Landslides

This module presents the Caltrans practice for investigating, characterizing, analyzing, and mitigating landslides as well as the requirements for the preparation of geotechnical reports.

Landslides affect the safety, stability, and operation of California highways. Landslides occur in natural and man-made slopes affecting rural highways and major freeways. The Geoprofessional (GP) provides landslide-related recommendations to clients during all phases of the project delivery process, in support of Maintenance, and during emergency response. Landslide-related work requests come from numerous sources including District Design, Maintenance Engineering, Field Maintenance, and Construction.

Investigation

The purpose of a landslide investigation is to characterize the landslide, identify the factors that influence behavior, and facilitate development of mitigation strategies and related geotechnical recommendations. The scope of the field investigation depends greatly on the size and complexity of the landslide, and the likely cost of appropriate mitigation.

Refer to the *Geotechnical Investigations* module for general instructions on performing the planning-phase site investigation (e.g., literature review, site visit) and the design-phase site investigation (e.g., site visit, selection of investigative methods, locations, and depths).

Chapter 7 *Organization of Investigation Process* of TRB 247 provides a description of the investigation process, considerations, and a checklist for planning a landslide investigation.

Understanding landslide movement and groundwater fluctuation are essential to accurately characterize a landslide. Therefore, a landslide investigation may require months or years to complete as time dependent data is collected by the monitoring of instruments. Consider the following when planning an investigation, instrumentation, and monitoring program:

- Plan the investigation to be proportional to the risks to public and worker safety, the impacts to operation of the highway facility, and the cost and complexity of likely landslide mitigation strategies. In other words, the investigation should not cost more than the mitigation.
- Collect data for a specific purpose that provides essential knowledge needed to provide risk assessment and design recommendations.
- Plan the investigation to fit within the timeframe for project development or assist the client in planning a project development schedule that allows for the appropriate investigation.

Preliminary Investigation

Review all information available in published sources and GeoDOG including reports, geologic maps, and relevant landslide maps from the California Geological Survey (CGS). CGS has a series of Highway Corridor Landslide Hazard Maps and corresponding reports for Caltrans.

Contact the local Maintenance office to obtain information about the site including history and current conditions. Maintenance typically will have records of work performed at the site. The conditions reported by Maintenance or other Caltrans personnel may not be evident at the time of the field investigation.

Field Investigation

For a small landslide, a field review may be adequate to characterize a landslide and allow for the determination of an appropriate mitigation strategy. The investigation of medium to large, complex landslides typically includes surface mapping, subsurface exploration, instrumentation and monitoring.

The use of Unmanned Aircraft Systems (UAS) can be used to provide enhanced visual perspectives, create three-dimensional terrain models, and monitor ongoing distress. The GP should consult with a GS UAS expert on the capabilities of this technology for the landslide investigation. Information on the UAS program and a list of Caltrans Remote Pilots is available on the Caltrans website.

Surface Mapping

Create a plan map of the landslide. Maps may range from rough sketches with approximate dimensions to detailed drawings on high-resolution terrain maps. The landslide plan map should show significant features including landslide boundaries, scarps, slope angles, materials and contacts, discontinuities, surface water, and seeps.

As-built or design plan sheets can be used as a base map for landslide mapping but may not extend far enough above or below the highway to show the entire landslide. Additional topographic data can be requested from Caltrans Surveys. Data collected using a Handheld Global Positioning System (GPS) unit can be used to generate topographic maps and augment existing Design survey data. Standard USGS 1:24000 topographic maps are generally too small scale to provide the required resolution for detailed landslide mapping; however, when no other base maps are available these topographic maps can be enlarged to a more useable scale using a photocopier. Digital terrain models generated from Light Detection and Ranging (LIDAR) data are excellent base maps for landslide mapping.

Exploratory Borings

Exploratory borings are commonly drilled for landslide investigations. Borings can reveal the location and geometry of slide planes, the groundwater surface, and the distribution of materials within the slide. Boring samples can be tested to provide soil strength parameters that greatly influence slide behavior and analyses of the slide. Borings also provide a means to gather downhole data and install instrumentation.

Locate borings within the slide mass to develop data on landslide geometry and movement that cannot be inferred from surface mapping or slide behavior. Large, complex landslides that threaten the highway and adjacent properties may be characterized using up to a dozen borings. Other large landslides that primarily affect the highway and adjacent undeveloped open space are commonly characterized by fewer than six borings. Smaller landslides may be characterized by performing as few as two borings.

