UNSTABLE SLOPES IN THE FRANCISCAN COMPLEX TERRANE: LESSONS LEARNED FROM URBAN QUARRY SLOPES IN THE SAN FRANCISCO BAY AREA

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Abstract: As the need for urban living space intensifies, an increasing number of former rock quarry sites have become prime real estate for residential living areas. This change in land use can result in inappropriate and potentially catastrophic consequences when residential structures are placed in close proximity to unstable quarry slopes that were not adequately investigated prior to development. Examples of this have occurred on the San Francisco peninsula where recent slope failures along several quarry faces serve as a testament to the variability of the Franciscan Complex terrane and the unique set of failure mechanisms associated with a given Franciscan rock type, underscoring the importance of a thorough geologic assessment prior to development. In two presented case studies, residential developments were adversely impacted by recent rock slope failures. Incomplete characterization of site geologic conditions and inadequate identification of critical slope failure mechanisms led to unsatisfactory setbacks and/or ineffective mitigation designs.

The Knockash Hill development in San Francisco is underlain by thinly-bedded “ribbon” chert of the Franciscan Complex that was previously mined for roadway aggregate. The steep quarried slope, located immediately above new residential units, presented an excellent geologic exposure of bedded chert that displayed adversely oriented discontinuities and weak shale interbeds. No less than seven rockslides have occurred within a 6-year period along these precipitous quarry slopes. These events sent debris into four new residential structures and buried a roadway. Ultimately, an elaborate network of rock bolts and belt beams was designed to mitigate rockslide hazards. The Stoneridge development, also in San Francisco, provides a similar example where several residential structures were impacted by recent rockslides from quarried walls. Currently, various levels of restricted residential use and phased evacuations are being used to address rockfall hazards until necessary engineering solutions can be implemented.

KNOCKASH HILL DEVELOPMENT

Site Setting and History

Knockash Hill is located within the southcentral portion of the City of San Francisco, California. This area was part of a rock quarry dating back to the late 1800s with active quarrying practiced until approximately 1965. The resulting slopes extend up to 150 feet high and are characterized by precipitous (45- to 90-degree) south-facing, quarried topography, with a broad bench at the base of the slope (Figure 1). The bench now contains a church and a 15-lot residential development, which was constructed in the early to mid-1990s (Figure 2). Prior to residential development, wire mesh netting and shallow rock anchors (less than 10 feet in length) were installed on the slope face and a 10-foot-high rockfall barrier wall was constructed at the base of the slope. The potential for slope failure beyond minor rockfall was apparently not recognized as a hazard and more significant mitigation measures were not implemented.

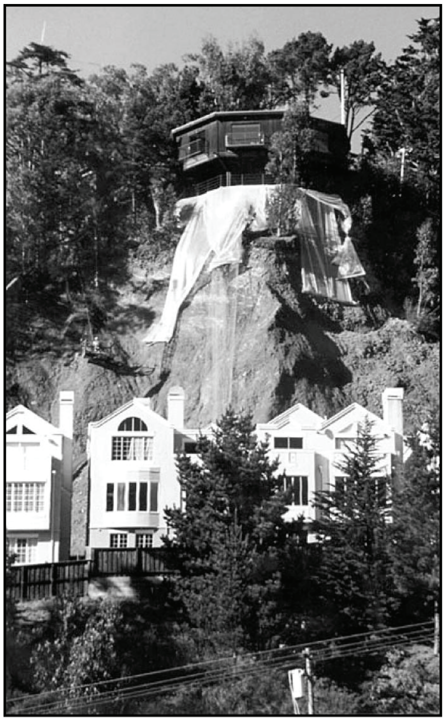

Figure 1. Newer residential development near base of Knockash quarry slopes.

