Characterization and Stabilization of Reactivated Ancient Landslide, Soledad Mountain Road, La Jolla, California

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ABSTRACT: Soledad Mountain Road transects Mount Soledad and provides one of the major accesses to La Jolla, California serving over 10,000 vehicles per day. On October 3, 2007, a catastrophic slope failure occurred along Soledad Mountain Road, destroying four homes and 61 meters of roadway and isolating eight homes from roadway access.

Ancient bedding plane landslides were largely unrecognized as potential hazards during design and construction of residential subdivisions in the 1950's and 1960's in many areas of southern California including Mount Soledad. Consequently, numerous hillside developments rest over these ancient landslides which may re-activate decades after construction. The Soledad Mountain Road failure was part of an ancient landslide unidentified during residential construction in the early 1960's. It is concluded that creep along the basal shear plane occurred as a consequence of the grading operation that removed much of the landslide's toe and eventually weakened the clay to the point of mobilization.

Landslide characterization included downhole geologic logging of large diameter boreholes. Stability and deformation analyses were performed with Limit Equilibrium stability programs and Finite Element modeling. Landslide stabilization included 119 shear pins up to 1.8 meters in diameter and 24.4 meters in depth and geosynthetic reinforced soils.

BACKGROUND

Soledad Mountain Road provides one of the major accesses to the community of La Jolla within the City of San Diego (City) serving over 10,000 vehicles per day. Pavement cracking and waterline breaks first were discovered around March and July 2007, respectively, within the 5700 block of Soledad Mountain Road. Initially, distress features were not linked to landsliding and were repaired as part of normal street and utility maintenance. However, over the course of several months additional distress features were noted by City crews including asphalt pavement cracking, sidewalk joint separations and water and gas line utility separations. These features indicated a headscarp condition forming within Soledad Mountain Road and adjacent properties. Simultaneously, a bulge in the suspected toe area of the landslide was developing along Desert View Drive Alley which parallels Soledad Mountain Road approximately 17 meters lower in elevation.

In early October 2007, officials contracted a geotechnical consultant to develop a mitigation plan to stabilize the roadway. It was recognized that, due to private property access restrictions, the stabilization would likely consist of Cast-In-Drilled-Hole-Piers (CIDH shear pins) within the City Right-of-Way. As precautionary measures, the water main within this portion of Soledad Mountain Road was shut down and then high-lined along the edge of the street, the sewer main within Soledad Mountain Road was video surveyed and pavement cracks were sealed.

Design of the shear pins required characterization of the landslide through subsurface investigation. The consultant coordinated with City officials to develop an exploration plan to identify the landslide geometry, movement depth and velocity, soil properties and groundwater conditions. The first phase of investigation was initiated immediately and included small diameter (200 mm) boreholes and installation of vertical slope inclinometer casings through the landslide basal rupture surface. By October 2, 2007, continuing progression of distress led officials to notify homeowners within the affected area not to sleep in their homes in case of acceleration of movement. On the morning of October 3, 2007, the second day of subsurface investigation, the landslide catastrophically failed, destroying four homes, displacing approximately 61 meters of roadway, snapping overhead power lines and severing utility lines. The failure mass slid east covering Desert View Drive Alley burying one home and isolating eight homes from roadway access. Homes surrounding the landslide were evacuated through door to door searches and through public announcement from helicopter. Fortunately, no fatalities or injuries occurred as a result of the event. The California Governor visited the site of the landslide and declared it a natural disaster which ultimately enabled State and Federal funding assistance for roadway repairs.

Following the landslide event and attention to immediate public safety issues, the subsurface investigation was modified to first acquire sufficient data to develop measures to prevent expansion of the failure area, secondly to stabilize Soledad Mountain Road sufficiently for vehicle access and thirdly to develop stabilization measures to reopen Desert View Drive Alley. Exploratory drilling, surface and downhole logging and sampling were performed nearly around the clock during the early portion of the project.

SITE DESCRIPTION

Located north of downtown, Mount Soledad is one of San Diego's most prominent land features rising over 244 meters above sea level situated between Interstate 5 to the east and the Pacific Ocean to the west. Mount Soledad essentially consists of a north-south trending ridge. Soledad Mountain Road roughly parallels the axis of the ridge. The site is located on the eastern flank of Soledad Mountain south of the summit. To the east, a steep slope descends approximately 122 meters to Interstate 5. Gradients on the ungraded portions of this slope (east of Desert View Drive) range from 1 to 1 to 2 to 1 (horizontal to vertical). The upper portion of the slope (west to east) is occupied by residential development along Soledad Mountain Road, Upper Desert View Drive (Desert View Drive Alley) and Lower Desert View Drive. These streets are subparallel and oriented in a general north-south direction in the study area, and are separated by 17 meters in elevation (Soledad Mountain Road to Desert View Drive Alley) and 11 meters in elevation (Desert View Drive Alley to Lower Desert View Drive).The approximate location of the site is shown on the Site Location Map (Figure 1). An aerial view of the landslide and adjacent slopes is presented on Figure 2. The study area generally involves the roadways at the 5700 block of Soledad Mountain Road and the 5700 block of Desert View Drive Alley.