Borehole sites on landslides are often difficult to access and may require the grading of access roads or placement of drilling equipment by helicopter. Such investigations are involved, expensive, and require the cooperation of numerous stakeholders. The total number and placement of exploratory borings is often dictated by the drill rig access or working platforms available to perform borings. When possible, locate borings near the middle and the point of greatest depth of a landslide. Also locate borings to identify undisturbed formation and stable ground above and below a landslide. Identifying the location and strength of stable ground can facilitate the design of mitigation features such as buttresses and retaining walls.

While uncommon elsewhere, downhole logging of bucket auger borings in landslides is practiced in Southern California. Bucket auger borings facilitate observation, measurement, and sampling of slip surfaces where the presence of groundwater or caving soil does not prohibit this technique.

In some circumstances, exploratory borings may be of little value in the evaluation and mitigation of landslides that have undergone a rapid mass movement event. Such landslides will generally be mitigated through mass grading. Prior to subsurface exploration, the GP should consult with the Branch Chief and Specialist to develop an economical exploration program that provides value to the evaluation and mitigation effort.

Gather disturbed or undisturbed soil samples for strength testing of materials likely to influence slide behavior or affect the performance of mitigation features.

<u>Laboratory Testing</u>

The laboratory testing program conducted for landslides is similar to testing programs conducted for the investigation of soil or rock cut slopes. The testing program should identify the material strength parameters that control the slide behavior. The strength of material at the head scarp has less influence on slide behavior than the material along the middle and toe of the slide where effective stress has greater influence.

The choice of strength tests to perform should be determined based on the stress conditions in the soil in relation to the 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 slope are saturated during failure. Effective strength parameters from these tests may be used to analyze the potential benefit achieved by dewatering. 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 sufficient.

Landslide behavior is often controlled by residual shear strength parameters of soil along the slide plane. When possible, determine residual shear strength by performing repeated direct shear tests or ring shear tests.

On many landslide projects, the laboratory testing program provides only limited information useful for the evaluation of slide behavior or the mitigation strategies. Slide behavior may be governed by thin discreet discontinuities. Even with significant laboratory data, the governing strength parameters are often estimated by means such as Hoek and Brown Failure Criterion or “back calculation” during model calibration. Strength parameters estimated through analytical methods should be compared to laboratory test results and reconciled when necessary. The results of previous landslide investigations in similar materials may serve as a basis for determining reasonable strength parameters.

Geophysical Techniques

Borehole and surface geophysical techniques can aid in characterizing the subsurface conditions of a landslide. Chapter 10 of TRB 247, *Subsurface Exploration*, discusses the various surfaced-based and borehole logging geophysical methods. Table 10-5 provides a list of borehole logging methods, their applications, and limitations.

Seismic refraction is a useful geophysical technique for investigating landslides. The velocity structure of a landslide mass; the depth to the failure surface; the lateral extent of a landslide; the location of contacts, faults, and discontinuities; and material rippability are variables that may be estimated using seismic refraction. Seismic refraction can help to interpolate conditions between boreholes. *Seismic Refraction Analysis of Landslides* (Narwold and Owen, 2002) discusses the use of seismic refraction in characterizing landslides and provides three case studies.

Instrumentation and Monitoring

Common instrumentation used by Caltrans in landslide investigations include slope inclinometers (SI), piezometers, crack meters, extensometers, and survey monitoring networks. The purpose of monitoring is to determine the depth to failure surface(s), direction of movement, rate of movement, aerial extent of movement, ground water elevations and fluctuations, correlation of rates of movement to rainfall and groundwater. Monitoring can also serve as part of a warning system during construction activity or for landslide management. The frequency of instrument measurement should be a function of the anticipated rate of movement or fluctuation.

SI are commonly placed in boreholes to identify the location of slide planes and the direction and rate of movement. SI equipped with time domain reflectometry (TDR) are often favored in landslides with more pronounced movement because this type of SI remains functional over greater displacements. SI equipped with in-place inclinometers featuring accelerometer sensors and remote data collection systems are practical for remote and difficult access sites.

Piezometers may be used to measure the occurrence and fluctuation of groundwater in or around the landslide. SI casing is sometimes modified to serve as both an SI and a piezometer. This dual instrument method requires some portion of the casing to be sand backfilled (as opposed to grouted) which may lead to bridging and voids around the casing thereby resulting in aberrant data.

Crack meters are typically low-tech monitoring systems that can be easily installed and monitored by the GP. Crack meters are typically lath, PK nails, survey stakes (hubs), or painted points/lines placed within the active slide mass paired with a similarly fixed monument placed on relatively stable ground beyond the active slide mass. Crack meters monitor the magnitude and rate of tension crack expansion by periodic measurement of distance (and sometimes inclination) by the GP. This technique can be used for short-term or long-term monitoring and is often employed during the initial measurements of landslide activity prior to the establishment of more elaborate monitoring systems.