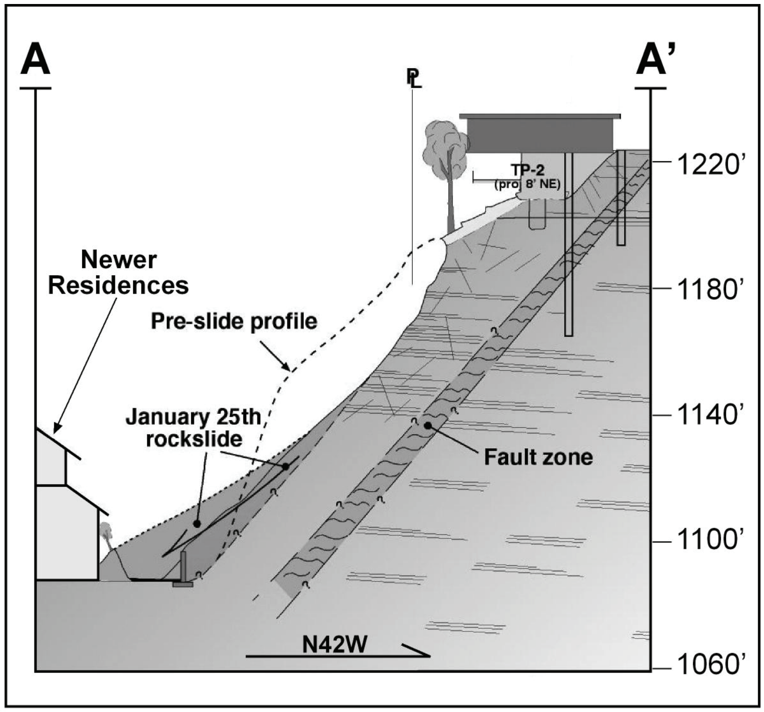

Figure 3. Geologic Cross Section through Knockash Quarry wall.

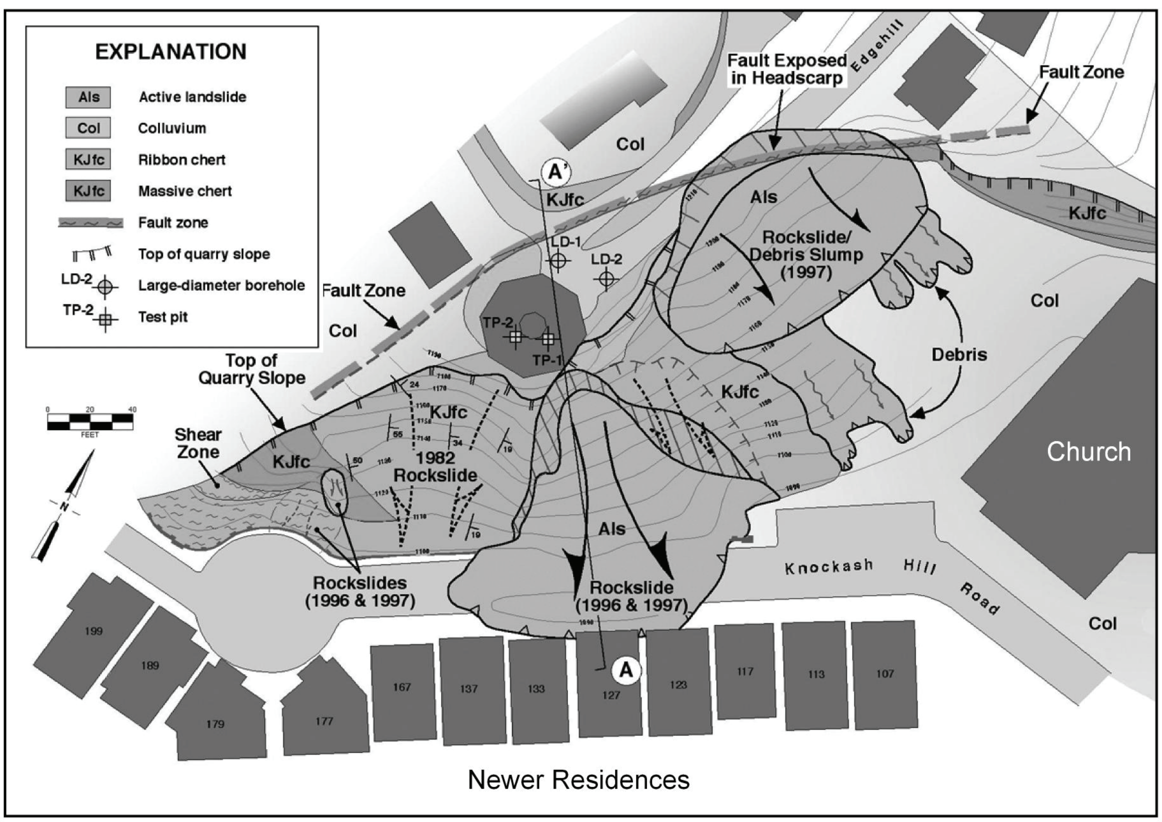

Figure 2. Knockash development Geologic Map.

