Soil Cut Slopes

Soil cuts are excavated along natural hillsides, through ridges and mesas, and into existing embankment. Any slope excavated into existing fill, alluvium, colluvium, residual soils, or weak sedimentary formation is considered a soil cut slope. Slopes excavated into highly fractured and weathered rock may also be considered soil cut slopes.

Soil cut slopes may be preferred over other roadway prism widening alternatives such as retaining walls because they require less cost and time to build, generate material that may be needed elsewhere on the project, allow for future widening, or offer a pleasing aesthetic. Temporary soil cut slopes are often necessary to facilitate construction of embankments, bridges, retaining walls, and detours.

The stability of soil cut slopes can be assured through appropriate geotechnical investigation, analysis, and design thereby preventing landslides, slip outs, slumps, severe erosion, safety issues, operational interruptions, and long-term maintenance costs. These guidelines present the Caltrans practice for investigating, analyzing, and designing soil cut slopes.

Investigations

The evaluation of soil slopes, and the design of stable slopes, depends on accurate characterization of the geologic conditions that will influence slope behavior. The investigation should identify the parameters necessary to perform stability analyses and slope design. The exploration program should also be developed with consideration of the potential use of excavated material elsewhere on the project.

Desktop Review

Prior to gathering geotechnical data by other means, site information should be gathered by performing a desktop review. Proposed soil cut slopes are often located along existing highways, therefore previously developed information may exist. Common sources of valuable site information are in Table 1.

Table 1. Source of Historical Data (after FHWA)

Information	Source
Aerial photos	California Geological Survey (CGS), U.S. Geologic Survey (USGS), local libraries, local and national aerial survey companies
Topographic maps	CGS, U.S. Geologic USGS
As-built plans and Log of Test Borings for existing roadways and structures	Caltrans Document Retrieval System, OGD daily files and project files
Structure maintenance and inspection reports	Caltrans Bridge Inspection Records & Information System (BIRIS)
Prior geotechnical investigations and reports; storm damage or landslide investigations and reports	Digital Archive of Geotechnical Data (GeoDOG), OGD daily files and project files, USGS landslide website.
Climate and precipitation records; drainage	Cal. Dept. of Water Resources (CDWR), Cal. Climate Data Archive
Geologic reports and maps	USGS, CGS
Soil survey	USDA, SoilWeb (UC Davis website)
Flood insurance maps	FEMA, USGS, CGS, CDWR
Seismic Hazard Map and fault database	USGS, Caltrans ARS Online
Previous and present land use and development	Land owners, city/county land development offices

Review of aerial photos and topographic maps can provide large scale information about geological conditions at a site. In the field, large features are often obscured by vegetation and therefore difficult to identify by surface mapping alone. Aerial photos shot from various vantage points may reveal signs of unstable slopes including tension cracks, scarps, hummocky terrain, fresh ground disturbance, or an abrupt change in stream flow direction.

Site Reconnaissance and Mapping

Reconnaissance of the host proposed cut slope terrain provides important information for the development of an exploration program. Complex sites may require detailed geologic mapping. During site reconnaissance, the GP will observe the behavior and performance of existing cut slopes and natural slopes. The GP should measure and record the geometry of the existing slopes and record any sign or cause of slope instability. Landforms identified during the office review should be checked during site reconnaissance to determine the underlying geology.

Changes in ground surface slope angle may reflect differences in the physical characteristics of soil and rock materials or the presence of groundwater or seasonal seeps. The occurrence of plant species that draw water from permanent or seasonal water tables indicates the presence of groundwater. Patterns in the vegetation may reveal patterns in soil type or seepage.

Subsurface Exploration

The subsurface exploration programs for soil cut slopes most commonly use geotechnical borings. Occasionally, Cone Penetration Tests (CPT) are used when the soils being investigated are not too dense, hard, or rocky, and level access exists. Seismic Refraction is sometimes used to estimate soil density and identify subsurface contacts. Subsurface exploration is conducted to: reveal soil types and geologic structure that cannot be otherwise determined; collect soil samples for laboratory testing; and gather groundwater information.