Extensometers are essentially more formal versions of the crack meter system that use anchored wires or rods to measure relative displacement of the landslide mass.

Survey monitoring networks yield a more 3-dimensional representation of slide movement. The two basic types of networks used by Caltrans are:

1. A series of points located along straight lines that cross the slide boundaries. Progressive vertical and horizontal displacement of the points along the line provides data on the limits and the rate of sliding.
2. Reflectors or survey hubs placed at discrete points about the landslide. The initial survey of each point provides the basis to which all future survey readings are compared. The collected data provides information on changes to each hub location in the X, Y, Z directions. The data are used to determine rate and direction of movement of the slide mass, or differential movement within the slide mass.

To assure performance of landslide mitigation measures, some monitoring programs extend years beyond the close of construction. In this circumstance it is necessary to budget long term funding to maintain and read instruments, analyze data, produce reports, and act on the findings. Long term monitoring requires coordination between GS Management, Program Management and District partners.

Landslide Classification

Classify landslides based upon the landslide material and the type of movement. The type of material is reported as rock, debris, or soil. Type of movement is reported as either a fall, topple, slide, spread, or flow. The landslide classification should be reported in geotechnical reports as part of the description of a landslide.

A three-digit number in the following sequence identifying the *state of activity*, the *dominant type of movement* and the *thickness of the landslide* should be reported on the landslide map based on the criteria below:

State of Activity

1 = Active: Landslide is moving (currently active) or movements have been recorded in the past (historically active). Movement may be episodic. Ground surface exhibits fresh cracks, abrupt scarps, displaced or damaged man-made features and disrupted and/or young vegetation.

2 = Dormant: Geomorphic features related to the landslide are relatively fresh but there is no record of historic movement. Cracks are generally absent or eroded; scarps may be prominent but are slightly rounded. Landslide surface is vegetated, but vegetation may be younger than the vegetation on adjacent slopes.

3 = Relict: Geomorphic features related to the landslide have been greatly eroded and are subtle. Scarps are rounded. The landslide surface is covered with mature vegetation which is indistinguishable from the vegetation on adjacent slopes.

Figure 9-7 in TRB 247 provides diagrams to help determine the state of activity, based upon the geomorphic features of active and dormant landslides.

Dominant Type of Movement

Section 8 *Type of Movement* in Chapter 3 of TRB 247 describes the 5 five different types of landslide movement:

1 = Fall
2 = Topple
3 = Slide
4 = Spread
5 = Flow

Maximum Thickness of Landslide

The maximum thickness of a landslide can be estimated from field observations, subsurface investigation, cross sections, and geophysical data.

1 = Less than 5 feet
2 = 5 to 15 feet
3 = 15 to 50 feet
4 = Greater than 50 feet

Landslide Mitigation

Landslide mitigation strategies are grouped into four categories: Avoidance, Stabilization, Protection, and Management. The categories trend from higher to lower cost, effectiveness, planning, and design effort; and from projects that are generally performed as Capital Improvement to SHOPP to Maintenance. The strategies are often used in combination, and the measures can overlap from one category to another.

Avoidance Sometimes referred to as ***Relocation,*** involves measures such as roadway realignments, bridges, viaducts, retaining walls, and tunnels to separate the highway from the adverse impacts of the landslide. Avoidance allows the landslide movements to continue following mitigation, but those movements no longer affect the highway.

Stabilization Involves measures such as earthwork, buttresses, dewatering, retaining walls, shoreline armor, anchor bolts, slope contouring, and drainage systems to preclude or minimize further landslide movement.

Protection Involves measures such as rock sheds, rockfall barriers, draperies, rockfall fences, and catchment ditches to protect travelers and highway features from the collateral damage resulting from landslide processes. Protection measures typically control rock and soil emanating from a landslide.

Management Involves measures such as monitoring systems, patrols, planned road closures, signing, periodic maintenance, and minor rebuilding to allow operation of the highway within a tolerable amount of movement and disruption. Management measures are often practical for large, slow moving slides when the obstacles to other mitigation strategies prove insurmountable.

In practice, landslide mitigation often begins with Management, progresses to include the simpler, lower cost measures of Protection and Stabilization, and when the highway can no longer be operated safely and economically, the mitigation progresses to more robust measures of Protection and Stabilization. Avoidance is often the final solution when other strategies prove non-viable, but in rare instances Avoidance can be the simplest strategy. The GP will perform Risk Assessment (Section 5) by considering all strategies. The selected mitigation strategy to assure a safe traversable roadway is chosen in partnership with District stakeholders.

