.

Section 3.2 also:

- Discusses a slope's factor of safety (the ratio of stabilizing forces to destabilizing forces), which can be affected by increases in moisture content.

- References several tools that provide simplified values for slope stability of homogenous slopes, including:

    - "**Stability Charts for Uniform Slopes,"** Radoslaw L. Michalowski, *Journal of Geotechnical and Geoenvironmental Engineering,* April 2002.
      http://www-personal.umich.edu/~rlmich/index_files/references/Michalowski SlopeCharts 2002.pdf

    - **Soil Mechanics Design Manual 7.01**, Naval Facilities Engineering Command, 1986.
      Citation at http://www.worldcat.org/title/soil-mechanics/oclc/17855543
      This manual provides slope stability charts for clay and silt soils and for submerged slopes.

Settlement and Volume Change

Settlement and volume change are discussed in Section 3.3 (see page E-11). Collapse can be caused by loose soils or soils with low moisture content that reduce in volume when wet; collapsible soils are typically geologically young and found in water-, wind- or gravity-deposited deposits. Risk can be mitigated by prewetting soil before constructing settlement-sensitive features, moisture conditioning and recompaction of collapsible soils, or treatment with chemical grouting. These treatments can reduce soil permeability, however.

- Expansive soils swell when moisture content increases, and typically contain the clay minerals montmorillonite or kaolin. Visual cracking in the soil is an indicator that it is expansive. Because expansive soils have clay, they are typically not suitable for stormwater infiltration.

Liquefaction of soils—in which sediments act like a fluid when exposed to rapid loading conditions like an earthquake—can occur if the soil is loose to medium-dense sandy soil or fine-grained soil with a plasticity index less than 12, saturated, and in a region with the potential to experience rapid loading conditions. (See page E-18.)

- Stormwater infiltration can increase the risk of liquefaction if the design increases the water table to a level that includes liquefaction-susceptible soils.
- Designers should evaluate whether a site is susceptible to liquefaction; the United States Geological Survey provides maps that designate liquefaction potential in parts of the United States, but its maps are not comprehensive. Local planning agencies may also have liquefaction susceptibility maps.
- Potential mitigation measures include removing loose sediments, infiltrating into deeper soils less susceptible to liquefaction, or densification of soils; however, these treatments may reduce soil permeability. Infiltration systems could also be designed with drainage trenches or barriers to avoid saturating liquefiable soils.

Guidelines for Evaluating and Selecting Modifications to Existing Roadway Drainage Infrastructure to Improve Water Quality in Ultra-Urban Areas, NCHRP Report 728, 2012.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_728.pdf
This report provides guidance for retrofitting stormwater management BMPs at existing highway facilities in dense urban areas. Chapter 3 describes general drivers and practices for BMP retrofits.

Chapter 4 describes specific stormwater management BMPs. In particular, Section 4.9 describes infiltration retrofits. While many DOTs have implemented infiltration BMPs when there are suitable soils, "Siting constraints and maintenance requirements are the main drawbacks for ultra-urban highway retrofits." This section does not, however, address vehicle safety or the potential for vehicle rollovers.

Urban Stormwater Management in the United States, National Research Council, 2008.
http://www.epa.gov/npdes/pubs/nrc_stormwaterreport.pdf
This report reviews the Environmental Protection Agency's permitting program for stormwater discharge under the Clean Water Act and recommends improvements. However, it focuses on stormwater BMPs' impacts on water quality, rather than their impact on vehicle safety.

Chapter 6 references soil amendments as one innovative stormwater management technique. Page 409 describes common reasons for opposition to infiltration techniques, including soil amendments. The objections described are typically related to insufficient effectiveness in clay soils, impact on groundwater quality, the effect of overirrigation of lawns and municipal wastewater treatment system capacity.