Consider the following when developing and performing an exploration program:

- Typically, one boring should be performed every 200 to 500 feet along each proposed cut slope greater than 20 feet high. The actual number of borings may vary based on the uniformity or variability of site geology and the quality of data that is acquired through other means
- At locations where more detailed slope stability analysis is necessary, additional borings perpendicular to the cut should be considered.
- Borings should extend a minimum of 15 feet below the bottom of cut elevation to allow for design changes that may deepen the cut and to provide adequate information on all soils that may influence slope stability analysis
- Boring depth should be increased at locations where base stability is a concern due to groundwater and/or soft or weak soil zones
- Borings should extend through any weak zones into competent materials.
- Auger borings will facilitate the collection of bulk samples at depth
- Field logging should include in situ testing such as Standard Penetration Test (SPT) for granular soils, and Pocket Penetrometer Test (PPT) and Vane Shear Test (VST) on cohesive soils. Undisturbed samples for lab testing may be collected in cohesive soils
- Samples should be gathered from the soil zones most likely to control slope behavior
- Hand augers, test pits, trenches, or similar means of exploration may be used in lieu of borings for investigating subsurface conditions for sliver cuts or shallow cuts, and where site access for large drilling equipment is restricted

Because site access is often very difficult at proposed soil cut slopes subsurface explorations are not generally conducted if a proposed slope will be cut into an existing slope where all the following conditions exist:

- The proposed slope is less than 20 feet high
- The proposed slope has the same or flatter angle of inclination as the existing slope
- The slope height does not increase significantly because of the cut
- There is no evidence of instability
- There is no evidence the material type is likely to be different at the new slope face
- The existing slopes provide good exposures of the underlying material
- There is no potential for seepage to be encountered in the cut

Groundwater Measurement

The presence of permanent or transient groundwater can greatly impact slope behavior. Borings will reveal the occurrence of groundwater at the time of the drilling. However, it may be necessary to install piezometers (open standpipe, vibrating wire, or pneumatic for groundwater pressure) to accurately determine the groundwater regime and to record any fluctuations. Ideally, the monitoring of piezometers should continue through at least one wet season. Continuous monitoring can be achieved by using electrical piezometers such as vibrating wire type in conjunction with digital data loggers.

The values of soil permeability and infiltration rate are generally determined based on correlations with grain size and/or knowledge of the site soil based on previous experience. However, borehole permeability tests, such as slug or pump tests may be conducted to facilitate the design of subsurface drainage features such as horizontal drains.

Laboratory Testing

Laboratory testing of representative soil samples is performed to determine the soil parameters that will influence slope behavior and the suitability of excavated material for reuse as compacted fill. The laboratory tests may include natural moisture content, grain size analysis, Atterberg Limits, corrosion, unit weight, shear strength, and R-value tests.

The choice of which type of strength test to perform should be based on expected stress conditions in the soil in relation to the anticipated failure mode and failure surface. Shear strength parameters of cohesive soils should be obtained from undisturbed soil samples using consolidated undrained (CU) tests with pore pressure measurement if portions of the proposed slope are saturated or might become saturated in the future. Effective strength parameters from these tests should be used to analyze long term stability of cut slopes or to evaluate long term effects on soil rebound upon unloading. Unconsolidated undrained (UU) tests can be used to obtain undrained shear strength parameters for short term stability analysis including seismic stability, or when it is determined that total stress/strength parameters are adequate. Repeated direct shear tests can be performed to determine residual shear strength parameters for soils located in existing landslide areas. Residual strength parameter should also be obtained for cuts in heavily overconsolidated clay: the removal of overlying soil can release locked-in stress and allow the clay to deform, causing its strength to drop to the residual value.