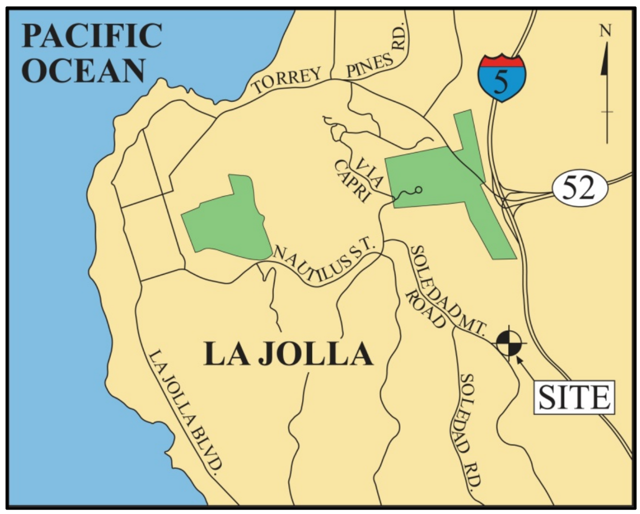

FIG. 1. Site Location Map

GEOLOGY

Geologic mapping for this study as well as published geologic maps (Kennedy, 1975) indicate the site is underlain by the Ardath Shale, a sedimentary unit consisting of dense, light brown to gray, very fine sandstone, siltstone, and claystone. This unit is underlain by the Eocene Mount Soledad Formation consisting of massive to thickly-bedded, moderately well-cemented, cobble conglomerate and interbedded sandstone. To the east and north of the site, the Ardath Shale is overlain by Pleistocene marine terrace deposits consisting of reddish brown, medium-grained sandstone and cobble conglomerate

The site lies near the crest of the Mount Soledad anticline, a broad, asymmetrical fold resulting from compressional forces that developed along a bend in the Rose Canyon Fault Zone (Figure 3). Bedding attitudes shown on the geologic map of the La Jolla Quadrangle (Kennedy, 1975) generally indicate low to moderate dips of from 10 to 16 degrees to the east and southeast. These attitudes are in general agreement with the findings of the study that indicate the predominant dip direction is to the east and southeast at inclinations of 5 to 20 degrees.

A common structural feature observed in large-diameter borings excavated during the study are bedding plane, or bedding parallel, shears. These features are ubiquitous in the borings and seem to occur at near regular intervals of 6 to 9 meters. These features can be the result of flexural slip along bedding surfaces as adjacent brittle sediments are tilted by tectonic forces or they can result from lateral stress relief in the walls of deep canyons where erosion has unloaded over-consolidated claystones or clay shales. On Mount Soledad where tectonic folding has occurred they are most likely the result of flexural slip faulting.

Bedding parallel shears are one of the most important preparatory factors in the bedrock that lead to high landslide susceptibility. The other major factor in landsliding is the direction and degree of tilt in the bedding (bedding attitude). Where bedding is steeply inclined toward the face of a natural or man-made slope there is a high risk of landsliding. Translational landslides that fail along bedding planes are dependent primarily on the magnitude of bedding tilt (dip), shear strength along bedding surfaces, and groundwater conditions.

Commonly, groundwater is encountered perched above sheared clays defining the basal rupture surface of reactivated ancient landslides. However, free groundwater was generally absent within the landslide during the geotechnical investigation.

FIG. 2. Aerial View of October 3, 2007 Landslide
Photo From Geo-Tech Imagery Intl.

FIG. 3. Mount Soledad Faults
Base Photo From Geo-Tech Imagery Intl. (Annotation Added)

Review of stereo-pairs of aerial photographs (San Diego County, 1928; U.S.D.A, 1953) indicates the presence of pre-historic landslides in the area of the October 3, 2007 landslide. The landslides are most apparent on the 1928 San Diego County photographs. By 1953 these landslides were more subdued and difficult to discern as a result of the development of unpaved roads and erosion.

On the 1928 County of San Diego photographs, a relatively small, well-defined pre-historic landslide can be observed as a superposed feature within a larger more subtle and highly eroded landslide. The northern limb of the larger slide as estimated from the aerial photographs extends an undetermined distance to the north of the October 3, 2007 landslide. The toe of the larger landslide could not be determined from a study of the photographs or topographic maps, but apparently extends to a significantly lower elevation than the smaller slide. Evidence of this larger landslide was observed in several of the exploratory borings and shear pins placed in and near the west side of Soledad Mountain Road and north of the headscarp.