Two small rockslides occurred during the early phases of residential development over the winters of 1993 and 1994. Then, a large rockslide occurred at the site in the winter of 1995 that impacted new homes at the west end of the partially completed development. This rockslide mobilized from the general vicinity of the two previous, smaller failures.

Cotton, Shires and Associates (CSA) was retained following the 1995 rockslide to perform a geologic and geotechnical investigation of the site and provide slope stabilization design recommendations. Following this geotechnical investigation, but prior to implementation of mitigation measures, four large rockslides occurred between December 1996 and January 25, 1997 (Figure 3). These failures damaged four residential structures and resulted in the forced evacuation of 13 residences.

One of the most instructive tasks performed in the early part of the investigation was the analysis of historical aerial photographs for each decade during the period between 1935 and 1995. It was immediately apparent that the quarry slopes were experiencing repeated rockslide failures at 5 to 15 year intervals, and that the quarry face was too steep for adequate slope stability. Between 1970 and 1995, portions of the slope face retreated at average rates between 2 and 6 feet per year. Following large rockslide events in the 1970’s and 1980’s, the bench at the base of the slope (location of the future 15-lot development) was nearly completely buried by slide debris.

Site Geology

The site is located in the Coast Range geomorphic province typically characterized by northwest-southeast trending ridges and intervening valleys controlled by folds and faults that resulted from the collision of the Farallon and North American plates and subsequent shear along the San Andreas fault system. The complex history of this accretionary belt has resulted in the emplacement of a variety of geologic materials onto the continental margin. The property is underlain by Cretaceous to Jurassic age bedrock (approximately 63 to 205 million years old). This assemblage is predominantly composed of a mélange of marine sandstone and interbedded shale, chert, volcanic and high grade metamorphic rocks, and serpentinite (Schlocker, 1958). Bedrock materials of the quarry site are characterized by a mixture of thin-bedded "ribbon" chert, and thick-bedded, massive chert “knockers.” Lesser amounts of sheared Franciscan sandstone, siltstone, and shale are located near the toe of the slope beneath the chert deposits. A pronounced shear zone comprised of pulverized Franciscan Complex shale, aligned roughly parallel to regional bedding, is located near the base of the slope. The shear zone provides weak basal support that has contributed to rockslide failures of the overlying chert.

Two primary sub-units have been identified within the ribbon cherts, including thin-bedded chert (1 to 6 inch thick beds) with interbedded red shale (beds 0.25 to 3 inches thick), and thick-bedded green chert with little to no shale. Very hard, resistant, thick- and thin-bedded green chert forms the steepest upper portions of site slopes. The ribbon chert has a regional dip of approximately 20 to 40 degrees to the northeast, but locally has very tight Chevron folds. The chert beds are hard, moderately strong to strong, and closely fractured. The interbedded shale is generally soft to moderately hard, weak to moderately strong, and pulverized to closely fractured. Slake tests indicate that the shale is highly reactive and subject to very rapid loss of strength and deterioration when immersed in water. Rapid weathering of exposed shale interbeds appears to contribute to surface weathering that may help explain the significant average annual slope face retreat observed in aerial photographs over several decades.

Hazard Assessment

Our observations and analysis indicated that the oversteepened quarry face had the potential to fail in several modes including as a shallow rockslide, a deep-seated rockslide, a rock topple, and a debris slide of talus and quarry debris. The primary factors responsible for rockslide failure within the ribbon chert appear to be: 1) the oversteepening of the rock mass due to quarrying; 2) exposure of ribbon cherts with slake prone shale interbeds; 3) the presence of a slope parallel shear zone 30 to 40 feet below the ground surface; and 4) intense rainfall episodes. Rapid slaking and swelling of the exposed shales results in accelerated weathering, fracturing, and dilating of the rock mass. The areas most susceptible to rocksliding appear to be those oversteepened slopes underlain by ribbon cherts that have high shale to chert ratios (between 25% and 50%).

Mitigation

Due to the high level of rockslide and rockfall hazards to downslope residential units, we recommended and monitored construction of several mitigation measures to reduce site hazards. A temporary rockfall catchment fence was constructed along the base of the slope. The wall consisted of steel H-beams, steel cables and wire mesh. The former quarry wall was graded to produce a uniform hillside at a slope inclination of 51°. The uppermost portion of the rock face was supported with a combination tieback and reinforced shotcrete retaining system. Tiebacks were installed at maximum 10 feet on centers. Reinforced shotcrete belt beams were also constructed at horizontal and vertical intervals across the remainder of the slope face and attached to rock anchors. A pattern of dewatering hydraugers was established along the slope face to prevent the buildup of water pressures in the hillside. Wire mesh netting was installed along the exposed rockface to reduce the rockfall hazard to structures and pedestrians below.