Table 2 summarizes some of the engineering evaluations commonly performed for soil cut slopes, required information for the evaluations, and the field and laboratory tests conducted to obtain information.

Table 2. Information Needs and Testing Considerations for Soil Cut Slopes (After FHWA)

Engineering Evaluations	Required Information	Field Testing	Laboratory Testing
• Slope stability • Bottom heave • Lateral pressure • Dewatering • Pore pressure • Soil softening / progressive failure • Fault rupture • Liquefaction	• Subsurface profile • Groundwater • Shrink/swell properties • Unit weights • Moisture content • Permeability • Consolidation parameters • Shear strengths • Geologic mapping • Seismicity / faults	• SPT • CPT • PPT/VST • Piezometer • Geophysical testing • Test pit • Trench	• Mechanical analysis • Atterberg Limits • Moisture content • Consolidation test • Hydraulic conductivity • Strength test (unconfined compression, triaxial, direct shear, torsional shear)

It is usually very difficult to determine accurate soil strength parameters of all soils and structural weaknesses within a slope. Laboratory tests conducted on samples containing a structural weakness such as a fissured clay zone are sometimes performed; but field tests such as a torvane are likely to yield more useful results. Soil strength parameters are often estimated through slope stability modeling of known failure scenarios for a given site, a process commonly referred to as “back calculation.”

Factors That Influence Slope Behavior

Common adverse behaviors of soil cut slopes include landslides, surficial sloughing and creep, and severe erosion. Table 3 summarizes important aspects of the stability of cut slopes.

Table 3. Important Aspects of Stability of Soil Cut Slopes
(After Duncan et al. 1987)

	Cohesionless soil slope	Cohesive soil slope
Factors that control stability	Internal friction Unit weight of soil Slope angle Pore pressures External water	Strength of soil Unit weight of soil Slope angle Pore pressures External and internal water
Failure mechanism	Surface raveling	Deep sliding, possibly extending below toe of slope Sloughing of very soft clay
Critical stages for stability	Long-term or earthquake	End-of-construction, long-term, or rapid drawdown
Analysis procedure	Effective stress or dynamic	Total stress, effective stress, or combination

Slope behavior is a function of numerous factors:

- Geometry (height, angle of inclination, benching)
- Material properties (friction angle, cohesion, weight, permeability, pore pressure, expansion/contraction)
- Groundwater conditions (phreatic water, perched water, seepage, pore pressure)
- Soil structure (layering, layer orientation, weak surfaces, fissures)
- External forces (seismic ground motion, surface loads)
- Surface conditions (vegetation, concentrated runoff, adjacent water bodies, erosion control, slope armoring, expansion/contraction)

Most of these factors and the related slope behaviors are familiar to the GP. Common adverse behaviors and their influencing factors are discussed below:

<u>Adverse Behaviors Related to Material Properties</u>

Adverse behaviors of cohesionless slopes typically occur at shallow depths. Sands are very susceptible to surficial sloughing, shallow sliding, erosion, and piping. Adverse behavior of cohesive slopes may be shallow or deep. Expansive clay slopes may experience surface degradation and creep due to seasonal wetting and drying cycles. Clay slopes are prone to relatively deep circular sliding, the steeper the slope the deeper the slide. Both natural slopes and fill embankments often consist of heterogeneous material which are difficult to represent by a simple set of soil parameters. Most soil slopes contain some amount of both granular and cohesive material and therefore can display mixed behaviors.

Adverse Behaviors Related to Surface Water and Groundwater

Most adverse slope behavior is greatly influenced by water. Concentrated storm runoff can result in severe slope erosion leading to a loss of structural support and catastrophic failure. Perched groundwater and infiltration from irrigation, rainfall, or snowmelt frequently causes surface sloughing and landslides. Water within a slope has the following effects on slope stability:

- Reduced shear strength of unsaturated soils by loss of apparent cohesion and reduction of friction between particles
- Increased seepage force acting downslope
- Reduced resisting force as saturation and increased pore water pressure results in reduced effective stress and shear strength
- Increased driving forces due to increased weight of the soil mass
- Degraded slope surface due to expansion/contraction and freeze/thaw

These negative consequences of water within a soil cut slope are generally more pronounced in slopes containing appreciable amounts of clay or silt.