Many of the landslide mitigation measures mentioned above are discussed in detail in Cornforth (2005), TRB Special Report 247 (1996), portions of the Geotechnical Manual specific to rockfall, retaining walls, etc., or are relatively self-explanatory. Three measures commonly practiced by Caltrans are briefly presented below:

1. Dewatering

Dewatering can influence the stability of a slide mass by both decreasing the driving force and increasing the resisting force. The decrease in driving force results from lowering the weight of the slide mass as saturation diminishes. The increase in resisting force results from the decrease of pore water pressure acting on the slide plane thereby increasing the effective shear strength.

Dewatering a landslide is generally accomplished in two ways:

i. Reduce the quantity of water entering the slide. Ravines and graben ponds often feed surface water into the head of a landslide. Grade and/or place drainage systems near the head scarp to divert surface water elsewhere.
ii. Remove groundwater from within the slide mass or surrounding terrain using vertical wells or horizontal drains.

2. Earthwork

Earthwork can be used for landslide mitigation in numerous ways:

- Decrease driving force by removing material at the head scarp.
- Increase resisting force by placing material at the slide toe.
- Increase resisting force by constructing buttress or shear key.
- Removing slide debris from roadway.
- Removing unstable material from slope.
- Grading to improve surface drainage.
- Grading to create catchment basins and berms.

Due to the relatively high impact and cost of material excavation, transport, and disposal, projects involving earthwork should strive to adhere to the principles of reduce, reuse, recycle, replenish, and dispose:

<u>Reduce</u> overall quantities by selecting maintenance and repair techniques and practices that reduce the overall footprint of disturbance and are the least disruptive.

<u>Reuse</u> suitable material on the same project, nearby projects, or for maintenance purposes. Organic material such as duff or topsoil may have appropriate surface applications. Avoid the export of exotic plant material elsewhere. Minimize multiple handlings of the material.

Recycle material for non-highway uses on other approved public or private development projects or activities. Minimize multiple handlings of the material.

Replenish sediment supplies to natural systems by removing or bypassing man-made barriers. Replenishment may occur where the highway or highway management practices inhibit natural flow of sediment.

Dispose of excess material that cannot be put to any other beneficial use. Minimize multiple handlings of the material.

Trucking is the conventional method for excess material transport. Trips over 10-miles one-way from the source are considered long-haul trips increasing transport costs exponentially. These heavy truck trips on narrow winding highways result in pavement deterioration, reduced roadway safety, and the release of greenhouse gases.

Along sections of the coast where the ocean serves as a natural recipient of sediment generated by rapid erosion and mass wasting, several alternative material transport mechanisms may be considered. These mechanisms include mechanically depositing material over the side of the highway; loading the toe area of natural landslides for gradual redistribution of material by wave action thereby simulating natural processes; barging material to approved offshore ocean disposal sites; and pumping material into the surf zone or beyond to avoid burial of intertidal habitats. These alternatives require working with coastal stakeholders and are best implemented if planned for in advance of slide events.

3. Structures

Structures are often used as landslide avoidance measures. Soil nail or ground anchor walls can be used to isolate the roadway prism from the effects of a landslide on the slope below. Bridges, tunnels, and viaducts can be used to skirt over, under, and around landslides. Rock sheds can provide protection to travelers from landslides activity above the roadway.

Like dewatering and earthwork, retaining structures are used to stabilize a landslide by increasing the resisting force or decreasing the driving force. Ground anchor walls or shear piles may be placed at the toe of (or within) a landslide to exert resisting forces opposed to the direction of movement. In some cases, fill walls have been placed on the toe of a landslide to increase the effective stress on the slide plane. A strategically placed wall may allow removal of some, or all, of the slide mass.

Risk Assessment and Project Development

To formulate an appropriate mitigation strategy, all landslide mitigation efforts require risk assessment. Informal or preliminary risk assessment may occur during emergency response or early project development. Formal risk assessment is recommended for project design and the GDR. The GP must use the following generalized project development process.