The smaller superposed landslide is manifested by an erosionally altered, arcuate, pull-apart basin or graben area and indistinct toe. By comparing the landslide limits on the 1928 aerial photographs with pre-development and post-development topographic maps it was noted that the limits of the October 3, 2007 landslide are nearly identical to the mapped limits of the smaller pre-historic slide. This conclusion was confirmed by geologic mapping of the landslide scarp exposed after the October 3, 2007 landslide occurred. For example, the northern portion of the scarp that formed perpendicular to Soledad Mountain Road exposes an older high-angle landslide slip surface that was not reactivated during the recent landsliding. In addition, several areas containing breccia-filled fissures that could have only formed during previous landsliding were observed on the scarp face. The southern limb of the October landslide is nearly coincident with a major zone of faulting exposed by several of the shear pin excavations.

The recent landslide can be classified as a re-activation of a pre-historic translational bedrock landslide that originally failed along bedding plane shears in the Ardath Shale that dip easterly toward Desert View Drive. The landslide is readily apparent in predevelopment aerial photographs. Later aerial photographs and comparison of pre-development topography with post-development topography indicate that the toe of the landslide has been partially removed by subdivision grading resulting in a slightly steeper slope configuration than the natural (pre-development) slope.

HISTORICAL SITE GRADING

Grading for Soledad Mountain Road occurred between 1953 and 1961. Grading for the adjacent subdivision, Soledad Corona Estates (lots immediately east of Soledad Mountain Road) occurred in 1960-1961. During construction of homes in 1961 along south Desert View Drive and along the east side of Soledad Mountain Road immediately south of the October 3, 2007 slope failure, a larger landslide occurred (December 14, 1961) that extended approximately half way across Soledad Mountain Road and encompassed several building pads and the descending slope area east of Soledad Mountain Road. At least eight homes under construction were destroyed. Based on review of an oblique aerial photo taken in 1961 (San Diego Historical Society), the toe of the landslide extended through the slope to just above Desert View Drive (Figure 4). The toe area of the slide on the northern flank appears to have transected the lower portion of the slope of the property at 5695 Soledad Mountain Road coinciding with the southerly boundary of the 2007 failure.

Design grading plans indicate that the 1961 landslide area was re-graded circa 1967. The grading (mostly within Soledad Corona Unit 3) was performed as part of improvements for a private road (Desert View Drive Alley) and included remedial grading (primarily drainage improvements and re-contouring) for the 1961 landslide area, grading of the central portion of the landslide into a very gently sloping large pad with a fill slope descending to Desert View Drive at Lots 26 to 34 (currently 5734 to 5638 Desert View Drive Alley). The pad area later became building pads for Lots 26 through 34 and the southerly end of the alley roadway.

The initial subdivision grading in 1961 apparently created slopes behind 5695 to 5735 Soledad Mountain Road at an average inclination of 1.5 to 1 (horizontal to vertical) or steeper. During the re-grading of the subdivision after the 1961 landslide (circa 1967) the backyard slopes at 5695 to 5735 Soledad Mountain Road were flattened to approximately 1.8 to 1 (horizontal to vertical).