The occurrence of groundwater will likely vary with the seasons and adjacent land use. Rainfall, irrigation, and surface water bodies influence the existence and location of perched and phreatic water tables, as does material type and soil structure.

Submerged or partially submerged soil cut slopes can present unique design challenges; however, such slopes are rare on Caltrans highway projects. The GP should consult appropriate design resources (e.g., Oregon Department of Transportation Geotechnical Design Manual Chapter 7) if the project involves submerged or partially submerged soil cut slopes.

Adverse Behaviors Related to Soil Structure and Residual Soils

Residual soils are derived from the weathering of rock; therefore, the behavior of cuts in residual soils tend to be influenced by soil structure. Slides are more likely to occur in residual soils along structural weaknesses inherited from the parent rocks such as clay layers or clay filled seams dipping out of slope. Fracture systems in the adjacent parent rock often convey groundwater to the slope through down gradient migration. High groundwater pressures commonly exist in intermediate geomaterial (IGM), partially weathered rock, and fresh rock. The groundwater may be confined by an impervious residual soil cover. If the soil cover is removed or reduced in thickness during a cut, a stability problem may develop.

For residual soils derived from claystone and shale, the most typical failure mode is a shallow slide associated with abnormally high groundwater in the underlying fissured shale. For residual soils of metamorphic and igneous rock, most slope failures occur in the upper layer and are usually related to high pore pressure due to rainfall. For residual soils originating from limestone and other carbonate rock, stability problems are usually related to sink holes, intense fracturing, and frequent interbedding of soft clay.

Adverse Behaviors Related to External Forces

Seismic events can induce significant inertia forces in a soil mass thereby triggering slope movement and landslides. In unusual circumstances, such as depressed highway alignments cut down into alluvial planes, soil cut slopes may be subject to liquefaction of the underlying soils. Soil cut slopes may be experience loading through the placement of a structure or embankment thereby increasing driving force and creating an imbalance with the resisting force leading to slope failure. All factors that will influence slope stability must be accounted for in soil cut slope design.

Soil Cut Slope Design

Soil cut slope design should follow Topic 304 of the Caltrans Highway Design Manual (HDM) and these guidelines. Soil cut slopes are often designed as compound slopes that include retaining walls at the top, bottom, or mid height.

Most permanent soil cut slopes inclined 2:1 are considered stable. However, the presence of unfavorable soil types, groundwater conditions, or soil structure may necessitate designs that may include flatter slopes, retaining structures, or dewatering. Steep soil cut slopes are often proposed where there is limited distance between grade separated highway features or limited distance between highway features and the right-of-way. Soil cut slopes may be inclined more steeply than 2:1 if the slope is relatively short (typically less than 15 feet in height) and displays strength derived from favorable remnant rock fabric, cementing, or cohesion. Slopes inclined steeper than 2:1 are common in weak sedimentary rock and residual soils derived from weathered rock. In these materials, the design of steep slopes will reduce the amount of direct rainfall and resulting erosion.

Cuts in overconsolidated cohesive soils consisting of stiff to very hard silt and clay of varying plasticity often contain pre-existing fissures, cracks, and other planes of weakness. These soils may stand at nearly vertical inclinations for a limited period. However, the relaxation of horizontal stresses in such soils can cause creep and lead to rapid failure. Slopes in such soils should be designed based on their residual friction angle and often must be inclined in the range of 1V:4H to 1V:6H.

Cut Slope Drainage Systems

The stability of soil cut slopes is often dependent on the appropriate design of drainage systems. Concrete lined drainage ditches above the top hinge and along slope benches help prevent the erosive effects of concentrated flow. Surface drainage may also control seepage from a soil cut slope. Surface drainage systems are typically designed by District Hydraulics with input from the GP.