STONERIDGE DEVELOPMENT

Site Setting and History

The Stoneridge residential development is located at a former quarry site in a region of moderately steep foothills along the northwestern flank of San Bruno Mountain within the southernmost portion of San Francisco. Quarrying activities dating back to approximately 1940 resulted in precipitous cut slopes that form a north-facing, semi-circular bowl approximately 560 feet in diameter. The Stoneridge development was constructed in the early- to mid-1990s on the former quarry floor with some residential structures located as close as 8 feet from the toe of surrounding quarry slopes (Figure 4). Significant rockfall hazards were apparently not recognized and no mitigation was developed during initial design of the project.

Multiple rockfalls during the winter of 2001/2002 resulted in the evacuation of a relatively new condominium building of the Stoneridge development. No protective barriers or walls were in place along the base of the steep slopes to help control slope debris in 2001. Emergency mitigations, implemented during the winter months of 2002, included light scaling and the installation of a rock catchment fence (nearly 700 feet long and 12 to 15 feet high) located near the base of the slope. CSA was retained to investigate the steep quarried slopes to develop recommended mitigation measures addressing immediate hazards, evaluate long-term static and seismic slope performance, and provide supplemental recommendations as needed.

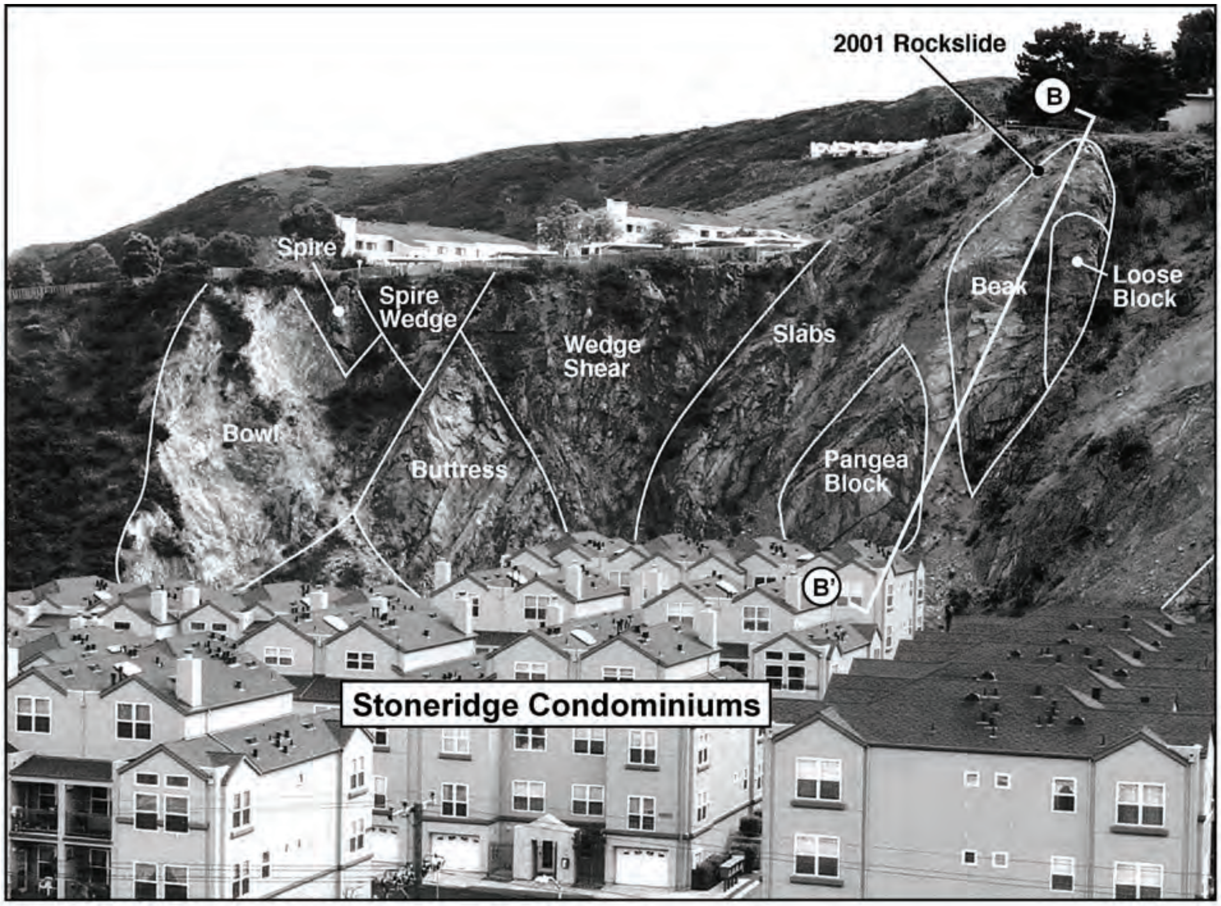

Figure 4. Stoneridge development within former quarry site.