1. Perform preliminary landslide review and characterization.
2. Identify the geotechnical conditions that influence instability.
3. Develop alternative mitigation strategies through a systematic consideration of Avoidance/Stabilization/Protection/Management measures.
4. Review the alternative strategies in consideration of the highway facility, constraints, and risks as listed here:
    a) Safety risks to travelers and Maintenance workers.
    b) Facility characteristic (traffic volumes, available detours, economic link, safety link).
    d) Consequence of immediate and long-term landslide activity.
    e) Complexity, schedule, and cost of alternative mitigation strategies.
    f) Complexity, schedule, and cost of project development.
    g) Relative effectiveness of alternative strategies.
    h) Necessary geotechnical investigation and data collection.
    i) Risks associated with insufficient geotechnical investigation (overly conservative and costly project, unstable project). Define the necessary investigation.
    j) Risks associated with insufficient project resources or schedule (repair may not address the problem). Define the necessary resources and schedule.
    k) Constructability issues: contractor, equipment, and material availability; complexity of construction; safety or workers and public during construction.
    l) Environmental Impacts.
    m) Future projects on the highway (i.e. widening).
    n) Aesthetics.
    o) Ongoing maintenance requirements and cost.
    p) Temporary vs. permanent mitigation.
    q) Does available funding allow for a project that mitigates the landslide or measurably improves corridor reliability?
5. Create a table of risks vs. benefits for the alternative mitigation strategies being considered. A decision matrix may be useful.
6. Present the alternatives, benefits, and risks to the project design team.
7. Select preferred alternative(s) for further development.
8. Perform the geotechnical investigation and analyses.

9. Based on unforeseen outcomes of the investigation and analyses it may be necessary to repeat portions of steps 2 through 8.
10. Finalize repair strategies, design, and construction recommendations.
11. Prepare Maintenance Support Memorandum or GDR as appropriate for the project.
12. Assist in the preparation of plans (formal or informal).
13. Identify construction safety risks and prepare construction safety plan or provide information adequate for the Contractor to prepare a construction safety plan.
14. Perform work (Maintenance and/or Construction activities). The GP will oversee and provide technical expertise for all landslide related construction activities.

In many cases it is impractical to completely stabilize a landslide; therefore, an assessment of the effectiveness of each strategy in conjunction with the associated risks and impacts will facilitate selection of appropriate mitigation. The selection may be documented in a decision matrix like Table 1.

Table 1: Landslide Mitigation Strategy Selection Matrix

Landslide Mitigation Strategy	**Score = 0 - 10**		**Score = 0-5**					**Total: (Max. 45)**
	Effectiveness	**Cost**	**Traffic Impact**	**Environmental Impact**	**Right-of-Way Impact**	**Constructability**	**Construction Duration**	
Total Removal of Landslide	10	2	0	3	4	2	1	22
Partial Removal of Landslide	7	4	1	5	5	4	2	28
Stabilize Landslide with Earthen Buttress	10	2	0	3	4	2	1	22
Stabilize Landslide with Horizontal Drains	2	4	2	5	5	2	2	22
Buttress with Anchored Soldier Pile Wall	10	4	5	2	3	2	2	28
Manage Landslide through Periodic Closures and Repaving	1	10	5	5	5	5	5	36

Landslide repair strategies are commonly estimated and programmed before a thorough field investigation starts, which results in major risks involving project funding and schedule. This can result in: 1) a geotechnical investigation that is overly abbreviated thereby leading to inaccurate assumptions and questionable analyses and design, or 2) a project that is insufficiently funded to perform the necessary mitigation. Early and thorough coordination with the District Project Development Team can minimize risks associated with estimating and programming.

The Coast Highway Management Plan (CHMP) contains a good qualitative description of considerations for several mitigation strategies for the Avoidance, Stabilize, Protection and Management approaches and provides input as to the likely project funding source.

Landslide Modeling

Landslide modeling employs charts, numerical equations, and/or computer programs to represent and simulate landslide geometry, soil conditions, and behavior. Given the complex nature of many landslides, the landslide model is an approximate representation of the actual landslide. The extent to which a model represents a landslide depends on the purpose of the model (preliminary models vs. final calibrated models), extent and validity of data gathered and used to construct the model, the modeling method employed, and the accuracy of the simulated slope failure mechanism. TRB 247 (Chapters 13-15) and Cornforth (Chapter 9) discuss slope stability modeling for landslids.

The purpose of landslide modeling is often twofold: 1) to better understand the mechanics of a landslide, and 2) to evaluate the effectiveness of proposed mitigation strategies.

<u>Modeling Practice</u>

Modeling may be performed for slides in soil, rock, and intermediate geomaterials. Landslide modeling differs from typical slope stability modeling in that failure limits and other critical conditions already exist and can be determined through site exploration, instrumentation, and testing. After the exploration program, models are developed to simulate the site conditions. To understand the slide behavior, the GP may attempt to simulate numerous slope configurations and ground conditions: the stability prior to the slide event; the instability during the slide event; the quasi-equilibrium following a slide event; and the effects of various mitigation alternatives.