Subsurface drainage systems help control the adverse effects of groundwater. Horizontal drains, relief wells, cut-off trenches, or underdrains may be designed to diminish groundwater within or beneath a slope. Subsurface drainage systems are designed by the GP.

Horizontal drains consist of slightly inclined borings drilled into a slope and fitted with perforated pipe; the pipe may be wrapped in filter fabric. Horizontal drains intercept and drain granular water-bearing soils or fractures. Drain installation is difficult in soils containing boulders, cobbles, or cavities. Horizontal drains require periodic refurbishing or replacement as they tend to become clogged over time.

Relief wells are vertical dewatering wells equipped with pumps and plumbing. Relief wells require permits, electrical power, control systems, and periodic refurbishment, and may require that permanent fees be paid to the water owner; therefore, relief wells are often considered a last resort.

Cut-off trenches are lateral ditches filled with permeable material and collector pipes located near the top of the cut slope to intercept and convey shallow ground water around the slope. Underdrains are similar ditches located along the base of a slope intended to reduce pore pressure and control seepage.

Slope Surface Treatment

Vegetation should be established on slopes to prevent long-term erosion and create a pleasing aesthetic. The use of straw wattles, jute fabric, or other soil surface stabilization methods may be required to establish vegetation on slopes. Recommendations for erosion mats and plant establishment on soil cut slopes are typically provided by the District Office of Landscape Architecture; the commonly recommended systems are available in the Caltrans Erosion Control Toolbox. The GP will provide recommendations when more robust erosion control measures such as Cellular Confinement Systems, anchored mesh, or slope armoring are deemed to be necessary to stabilize the slope surface.

Temporary Soil Cut Slopes

Temporary soil cut slopes should undergo appropriate design and review. During project planning and design, the GP should evaluate potential temporary cuts that may influence construction staging, right-of-way requirements, the need for shoring, or the need for alternative designs. During project construction, it is often necessary for the GP to review temporary cuts proposed by the Contractor.

Temporary cuts inclined 1H:1V are common on Caltrans construction projects. These cuts in both natural slopes and embankment fill are typically stable in the short-term;

however, cuts greater than 25 feet in height are likely to experience problems if they exist for long periods or are exposed to extreme weather events. Steeper temporary soil cuts may be utilized by contractors when site-specific soil testing and analyses reveal the slope meets minimum stability criteria for temporary slopes. The design of all temporary cut slopes must follow Cal/OSHA requirements and the Caltrans Trenching and Shoring Manual.

Stability Improvement Techniques

Table 4 summarizes numerous methods that can increase the stability of a soil cut slope.

Table 4. Categories of stabilization techniques for soil cut slopes

Category of Stabilization	Stabilization Techniques
Load distribution	• Flattening slope • Slope buttressing
Surface/subsurface drainage	• Swale/ditch • Downdrain • Underdrain • Interceptor (cut-off) drain • Horizontal drain • Relief well
Slope protection	• Vegetation • Erosion control mats / blankets • Soil confinement systems • Anchored wire mesh • Rock / concrete riprap • Slope paving
Earth retaining systems	• Buttresses / berms • Gravity walls • Semi-gravity walls • Non-gravity cantilever walls • Soil nail / ground anchor walls • Prefabricated modular walls

Slope Stability Analysis

It is not necessary to perform stability analyses on all proposed soil cut slopes. Past performance of nearly identical slopes is the best predictor of future performance of new slopes. Stability analyses should be performed on all proposed soil cut slopes where stability is questionable. Cut slope stability may be questionable if one or more of the following conditions exist:

- Cuts greater than 20 feet high
- Cuts steeper than 2H:1V
- Cuts with irregular geometry
- Cuts within adverse or weak structure
- Cuts where high groundwater or seepage forces are present
- Cuts in weak soils
- Cuts above weak soil and high groundwater
- Cuts in old landslides or in formations known to be susceptible to sliding.
- Cuts in transition zones (cut/fill, soil/rock)
- Cuts above or below structures

