Combating Landslides in Southern California

By Gregory Axten, P.E.

Along with the record and near record rainstorms of the 2004/2005 rainy season, southern California experienced a resurgence of small, medium, and major landslides throughout the hillside areas. From late December to February of 2005, hardly a week would pass without major news coverage of the crumbling hillsides and collapsing homes. Whether it be the beautiful climate, the fast pace of our living, the high rents and struggle to make the next big mortgage payment, or simply the rose-colored Hollywood sunglasses, southern Californians quickly forget the risks of living on hillsides prone to instability. In virtually every major rainy season for decades, such as 1969, 1978, 1980, 1983, 1993, 1998, and 2005 major slope failures have occurred. *Figures 1, 2*, and *3* depict just a few significant landslides.

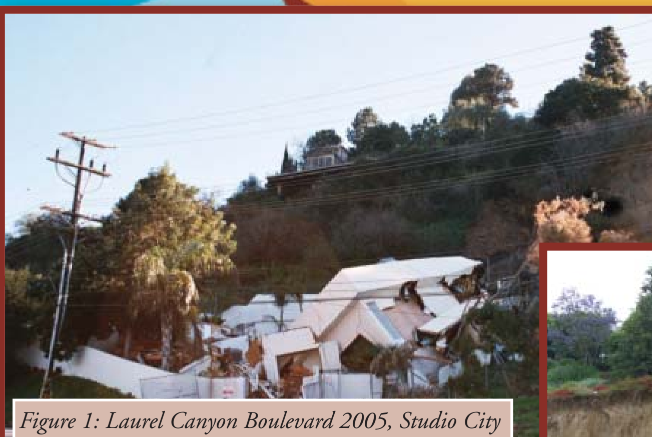

Figure 1: Laurel Canyon Boulevard 2005, Studio City

Figure 2: Aerial view of Laguna Niguel landslide, 1998

Figure 3: Hidden Hills Road, Yorba Linda, 2005

In this past season, our office has been dealing with more than a dozen newsworthy landslides and in excess of 100 smaller landslides. In all of the cases, some inherent weakness existed within the hillside area which went undetected. In some cases, pre-existing ancient landsliding existed which went undetected at the time of the original development. In other cases, distinct planes of weakness, such as clay seams, existed without identification or otherwise due consideration. Still, in other cases, no discrete point of weakness went undetected, but rather, a generally weak soil condition or bedrock condition was overlooked or otherwise misunderstood as a result of improper testing at the time of original development. Whether a discrete point of weakness or a generalized condition, inherent weaknesses pre-existed in every case.

Inherent weaknesses alone seldom result in a major instability. Although occurrences could be sited where excavations undermining slopes resulted in instability, water has usually been added to the weak system to trigger the instabilities. All too often rainfall water is blamed for causing hillside instability. Although water plays a significant roll in triggering instability, in most cases, the rain cannot be reasonably blamed for "causing" the problem. Since water in many cases is understood to exist or otherwise assumed to exist, water is therefore a design parameter. As such, in many cases blaming the landslide on water is like blaming the rain for a roof leak.

Treating hillside instability often involves substantial structural systems for adding strength and restraint. Although incorporating drainage systems and grading are frequently employed as secondary components in the development of repair plans, structural systems are rapidly gaining in popularity and becoming the first line of defense in major slope repairs. Where factors-of-safety need to be re-established to levels consistent with approvals for construction (i.e., at least 1.5), structural systems are almost always employed.

In earlier decades, landslides were commonly dealt with primarily by buttress or shear key-style grading techniques and de-watering systems to mitigate the future build-up of groundwater. With the high density of development in California hillside areas, boundary conditions with existing structures almost always command structural support systems. More than ten years ago, the most popular form of a structural system was the classic caisson and grade beam system, alternatively taking the form of soldier piles or shear pins. For distinction,

Figure 4: Soldier pile wall, Laguna Beach

shear pins rely on the shear capacity added by interrupting a discrete landslide surface with reinforced concrete and steel elements, whereas caisson and grade beam systems and soldier pile walls add considerable shear and bending resistance to, in essence, create a below grade, retaining wall system. A soldier pile wall is depicted in *Figure 4*.

From a geotechnical perspective, the key to proper design of stabilization systems consisting of a primarily vertical structural element is precision in estimating the destabilizing earth pressures and available passive resistance. Structural engineers usually accept the geotechnical consultant's geometry, groundwater, and geotechnical earth pressure criteria, after which the structural engineer employs structural computational methods to determine the section properties for elements of appropriate strength and stiffness. Rudimentary analyses satisfy force and moment equilibrium, as well as estimate shear and bending stress distributions. Thereafter, deflection estimates can also be developed. In recent years, more complex soil/structure interaction analyses are conducted to better estimate the total deformation of the systems. Taking a closer look at the soil/structure interaction problem commonly results in the conclusion that the deformation in a simple pier system will be greater than can be reasonably tolerated, or designing a cantilevered system to limit total deformation to a tolerable level is simply not practical. Problems with deformation in the stabilization systems incorporating primarily vertical elements is believed by this consultant to be the reason why tieback anchors have steadily gained popularity for treating landslide conditions.