The GP must identify appropriate stability analyses to represent the landslide. Landslide stability analyses are typically based on a two-dimensional cross-section of the slide, generally through or near the mid-width (Cornforth), but also for other cross sections likely to govern unstable behavior. Landslide models yield a factor of safety for a user defined cross section of materials, material properties, applied loads, and groundwater conditions.

Landslides may be relatively simple and the underlying mechanics clear, such as a rotational slide in a homogenous embankment fill that has been subject to a saturation event, or a translational slide of a large rock slab. Because the mechanism is understood, a rough model may be developed using slide geometry measurements and estimated strength parameters. The model can then be used to evaluate the merits of various mitigation measures. This practice is common during many emergency response efforts that are progressing rapidly.

Complex landslides require iterative modeling to fully reveal the underlying mechanics. Once the mechanism of a complex landslide has been simulated and confirmed by model performance, mitigation strategies are applied to the model and evaluated.

Landslide models should be simplified to the greatest extent possible. Simple surface and subsurface contact geometry will minimize the potential for error. In general, a representative landslide model should be developed in a progression from simple to complex. More complex geometry, external loading, groundwater conditions, and structure should be added incrementally while observing output results for both anticipated and unexpected behavior.

If a landslide model represents the slope geometry, slide surfaces, distribution of materials, and discontinuities correctly, the only remaining variables are the shear strengths of materials and pore water pressure.

Preliminary Modeling

Preliminary and ongoing landslide models are of great value after the initial field reconnaissance and before the subsurface investigation. Preliminary modeling can indicate such parameters as the likely depth of slide surfaces and the zones of soil units that most influence slide behavior. Preliminary models can be developed based on initial field maps and cross sections, and estimated soil strength parameters derived from experience with similar materials and formations. Use preliminary model results to estimate the appropriate depth of borings and sampling locations.

Model Calibration

Landslides mechanics are typically modeled and calibrated by constructing a model that represents site conditions immediately prior to a slide event that has disrupted landslide equilibrium. Model parameters such as soil weight, strength, and pore water are subsequently adjusted within limits revealed by the investigation program until the model output indicates a factor of safety of 1.0. This process is often termed *back analysis*. B*ack analysis* often results in a greater certainty in strength parameters that are difficult to measure through testing. The shear strength of material along the slide plane is often determined through *back analysis.*

Models of active landslides should be calibrated at a factor of safety from 0.95 to 1.0. The GP should utilize supporting information in assigning a rational factor of safety value for a given slide simulation. A factor of safety less than 1.0 is sometimes assigned to models of slides that are moving.

In the *back analysis*, the GP should attempt to simulate the conditions that contributed or caused failure (such as high groundwater levels or a seismic event), as close as possible to the actual conditions that existed at the time of failure. In the case of uncertainty, it is recommended that assumptions of more extreme conditions such as higher groundwater levels or ground accelerations not be made. Assuming a higher than actual piezometric surface or ground acceleration may lead to overestimation of the shear strength of materials.

<u>Sensitivity Analysis</u>

Model calibration includes a sensitivity analysis where model parameters such as piezometric surface, cohesion, or friction angle are held constant except for the single parameter being evaluated. This parameter is then varied within a reasonable range of values and the effect on model results is observed. This analysis reveals how sensitive the model is to changes of each parameter. Changes in some parameters may have little influence on model behavior while changes in other parameters may have great influence. The more sensitive parameters may indicate where investigation and testing should be focused. In general, changes in cohesion and piezometric surface will have the greatest effect on model stability. Additionally, models that appear to be overly sensitive or behave in a counter intuitive manner may contain errors.

<u>Mitigation Modeling</u>

Once a model has been calibrated, mitigation strategies are typically modeled by reconfiguring versions of the calibrated model to simulate the final slope geometry and the presence or effect of the various mitigation strategies. The relative increase in the factor of safety may be used to judge the effectiveness of a proposed mitigation.

It is important to recognize that, if a landslide has been sufficiently modeled, it is often not necessary for the governing strength parameters to be precisely determined to evaluate the <u>relative</u> effectiveness of various mitigation strategies. The GP should determine an appropriate amount of model development to suit the project.

For example, since it is difficult to test the in-situ soil strength of granular soils that may comprise a landslide, a landslide in granular material may be simulated using assumed soil strength parameters. Subsequently, various stabilization strategies such as slope buttressing, grading, and dewatering can be simulated thereby allowing comparison of the relative effectiveness of each strategy.