Reference Books and Additional Research

Soil Strength and Slope Stability, Second Edition, J. Michael Duncan, Stephen G. Wright and Thomas L. Brandon, John Wiley & Sons, 2014.
http://www.wiley.com/WileyCDA/WileyTitle/productCd-1118651650.html
This book notes that the fundamental requirement for slope stability is that "The shear strength of the soil must be greater than the shear stress required for equilibrium." Increased pore pressure due to water seepage is one cause of decrease in shear strength, and this shear strength can change rapidly in soils with high permeability. Low-permeability clay soils can also have high secondary permeability due to cracks, fissures or lenses of more permeable materials. Relevant chapters include:

- Chapter 5 provides extensive formulas for calculating the shear strength of soils, including equations for granular materials like sand or gravel and for silts or clays.
- Chapter 7 discusses several methods for analyzing slope stability, including bearing capacity equations, slope stability charts, computer programs, and spreadsheet software. An appendix offers stability charts for a variety of soil types and pore water pressure conditions.

Following is an excerpt from the book's description:

> *Soil Strength and Slope Stability, Second Edition* presents the latest thinking and techniques in the assessment of natural and man-made slopes, and the factors that cause them to survive or crumble. Using clear, concise language and practical examples, the book explains the practical aspects of geotechnical engineering as applied to slopes and embankments. The new second edition includes a thorough discussion on the use of analysis software, providing the background to understand what the software is doing, along with several methods of manual analysis that allow readers to verify software results. The book also includes a new case study about Hurricane Katrina failures at 17th Street and London Avenue Canal, plus additional case studies that frame the principles and techniques described.
>
> Slope stability is a critical element of geotechnical engineering, involved in virtually every civil engineering project, especially highway development. *Soil Strength and Slope Stability* fills the gap in industry literature by providing practical information on the subject without including extraneous theory that may distract from the application. … Topics include:
>
> - Mechanics of soil and limit equilibrium procedures.
> - Analyzing slope stability, rapid drawdown, and partial consolidation.
> - Safety, reliability, and stability analyses.
> - Reinforced slopes, stabilization, and repair.
>
> The book also describes examples and causes of slope failure and stability conditions for analysis, and includes an appendix of slope stability charts.

Slope Stability Analysis and Stabilization: New Methods and Insight, Second edition, Y.M. Cheng and C.K. Lau, CRC Press, 2014.
https://www.crcpress.com/product/isbn/9781466582835
This is a reference book for analyzing slope stability and the stabilization of slopes. It includes design charts, reference tables and recommendations for a variety of soils and soil conditions.

From the book description: “Using a unified approach to address a medley of engineering and construction problems, *Slope Stability Analysis and Stabilization: New Methods and Insight, Second Edition* provides helpful practical advice and design resources for the practicing engineer. This text examines a range of current methods for the analysis and design of slopes, and details the limitations of both limit equilibrium and the finite element method in the assessment of the stability of a slope. It also introduces a variety of alternative approaches for overcoming numerical non-convergence and the location of critical failure surfaces in two-dimensional and three-dimensional cases.”

“Failure of Soil Under Water Infiltration Condition,” Meen-Wah Gui, Yong-Ming Wu, *Engineering Geology*, October 2014.
Citation at http://www.sciencedirect.com/science/article/pii/S0013795214001628
This research investigated the impact of water infiltration on shear stress and eventual failure of unsaturated soil. Two types of tests evaluated this impact: the constant-suction shearing test and the shearing-infiltration test.

The soil tested was a red lateritic (iron- and aluminum-rich) soil obtained from the Linkou terrace in northwest Taiwan.

Shearing-infiltration tests indicated that infiltration reduced the matric suction (negative pore pressures) of the soil due to the generation of excess pore-water pressure. While matric suction typically contributes to a soil’s shear strength, in this case the reduced matric suction was not accompanied by reduced shear strength. Instead, unsaturated soil failed under a constant shear stress applied before infiltration. Water-infiltration-induced failure was found to be caused by excessive soil deformation and softening. The authors suggest further study, as the results run counter to traditional beliefs that water infiltration is the cause of reduced soil shear strength and soil stability.

Additionally, the paper suggests that “Slope instability problems, which have always been treated as a shear strength problem, appeared to be a volume change (strain deformation) problem instead,” and that minimizing unnecessary deformation of the slope rather than attempting to increase shear strength may be a better method of preventing rainfall-induced landslides.