Tieback systems are commonly installed in a subhorizontal fashion, usually at about 20 degrees from horizontal. *Figure 5* depicts a typical tieback drilling operation. Since the installation is subhorizonal, it should be intuitively obvious that such systems are considerably more efficient lateral-resisting elements than classic, cantilevered caisson or soldier pile walls. A tieback anchor is a pressure grouted bar or bundle of high-strength cables (note bundle of cables at right side of *Figure 5*) bonded within the firm underlying materials by high-strength concrete grouting. The free end of the tieback system is typically post-tensioned against an exposed or a concealed compression wall. In some cases, caissons and grade beams or soldier piles are utilized in conjunction with the tieback system. In essence, the tieback system provides the head restraint to limit the otherwise intolerable movement. Keys to properly designing tieback systems include identifying appropriate bond strengths within the firm underlying stable material and identifying the appropriate bearing capacities in the comparatively soft near surface, over-burden materials. Identifying the appropriate bond strengths is commonly supported by testing, as well as the experience and judgment of the geotechnical engineer. Appropriate bond strengths can vary widely among the tremendously variable soil and bedrock conditions which exist throughout Southern California. Unconfined compressive strengths can vary from a relatively few psi in soft soil materials to on the order of 20,000 psi in hard crystalline bedrock.

Sometimes, available bond strength can be deceptively low. An example of a particularly weak bedrock is the Capistrano Formation covering much of south Orange County. This bedrock is widely recognized to be relatively weak, considerably expansive and severely corrosive. Although relatively deep, unoxidized portions of the Capistrano Formation are considerably stronger, most of the upper portion of the formation which is the subject of investigations has strength comparable to a stiff soil. The bedrock is so weak that allowable bond stress confirmed by testing has been as little as 7.0 psi for post-grouted tiebacks. For tieback anchors the approximate values for bond stress are also available from several authoritative sources, such as the just published *Foundation Engineering Handbook* (Robert W. Day, McGraw Hill Companies, 2006). In that handbook, Table 11.2 presents ultimate bond stress for tieback anchors. The emphasis is on the characterization of ultimate values. Appropriate factors-of-safety should be applied to the ultimate values. As for any similar analysis, the factor-of-safety should increase with the degree of uncertainty. Commonly, factors-of-safety range from about 1.5 to 3.0.

In common design and construction practice, tieback systems are given a preliminary design by the geotechnical and structural engineering consultants. Plans and specifications are usually prepared on a "performance basis." Performance-based tieback installations require the contractor to utilize his unique knowledge, experience, equipment, and technical capabilities to achieve the desired service load on each tieback with proof testing and creep testing of actual anchors utilized to confirm the desired result. For tieback anchors, high pressure, post-grouting techniques are typically utilized to enhance the bonded section's shear capacity with the surrounding earth materials. Usually within about 24 hours of initial grouting of the bonded lengths, high pressure grouting is reapplied to the system via embedded high-pressure tubing and valves or sacrificial exploders which serves to fracture the initial grout and induce considerably higher confining stresses between the bonded system's grout and the surrounding earth materials. Occasionally, multiple generations of post-grouting are employed. Grout pumps usually capable of delivering at least 1,000 psi gauge pressures are utilized. In practice, actual fracturing and grouting pressures in the range of 400 to 600 psi are common with post-grouting pressures achieving over 1,000 psi on occasion.

Proof tests are commonly conducted to about 133 percent of the service load, with deformation and loads recorded over a period of about 30 minutes. Creep tests are usually conducted in a range of 133 to 150 percent of the design load over periods up to about 24 hours. While proof tests are conducted on all anchors, creep tests are usually conducted on about five to ten percent of the anchors. The Post-Tension Institute criteria are most often referred to for test specifications (*Recommendations for Prestressed Rock and Soil Anchors*, 1996). Where failures occur, the results of the proof testing and creep testing are utilized to estimate the available service loads, as constructed, and

Figure 5: Tieback anchor installation with isolated compression blocks

Figure 6: Complex repair of Laguna Niguel landslide

in turn, form the basis for determining the capacity and number of supplemental restraints. In Southern California applications, service loads are commonly in the range of 100 to 300 kips. Although less frequent, even higher service loads (e.g., 500 kips) are possible, particularly in relatively hard-rock sites where bond stresses of 100 psi are easily attainable.