<u>Common Modeling Methods</u>

Refer to Cornforth (2005) Chapter 9, TRB 247 Chapters 13 through 15 to determine appropriate stability analyses to simulate a given landslide. Appropriate stability analyses may be relatively simple. Infinite slope analyses should be conducted for shallow slope failures in soil that roughly parallel the ground surface. Many translational landslides in rock may be modeled using relatively simple mathematics as block or wedge failures along distinct planer discontinuities. Landslides in homogenous materials with semi-circular failure surfaces may be quickly characterized using charts available in NAVFAC

DM-7 (2005). Landslides in transitional material may be modeled as rock and again as soil to determine the model that demonstrates the most representative behavior.

Develop landslide models using widely accepted, two-dimensional, limit equilibrium methods of slope stability analysis such as Simplified Janbu, Modified Bishop, Spencer, and Morgenstern-Price. While the latter two methods are preferred for slope stability modeling by many GPs, it should be recognized that the primary reason for modeling a landslide is to estimate the increase in stability that may be achieved by the proposed mitigation alternatives. Therefore, the method used to develop the calibrated landslide model should also be used to develop the models of various mitigation alternatives. The general modeling methodology is as follows:

- Use the information gathered from the landslide investigation to prepare critical cross sections of the landslide geology. The cross sections should include the ground surface profile, slide surface geometry, subsurface contacts, subsurface materials and their assumed or tested strength parameters, and groundwater surfaces.
- Consult geotechnical archives, colleagues, and specialists to discover previously developed models representing similar landslides. Use an appropriate model as an informal template.
- Using the data tables in the modeling software, enter the cross-section geometry, soil strengths, groundwater surfaces, and loading conditions.
- Define the critical failure surface, or the range of critical failure surfaces to be searched, as revealed by the investigation and critical cross sections. The failure surface may be translational, rotational, or irregular. If the developed information is insufficient to determine the landslide mechanism, develop models representing all suspected failure mechanisms. The mechanism resulting in the lowest factor of safety is the likely failure mechanism.
- Run the model to calculate the critical failure surfaces and/or determine factors of safety. The factor of safety of an active landslide should be near 1.0; however, the GP must apply judgement in evaluating the model output. Slightly higher or lower factors of safety may be rational model outputs depending on the conditions being modeled. For example, just prior to high rainfall that triggered a landslide, the representative model may have a low piezometric surface and a factor of safety slightly greater than 1.0. Raising the piezometric surface to simulate the influence of rainfall may result in a factor of safety slightly less than 1.0.
- Debug the model. One or more errors may have been incorporated into the initial model. For example: failure surface searches running through air may produce erroneous model results; vertical contacts may produce erroneous model results; data table input values may have been transposed; different strength values may have been applied to the same geologic unit. An error may cause the model run to abruptly abort. Irrational search limits may cause the model run to finish but with illogical results. For example, a significant length of failure surface passing through strong material as opposed to an adjacent weak material may indicate the

search limits did not allow a search of the weakest surfaces. It may require several runs and revisions to debug the model.

- Calibrate the model by adjusting model parameters within the range of uncertainty until the factor of safety of the active landslide is just below 1.0. Compare the calibrated model to site geology and test data to verify that the model construction and results are supported by the data gathered. For example, if you needed to drop the friction angle of a material below a reasonable value to simulate a failure, then there is likely some other part of the model that needs adjustment. Reevaluate the compiled data and gather more data if necessary.
- Use the calibrated model as the basis for development of modified models that simulate the effect of proposed mitigation strategies. It is helpful to remember that you are often not modeling the actual strategy but rather the effect of a strategy. For example, the effect of horizontal drains is not typically modeled by placing a drain in the model but rather by defining a lowered piezometric surface. Similarly, even though a ground anchor wall or shear piles may be simulated and depicted in the graphical output of the model, the wall may only affect the model as a defined load applied at a defined location in a defined direction. When applying forces to the limit equilibrium model, care should be taken so that all base forces remain compressive and no tensile forces are introduced.

Modeling Software

Programs commonly utilized for landslide modeling are GSTABL7, SLOPE/W, SLIDE, and RockPack. These programs can provide safety factor calculations by limit equilibrium methods. Most software packages include example files that model slope stability and mitigation that may aid the GP in model development.

Factor of Safety Criteria for Landslides

Cornforth (2005) Chapter 10 discusses the factor of safety and guidelines for setting minimums as a function of investigation rigor and landslide size. The suggested minimum static factors of safety range from 1.5 to 1.15. Slope stability factors of safety falling in the same general range can be found in numerous other sources. However, for the Caltrans GP, these target criteria are often no more than tenuous goals for highway related landslide stabilization. Landslides may be complex features with large dimensions that often extend well beyond the highway right-of-way. Geographic features such as mountains, rivers, and oceans may limit or preclude investigation and available mitigation strategies. Landslides may occur along remote highways that act as lesser or greater transportation links. Numerous stakeholders with competing interests and viewpoints may be involved in all aspects of remedial activities. Funding for landslide mitigation may be limited.