Impact of Soft Shoulders on Vehicle Rollovers

The published research we identified in this area primarily provides guidance in modeling how vehicle wheels interact with soils and in modeling stability of vehicles as they travel on soft (or other) soils.

Recommended Resources

The following three resources, although older, were recommended by Frank Julian of the FHWA Resource Center (see our interview on page 6 of this Preliminary Investigation). They include a foundational 1986 FHWA report on the topic and two conference papers.

Rollover Potential of Vehicles on Embankments, Sideslopes and Other Roadside Features, FHWA, 1986.
http://www.mchenrysoftware.com/Rollover Potential of Vehicles.pdf
This project studied how vehicles interact with various roadside features to determine their potential for causing vehicles to roll over. The research found that different classes of vehicles

show differences in rollover tendencies, but that the existing accident database did not have the necessary information to define roadside feature geometry that caused rollovers. The report concluded that the side-slope of fill embankments should be no steeper than 3:1 and preferably flatter for fill heights greater than 3 feet. It also recommended rounding slope breaks (see page 159 of the report).

According to then-current data, 85.7 percent of vehicles in rollover accidents were sliding at the start of the rollover (see page 16 of the report). Nearly half of vehicles were skidding horizontally to the direction of travel, and 36 percent were moving at a slip angle of 60 degrees. Nearly half of rollovers involved impact with a roadside feature. Among fatal vehicle rollover accidents, embankments and culverts or ditches were each the first object struck in about 18 percent of incidents; however "All Other Objects" were the first object struck in 57.6 percent of incidents.

The report cited a field study of crash sites in New Mexico that found that relatively small objects—including edge dropoffs and soft soils—were the most probable cause of vehicle rollovers (page 28). (The cited study is *A Survey of Single Vehicle Fatal Rollover Crash Sites in New Mexico,* J.W. Hall and P. Zador, Insurance Institute for Highway Safety, unnumbered report, November 1980. See the abstract for a *Transportation Research Record* paper summarizing the study at http://trid.trb.org/view/1981/C/174262.)

Chapter 3 described adjustments to the Highway-Vehicle-Object Simulation Model to improve its applicability to vehicle rollovers. Among other adjustments, it modified the model to address tire sinkage into soft soil. The model requires the following sequence of calculations:

- Extent of tire sinkage.
- Sideslip angle of tire.
- Projected area of tire/soil interface.
- Motion-resistance force for a tracking wheel.
- Addition of plowing force to the circumferential and side forces of the tire.

"Characteristics of Soil-Tripped Rollovers," N. Cooperrider, S. Hammoud and J. Colwell, SAE Technical Paper 980022, 1998.
Citation at http://papers.sae.org/980022/

Abstract:

Techniques for soil-tripped and curb-tripped rollover testing have been developed and reported in earlier papers. The tests reported in these earlier publications were conducted with a variety of vehicles launched at speeds close to 30 mph.

Several additional soil-tripped rollover tests were conducted using a single model of mid-sized sedan launched at speeds ranging from 13 mph to 42 mph. This test series provided information about the minimum trip speed and the influence of trip speed on the characteristics of vehicle rollover.

The results of this test series as well as the previously reported tests have been studied to obtain insights about minimum trip speeds, furrow characteristics, angular velocities, rollover distances, trip and post-trip decelerations and the influence of speed on rollover mechanics.

"An Examination of Furrow Tripping and Vehicle Rollovers," *Proceedings of the Canadian Multidisciplinary Road Safety Conference IV,* 1985.
Citation at https://www.worldcat.org/title/an-examination-of-furrow-tripping-and-vehicle-rollovers/oclc/173447551
No abstract is available.

Recent Research and Guidance

The following additional resources focus on modeling the dynamics of vehicle tires and soft shoulders.

"Rollover Simulations for Vehicles Using Deformable Road Surfaces," Tim Palmer, Brian Honken, Clifford Chou, *12th International LS-DYNA Users Conference,* 2012.
http://www.dynalook.com/international-conf-2012/automotive01-a.pdf
This project highlighted the capabilities of the LS-DYNA modeling software package to simulate the impact of deformable road surfaces on vehicle rollovers.