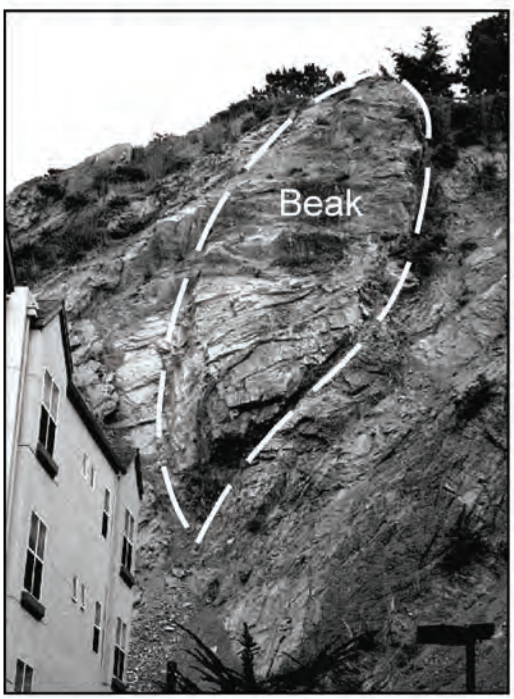

Figure 5. Large sandstone block perched above building.

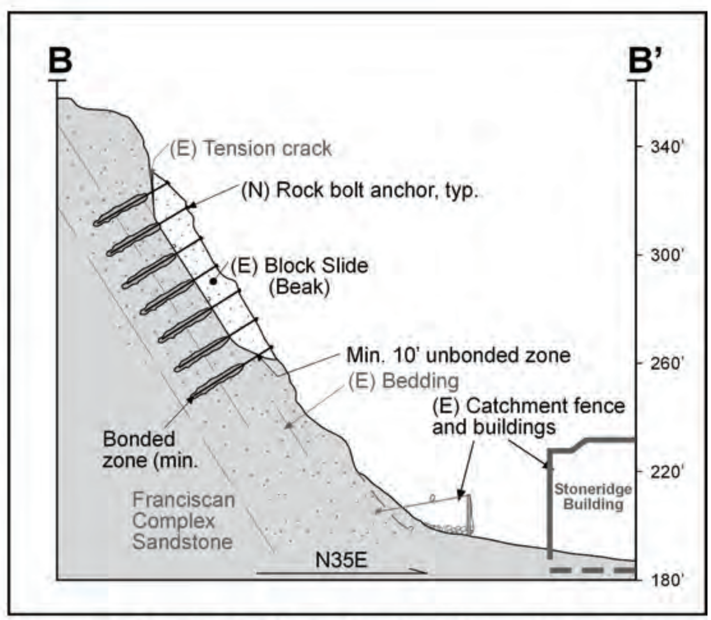

Figure 6. Geologic Cross Section through Stoneridge quarry wall.

Detailed geologic mapping of the entire rock slope was performed to identify priority areas warranting immediate mitigation. This work required rock climbing techniques and over 20 rappels were completed down the quarry slopes to collect rock quality and discontinuity orientation data. Three quarry-slope areas were identified as posing high risks to persons and residential structures. These areas were mitigated in February and March of 2003 by: scaling a large, potentially unstable block; installing 10 rock anchors to secure a second loose block; and installing 4,000 square feet of slope wire mesh netting in an area prone to rockfalls. A monitoring and evacuation protocol program was established during the 2003/2004 and 2004/2005 winter months. The primary purpose of this program was to provide a warning system and evacuation protocol for residents in case of slope instability, particularly during of high intensity rainfall events, which were of special concern.

Site Geology

Interbedded resistant sandstone and pulverized shale of the Franciscan Complex are exposed throughout the quarry (Bonilla, 1971). Cut slopes range in height from 50 feet to nearly 160 feet, and vary in steepness from 40-degrees to nearly vertical. In general, the steep, southern portion of the quarry contains mostly sandstone with thin shale interbeds. The rock units display very consistent, steep (45- to 67-degree northeast dipping) bedding inclinations in the eastern and western portions of the quarry.