Modeling may reveal that available mitigation strategies provide only marginal improvement to stability, or possibly no improvement in stability. Some landslides may simply defy stabilization and creep relatively slowly or move in small, punctuated events.

The GP may ultimately provide recommendations that yield only a modest increase in stability, and some landslides may remain at a factor of safety of less than 1.0 following mitigation efforts.

For landslide stabilization efforts, static factors of safety of 1.3 should be achieved where reasonable. Elsewhere, the goal of landslide stabilization should be to attain the highest achievable factor of safety while working to satisfy stakeholders and working within geographic and budgetary constraints imposed on the project. At a minimum, any landslide stabilization strategy should strive for a minimum ten percent (10%) increase in static stability.

Seismic factors of safety may be evaluated by applying a horizontal acceleration of 1/3 the peak ground acceleration (PGA) to the landslide model. Any landslide stabilization project should strive to achieve a minimum seismic factor of safety of 1.0. However, due to project constraints, the available mitigation alternatives may not provide a seismic factor of safety meeting this minimum target.

A seismic factor of safety evaluation should be conducted for all proposed landslide mitigation strategies regardless of the outcome. Such an evaluation will serve to fully document the designed slope stability condition. Proposed landslide stabilization designs should either meet minimum static and seismic stability targets or the proposed design should be supported by an appropriate risk assessment.

Reporting

Present landslide recommendations in accordance with the *Geotechnical Design Report* module. Present recommendations for specially designed walls or structures in a Foundation Report.

Include the following in the *Analysis and Design* section of the Geotechnical Design Report:

- Description of slide geometry including the slide boundary and depth to failure surface.
- Plan map and typical cross section of the landslide.
- Geological interpretations and factors causing the landslide.
- Analyses and procedures including the names and descriptions of software applications used for data reduction and interpretation.
- Model description and output
- Groundwater elevation used for analyses and design.

Include the following in the *Recommendations* section of the Geotechnical Design Report:

- Proposed mitigation footprint, plan view, and cross-section, if applicable
- Specifics listed below for various improvement recommendations.

Drainage

- Surface drainage
    - Brow ditches
        - Location
    - Lined ditches
        - Location
        - Liner type
        - Cushion fabric
- Subsurface drainage
    - Horizontal Drains
        - Location (provide plan map)
        - Inclination
        - Length
        - Number
        - Spacing
        - Slot size
        - Orientation

        - Collector system
    - Drainage wells
        - Depth
        - Diameter
        - Permeable Backfill
        - Spacing
        - Location, number and inclination of outlet pipes
        - Diameters of belled out portions
    - Deep under drains
        - Location
        - Depth
        - Limits of UD
        - Location, number and inclination of outlet pipes
        - Permeable material

<u>Earthwork</u>

- Buttresses
    - Plan view and cross section showing geometry
    - Material type
    - Drainage details
    - Cut slope and finished grade slope ratios
- Stability Trenches/Shear Keys
    - Plan view and cross section showing geometry
    - Material type
    - Drainage details
    - Cut slope and finished grade slope ratios
- Slide removal
    - Plan map and cross sections
- Regrading
    - Plan map and cross sections
    - Drainage considerations
- Roadway Realignment (Avoidance)
    - Geologic map along proposed alignment

Structures

- Bridges/Viaducts
    - Location
    - Limits
- Retaining Walls
    - Location
    - Limits
    - Height/depth
    - Wall type
- Slope stressing
    - Location

References

1. Cornforth, D., 2005- Landslides in Practice. Investigation, Analysis, and Remedial /Preventative Options in Soils, John Wiley & Sons, 2005
2. TRB, 1996- Landslides, investigation and mitigation, Special Report 247, Transportation Research Board, National Research Council, 1996.
3. Philip L. Johnson and William F. Cole, 2001, The use of large-diameter boreholes and downhole logging in landslide investigations: *in* Horacio Ferriz (ed.) *Engineering Geology in Northern California*, California Department of Conservation, Division of Mines and Geology, Bulletin 210, p. 95-106.
4. Coast Highway Management Plan (CHMP) – Guidelines for Landslide Management and Storm Damage Response – March 2004
5. C. F. Narwold, W. P. Owen, Seismic refraction analysis of landslides: Proceedings of the 2nd annual conference on the application of geophysical and NDT methodologies to transportation facilities and infrastructure, 2002, FHWAWRC-02-001.