Stability Modeling

Simple stability charts (NAVFAC, Abramson, et al. 1996) can be used for slope stability analyses to determine if a proposed cut slope will be stable. If the stability of a proposed slope is questionable, or if complex conditions of the proposed slope exceed the simplified conditions represented by the charts, more rigorous computer programs such as SLOPE/W, SLIDE, XSTABLE, ReSSA, are used by the GP. These programs use limit-equilibrium methods that satisfy forces and moments and allow the selection of various analyses methodologies including Bishop, Janbu, Spenser, Sarma, Morgenstern-Price, and general limit-equilibrium.

Limit-equilibrium analysis methods do not truly simulate the potential failure mechanism of a slope because all limit-equilibrium methods assume failure at a constant factor of safety along the entire slip surface. This simplified analysis neglects several factors including the stress-deformation behavior within the slope itself. Nevertheless, limit equilibrium analysis methods are widely used by the GP as a tool for slope design. More advanced computational methods such as finite element (e.g., PLAXIS) and finite difference methods (e.g., FLAC) are increasingly used to predict failure mechanisms and slope movements in two-dimensional and three-dimensional models. However, because of the heterogeneity of soil and the difficulty of precisely identifying subsurface contacts and soil strength parameters, more advance computational methods do not necessarily provide more accurate predictions of slope stability.

A stability evaluation is conducted for each unique, critical proposed slope configuration through the following process:

1) Develop representative cross sections for analyses. Critical slope configurations are commonly the tallest cut with the weakest ground conditions. The developed cross sections should extend well beyond the top of the proposed cut. The following information must be established for the cross sections:
    - Existing and proposed slope surfaces with vertical plane geometry coordinates.
    - Distribution of surface and subsurface soil units with vertical plane geometry coordinates
    - Estimated or established unit weight and strength parameters for each soil unit
    - Location of the water table and flow characteristics with vertical plane geometry coordinates
    - Location and strength of any structural weakness
    - Location and magnitude of external loading
    - Location and parameters of proposed stability enhancement features such as buttresses or retaining walls
2) For simple slopes use NAVFAC charts to evaluate stability. For more complex slopes use a more rigorous computer program. Develop computer models by creating electronic files representing each critical cross section created in Step 1.
3) Select the evaluation methodology and refine search criteria to debug the models.
4) Calibrate the models: Use any actual slope failure scenarios observed at the site to "back calculate" unknown soil strength. Refine the models to eliminate unreasonable results such as the weakest failure surface extending through the strongest material.
5) Run the program for each slope model to yield factors of safety for the proposed slopes.

Consider all short and long-term conditions likely to influence stability. Consider soil drainage characteristics and the loading condition. Stability analyses are generally categorized as:

- Drained – for long-term, or very slow loading or rapid draining conditions
- Undrained – for short-term or rapid loading conditions
- Intermediate – for staged construction or rapid drawdown conditions

If pore water pressures can be measured or calculated, effective stress may be used for slope stability analysis, otherwise total stress should be used. Table 5 summarizes the analysis methods and corresponding shear strength parameters used for different loading conditions.

Table 5: Shear strength, drainage condition, pore pressure, and unit weight for slope stability analysis (after Duncan 1992)

	Undrained	Intermediate	Drained
Analysis procedure and shear strength for free draining soils	Effective stress analysis, using c and Φ’	Effective stress analysis, using c and Φ’	Effective stress analysis, using c and Φ’
Analysis procedure and shear strength for impermeable soils	Total stress analysis, using c and Φ from in situ UU or CU tests	Total stress analysis, using c_u from CU tests and estimate of consolidation pressure	Effective stress analysis, using c and Φ’
Internal pore pressures	No internal pore pressure for total stress analysis, set u=0	No internal pore pressure for total stress analysis, set u=0	Φ from seepage analysis
	Φ from seepage analysis for effective stress analysis	Φ from seepage analysis for effective stress analysis	
External water pressures	Include	Include	Include
Unit weights	Total	Total	Total