The paper cites National Highway Transportation Safety Administration data showing that the majority of vehicle rollovers are caused by soil tripping—where a vehicle interacts with the deformable and higher-friction surface of the soil before rolling.

LS-DYNA has 23 different material models, one of which (MAT 5 SOIL_AND_FOAM) allows the software to simulate soil behaviors. The paper describes the test procedures necessary to obtain the material properties necessary for a simulation. These properties include density, shear modulus, bulk modulus for unloading, pressure cutoff for tensile fracture, yield function, and pressure-volumetric curve. Test procedures to collect this data include tri-axial compression tests and constrained compression tests.

"A Simulation Framework for Assessing the Safety Effects of Soft and Hard Shoulders as Examples of Forgiving Roadside Treatments," Philippe Nitsche, Rainer Stütz, Peter Saleh and Peter Maurer, *Procedia Social and Behavioral Sciences*, 2012.
http://www.sciencedirect.com/science/article/pii/S1877042812028157
This paper presents a framework for "forgiving roadside design" to mitigate the consequences of run-off-road accidents, including rollovers. The paper evaluated a three-dimensional model of a high-accident site in Austria, along with data from the Austrian road accident database. For that site, researchers modeled appropriate safety treatments before simulating run-off-road accidents. One of these modeled treatments was a soft shoulder, described as a gravel stripe with higher friction than grass but less friction than the road surface. According to the simulation, the soft shoulder minimized the likelihood that vehicles would enter the roadside, but it was more likely to cause vehicles to slide along the road, posing danger to other road users. See Section 3.3 of the paper for details.

Dynamics of Wheel-Soil Systems: A Soil Stress and Deformation-Based Approach, Jaroslaw A. Pytka, CRC Press, 2012.
https://www.crcpress.com/product/isbn/9781466515277
This book is a reference guide for soil stress and deformation measurements under vehicle load. Relevant sections include:

- Section 1.2.2 describes current major research problems related to vehicle impact and soil compaction (see pages 19-23). Relevant topics include methods for modeling soil compaction and stress analysis in soil compaction studies.

- Chapter 2 describes the measurement of soil stress and deformation.
- Chapter 4 describes the stress states of soils under wheeled vehicle loads. The authors conducted research to measure soil stress state under moving vehicles.

  Tests were conducted on three soil surfaces—sand (bulk density 1.72 grams/cubic centimeter), loess (1.64 grams/cubic centimeter), and turf (described as "typical forest surface)—and on snow cover. In dry tests, the stresses were highest in loess and lowest in turf. However, when the soils were moist, stresses increased significantly in sand, decreased significantly in loess, and decreased somewhat in turf. The reason is likely that loess and loamy soils have increased plasticity when water is added, reducing stresses. Sand, on the other hand, experiences increased viscosity and interaction among grains when water is added.
- Chapter 8 describes modeling of a wheel-soil system, based on soil stress and analysis of the deformation state.

Modeling, Analysis, and Measurement of Passenger Vehicle Stability, Massachusetts Institute of Technology masters' thesis, Steven C. Peters, 2006.
http://dspace.mit.edu/handle/1721.1/38282
From the Abstract: "This thesis investigates the stability limits imposed by off-road terrain conditions and techniques for measuring vehicle stability in the presence of off-road terrain factors. An analysis of the effects of terrain slope, roughness, and deformability on vehicle rollover stability in road departure scenarios is presented. A simple model that captures the first-order effects of each of these terrain features is presented and used to compare the relative danger posed by each factor. A new stability measure is developed that is valid in off-road conditions, which include sloped, rough, and deformable terrain. The measure is based on the distribution of wheel-terrain contact forces and is measurable with practical sensors. The measure is compared to existing stability measures and is able to detect wheel lift-off with greater accuracy in off-road conditions. The measure is experimentally validated with wheel lift-off detection as well. An uncertainty analysis of the measure is presented that assesses the relative importance of each sensor and parameter in the measure."

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