Compression blocks to which the anchors are tensioned are sometimes designed as isolated anchor blocks (*Figure 5*). In Southern California applications, where sedimentary formations and soft clayey overburden soil is common, continuous structural compression walls are common. With available bearing pressures on the order of 5,000 pounds per square foot, strip-style compression walls of 8 to 10 feet in height and 18 inches to 2 feet thick frequently occur. Shotcrete techniques are commonly employed in the construction of the compression walls. The structural engineer should take special care in the designing and detailing reinforcing for the shotcrete style of construction.

In designing tieback systems, care should be taken wherever possible to limit potential conflicts between tiebacks. An alignment tolerance of one to two degrees is reasonable in many cases, but for 200-foot long tiebacks at six-foot spacing, a one degree tolerance would result in a risk of conflict. In most cases, conflicts do not tend to be a problem in parallel applications. Special care must be taken, however, in identifying potential conflicts when proposed stabilization schemes wrap tiebacks around a hillside creating a crossing pattern. The geotechnical consultant and structural engineer should combine their efforts to limit potential conflicts by rational design and alignment specifications.

Since landsliding most often occurs in one overall direction, it is realistic in many cases to design a system of tieback improvements utilizing parallel compression walls where potential conflicts are minimized. Sometimes combinations of restraining element systems are useful in simplifying the system and minimizing conflicts. A less critical flank might be accommodated by a caisson system. In the final design, detailing and construction of tiebacks, careful attention should be paid to corrosion protection. Techniques commonly referred to as double corrosion protection are usually adopted in tieback applications, but triple corrosion protection systems are also available. These systems utilize combinations of grout cover, corrugated plastic sleeves, and occasionally epoxy coatings to accomplish the corrosion protection.

Large landslides will usually be treated at least in part by grading techniques. When tiebacks are employed, the grading may only involve a relatively narrow zone to cover the tieback systems and provide for landscaping. Sometimes the use of boundary structural restraint systems allows for the complete removal and re-compaction of landslide debris. In large-scale landslides, as might be expected, combinations of techniques are utilized. In 1998, in Laguna Niguel, a massive landslide occurred which ultimately resulted in a loss of nine moderate to upscale single-family detached homes and 52 townhome-style condominium residences below. The approximately 16 million dollar repair effort included 64, heavily-reinforced, large-diameter caissons extending to depths of an excess of 100 feet. This system, which included a buried conventional retaining wall at the top of the grade beam, initially included a single row of high capacity tiebacks to serve as an emergency repair in order to save a road alignment and to protect property further upslope.

As the next phase of repair proceeded, four additional rows of high-capacity tiebacks were anchored to supplemental compression walls, constructed as excavating landslide debris proceeded to depths of over 70 feet below the salvaged roadbed. In the immediate flanks of the caisson wall and tieback area, soil nails and light structural sheets were added. Other areas of the hillside employed high-capacity tiebacks and compression walls without caissons. With the head area stabilized, large-scale grading clean-outs of landslide debris proceeded with installation of multiple subdrainage systems below the compacted fill and the construction of a large-scale gravity buttress. An overview of the in-progress Laguna Niguel landslide repair is presented in *Figure 6*. To accomplish the successful completion of the stabilization, careful coordination was necessary among the offices of the geotechnical consultant, structural engineer, and contractor. In conjunction with the construction and the post-construction monitoring, high sensitivity, electronic tiltmeter-style instrumentation was utilized as well as conventional inclinometer installations. Assessing the instrument data in succeeding years has confirmed the successful stabilization.

In dealing with the many other landslides which have occurred this past year, various repair systems will undoubtedly be employed. In a number of circumstances, tieback systems have already been designed to provide temporary improvement. Some systems are in place, and others are planned for implementation as soon as possible. Successful treatment of a major landslide can take a few years from the date of the landslide occurrence. Assembling teams of experienced geotechnical and structural professionals, as well as experienced contractors, is essential to limiting the extent to which property and improvements are lost and cost for remediation is minimized, while providing a high degree of confidence in the long-term stability of the repaired slopes. Clear and carefully planned communications with the governing agencies is also an important component in developing a plan to effectively combat landsliding. Frequently, agency professionals have far less experience with the investigation, testing, analysis, and treatment techniques than those professionals retained by the property owners. Although the governing agencies can create unnecessary and expensive hurdles to overcome, in most cases, agencies facing major landslide damage in their jurisdictions are willing to work with the experienced, private sector design professionals and become educated, as necessary, to understand the essential elements in the processes that are necessary to achieve a successful result.▪

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