For cut slopes, the consolidation process can usually be assumed to be completed prior to construction. For such slopes, the short-term loading condition such as end of construction, rapid drawdown, or seismic loading, is best modeled using the intermediate analysis, whereas the long-term loading condition corresponds to the drained analysis. Occasionally, the undrained analysis may be warranted for cuts in soft cohesive soils where high excess pore water pressures are likely to develop due to construction activities.

The groundwater table within a planned cut section will fall due to the cut. As the water table falls, an increase in safety factor will likely occur. However, for the intermediate analysis, the water table should be modeled at its maximum anticipated elevation. Long-term (drained) conditions are modeled by assuming the groundwater table has fallen and excess pore water pressures have dissipated. The long-term condition is frequently the most critical concern for cuts in soils. Highly plastic clays may experience severe swelling and softening, and commonly exhibit significant potential for sloughing-types of slope failures. Long-term conditions in these soils may be more accurately modeled by neglecting cohesion altogether.

It is important to identify and accurately model seepage within proposed cut slopes so that adequate slope and drainage are employed. For slope stability analysis requiring effective stress/strength parameters, pore pressures must be known or estimated. This can be done using one of several methods.

- Piezometers (phreatic or confined piezometric surface)
- Manually prepared flow net
- Numerical solution such as finite element or finite difference analysis (provided adequate boundary information is available)

The pore pressure ratio (Ru) can also be used. However, this method is generally limited to use with stability charts or for determining the factor of safety for a single failure surface.

Modeling of Seismically Induced Phenomenon

Model seismically induced inertial forces by conducting a pseudo-static slope stability analysis where the seismically induced inertia force is represented by a seismic coefficient equal to 1/3 of the estimated peak horizontal ground acceleration. Pseudo-static stability analysis can be performed using either the total stress or effective stress analysis. The effect of vertical acceleration on slope stability is ignored.

Model the effect of seismically induced liquefaction of soils underlying the proposed cut slope by assigning post-liquefaction residual soil strengths to the potentially liquefiable zones. The seismic coefficient should be set to zero in this case. The total stress analysis approach is more convenient for post-liquefaction stability analysis as it avoids the estimation of excess pore water pressures induced by seismic loading.

Factor of Safety

The static (or service state) factor of safety of soil cut slopes should generally conform to AASHTO LRFD Section 11.6.2.3 as stated below:

The evaluation of overall stability of earth slopes with or without a foundation unit should be investigated at the Service I Load Combination and an appropriate resistance factor. In lieu of better information, the resistance factor, Φ, may be taken as:

- *Where the geotechnical parameters are well defined, and the slope does not support or contain a structural element Φ = 0.75* (equivalent to a safety factor of 1.3).
- *Where the geotechnical parameters are based on limited information, or the slope contains or supports a structural element Φ = 0.65* (equivalent to a safety factor of 1.5).

For pseudo-static (seismic) analysis of slopes unrelated to structures use Φ = 0.95 (equivalent to a safety factor of 1.05). For pseudo-static analysis of slopes that involve or are adjacent to walls and structure foundations use Φ = 0.9 (equivalent to a safety factor of 1.1).

For temporary soil cut slopes use Φ = 0.83 (equivalent to a safety factor of 1.2)

These factors of safety should be considered minimum values. The GP should decide whether a higher factor of safety is warranted based on the consequence of failure, experience with similar soils, and uncertainties in the analyses.

Use of Excavated Materials

Soils excavated from roadway cuts may be suitable for placement as structure backfill or embankment. The GP should test soil samples gathered from the sites of planned slope excavations to determine if the generated material will meet the gradation requirements detailed in the Caltrans Standard Specifications.