During our analysis of historic aerial photographs, evidence of several past quarry wall failures was observed. The majority of these slope failures occurred along the southern and southeastern portions of the quarry. Quarry blasting likely fractured and weakened the rock contributing to slope failures. Observed failures varied from shallow rock and soil slides to deep-seated rockslides. More recent rockslides and rockfalls have been documented in 1974, the mid-1980s, 1998 and 2001. Rockslides occurred in the southern and southwestern portions of the quarry cut and generally appear to be shallow (less than 3 feet in thickness). We understand that some of the past rockslides occurred during relatively heavy rainfall events. The primary types of past slope instability include shallow rockslides along the upper portions of the steep quarried slopes, rock topple and rockfalls.

Hazard Assessment

Shallow rockslides and rockfalls are relatively common along the upper portions of the quarry slopes, and were responsible for the December 2001 Stoneridge evacuation. The site investigation revealed the potential for deep rocksliding of large resistant sandstone blocks, such as a large block referred to as 'The Beak' that was identified during our detailed geologic mapping (Figure 5). The Beak has a calculated volume of approximately 1,000 cubic yards and has not been exposed to violent seismic ground shaking to date. During the 1989 Loma Prieta earthquake, the site likely experienced maximum ground accelerations of approximately 0.10 to 0.15g (Borchert and Holzer, 1994). The property is located approximately 4.6 miles from the active San Andreas fault and mean peak horizontal accelerations of at least 0.5g are anticipated (Sadigh, 1997). Dynamic site response could potentially result in topographic amplification and maximum rock accelerations near the rim of the quarry exceeding 1.0g. Considering that The Beak displays evidence of recent movement, we concluded that this block has a high potential to fail during a nearby strong seismic event thereby exceeding the capacity of the existing catchment fence (Figure 6).

In order to estimate the trajectories, velocity, bounce height, and runout distances of rocks at the existing catchment fence location, we used the "Colorado Rockfall Simulation Program, Version 4.0" (CRSP, Jones, Higgins and Andrew, 2000). The CRSP estimates rockfall bounce heights, velocities and kinetic energies at a specified analysis point. The results are dependent on the slope profile, the material properties of the slope and the material properties of the individual rocks comprising the rockfall. Due to the number of variables used by CRSP and the complexity associated with rockfall events, it is generally desirable to perform field rockfall tests at a project site in order to better calibrate the CRSP program. We observed (and recorded with video cameras) scaling of loose rocks during interim remedial measures. Collected data was utilized to check CRSP program results for consistency with the behavior of observed rockfalls. Rockfall simulations reveal that along the steeper areas of the quarry slopes there is a potential for a small percentage of rockfalls to follow trajectories that would clear the existing 12- to 15-foot high catchment fence and impact the adjacent condominium building.

Mitigation

To reduce the hazards to residential facilities at the toe of the slope, we recommended in 2005 that supplemental mitigation measures be implemented including additional light scaling of select slopes, installation of an additional 20 tensioned, double corrosion protected rock anchors (50 kip capacity) to secure a large incipient block failure (The Beak), application of wire mesh slope netting on select slopes to reduce rock bounce heights, and adoption of a periodic inspection schedule to monitor slope conditions and the performance of installed mitigation measures. Total estimated cost for the completion of supplemental recommended mitigation measures was $700,000 in early 2005.

Summary

Development near quarried slopes must be approached with caution and be based on detailed geologic and geotechnical investigations. It would be prudent to assume that most west coast quarries may contain graded slopes that have not had sufficient time to reach long-term states of equilibrium. Impacts of progressive weathering of recently exposed rock faces should be considered. The ribbon chert rockslide failures at Knockash Hill provide a valuable case study of the mechanisms of slope failure of ribbon cherts in an oversteepened quarry face. Shale to chert ratios should be measured to assist in the identification of potentially unstable slope areas. Many quarry slopes have not yet been subjected to major local earthquakes and analysis of stability under seismic conditions should be completed when evaluating residential development of former quarries. Impacts of topographic amplification of seismic ground motions should also be considered. Analysis of historical aerial photographs often provides an instructive record of past slope performance. Inadequate recognition of site hazards is often associated with incomplete characterization of geologic conditions leading to inappropriate mitigation design.

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