The GP should provide earthwork factors. Soil excavated from cuts and then compacted for embankment construction typically has a shrinkage factor. Shrinkage values vary based on soil type, in-place density, method of fill construction and compaction effort. Soil waste typically has a swell factor because material is often end-dumped at the waste site. Determine the shrinkage/swell factor for soil that will be reused by proctor tests. Corrections may need to be applied for oversized particles screened out of excavated material. Local experience with similar soils can be used to determine shrinkage/swell factors. Typical shrinkage/swell factors for various soils and rock are in Table 6.

Table 6. Approximate Shrinkage/Swell Factors (from Alaska DOT, 1983)

Material	In Situ wet unit weight (pcf)	Percent Swell	Loose Condition wet unit weight (pcf)	Percent Shrink (-) or Swell (+)	Compacted wet unit weight (pcf)
Sand	114	5	109	-11	129
Sand Gravel	131	5	124	-7	141
Silt	107	35	79	-17	129
Loess	91	35	67	-25	120
Rock/Earth Mixtures					
75% R/25% E	153	25	122	+12	136
50% R/50% E	139	29	108	-5	146
25% R/75% E	125	26	99	-8	136
Granite	168	72	98	-28	131
Limestone	162	63	100	+31	124
Sandstone	151	61	94	+29	117
Shale-Siliceous	165	40	118	+25	132
Siltstone	139	45	96	+9	127

Construction and Performance Monitoring

A construction monitoring program will ensure that the actual soil materials encountered in the field are the same as those considered in the design, the actual material strengths meet the design requirement, and the construction is performed in accordance with contract plans and specifications. If conditions are found that differ significantly from those anticipated, the GP can assist in the development of strategies that will assure slope stability.

Soil cut slope excavation should be carefully controlled during the wet season. Slopes that are susceptible to erosion should be immediately protected as they are exposed. It may be necessary to specify no delay between slope excavation and landscaping or armoring. Temporary drainage and/or erosion control systems are often necessary to protect cut slopes during project construction.

Excavated materials should not be stockpiled near the crest of a cut slope.

Cut slopes may be instrumented and monitored for short-term and/or long-term performance. Slope deformation may be monitored by periodic measurements of survey monuments and slope inclinometers. The function of drainage systems may be monitored by periodic measurements of piezometers. Slope deformation or rising groundwater may signal the need for a renewed evaluation of slope stability.

Reporting

Soil cut slope recommendations must be reported in accordance with the Geotechnical Design Reports module.

References

1. Abramson LW, Lee TS, Sharma S, Boyce GM (2001) Slope Stability and Stabilization Methods, 2nd Ed., John Wiley & Sons, Inc.
2. Alaska DOT, Geotechnical Procedures Manual, 1983.
3. American Association of State Highway and Transportation Officials (2012) AASHTO LRFD Bridge Design Specifications, 6th Edition.
4. Cruden DM, Varnes DJ (1996) Landslides: Investigation and Mitigation, Transportation Research Board. In: Turner AK, Schuster RL (eds) Landslide types and process, National Research Council, National Academy Press, Special Report 247:36–75
5. Duncan JM (1992) State-of-the-art: Static Stability and Deformation Analysis. In: Proc. Of Specialty Conf. Stability and Performance of Slopes and Embankments-II, ASCE, Berkeley, CA, June, Vol. 1, 22-266.
6. Duncan JM, Wright SG, Brandon TL (2014) Soil Strength and Slope Stability, 2nd Ed., John Wiley & Sons, Inc.
7. Naval Facilities Engineering Command (2012) Soil Mechanics, Design Manual 7.01.
8. National Highway Institute (2005) Soil Slope and Embankment Design, Publication No. FHWA-NHI-05-123.
9. WSDOT Geotechnical Design Manual, October 2013
10. Oregon DOT Manual 2018
11. NHI, 2005, Soil Slope and Embankment Design, Publication No. FHWA-NHI-05-123