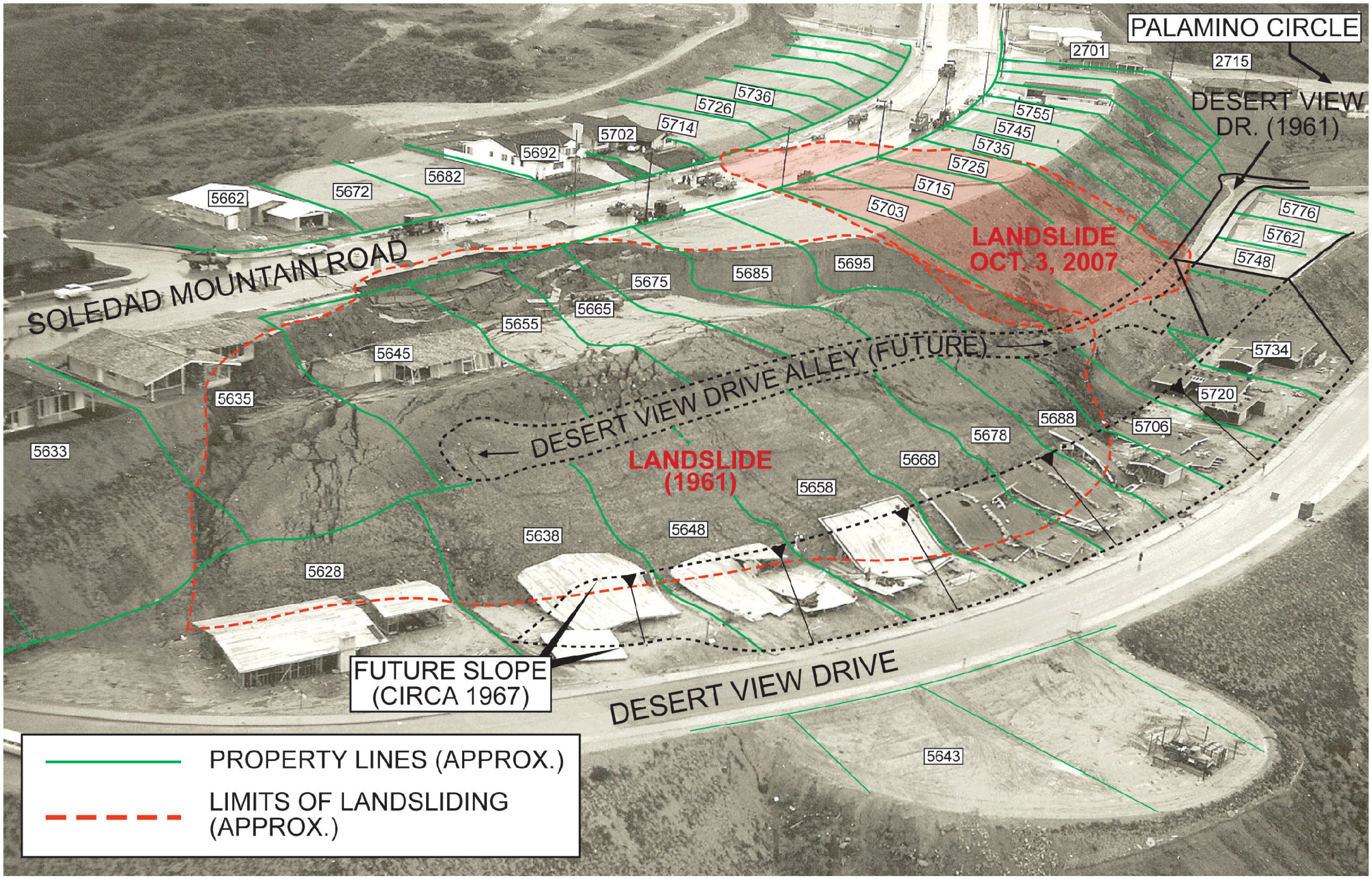

FIG. 4. 1961 Aerial Photograph
Base Photo From San Diego Historical Society (Annotation Added)

DISTRESS FEATURES AND PROGRESSION OF LANDSLIDE FAILURE

After the landslide failure (October 3, 2007), it was determined that minor pavement repairs within Soledad Mountain Road, within the landslide area, were performed beginning in March 2007 and waterline repairs were performed beginning in July 2007. Waterline repairs were reportedly to pull-apart separations where service lines met the main. Several gas line services were also repaired prior to the failure.

Foundation distress at a residence on the north margin of the landslide had been noted by a geotechnical consultant in August of 2007. The distress included minor exterior stucco cracks and footing cracks and separation of the chimney from the house (approximately 25 mm). Also noted was damage to the stucco at the garage (cracks up to 38 mm), heaving of the garage floor slab, separation of the garage footing from the floor slab and a separation between the garage slab and the driveway of 25 to 50 mm. The consultant's report also mentioned that a portion of the concrete driveway adjacent to the garage had been replaced approximately 3 ½ years prior to 2007 site inspection. The distress noted in the consultant's report had been generally attributed to a combination of soil expansion and differential settlement.

Several days before the October 3, 2007 failure, distress features at the margins of the landslide became more pronounced and bulging at the toe of the landslide contributed to a leak in a fire hydrant on the west side of the alley. The most significant distress features were in the aforementioned residence and the north boundary of the landslide within Soledad Mountain Road. It was later discovered that the northern margin of the landslide was defined by a clay-lined high angle shear, possibly a fault splay.

The landslide failed at approximately 8:50 am on October 3, 2007. A sudden drop of the pavement of approximately 15 mm occurred across the head of the landslide at Soledad Mountain Road followed by snapping of power lines. Several minutes elapsed prior to the major episode of displacement that resulted in translation of the residential structures 5703 to 5725 and rear yard slope approximately six meters toward the east and a drop in elevation in the street and building areas (5703 to 5725) of approximately three meters. Run-out at the toe area buried the front of the residence at 5734 Desert View Drive Alley and the alley was covered with up to 4.6 meters of landslide debris from the north end of 5720 to the south end of 5748. A free-standing wall at the east side of the alley at 5748 was also covered with landslide debris. The limits of the landslide are shown on the Geologic Map, Figure 5. A photograph of the landslide after the failure is shown on Figure 2.

FIELD EXPLORATION AND LABORATORY TESTING

Field exploration included field reconnaissance and geologic mapping of landslide features; and drilling, logging and sampling of trenches, test pits, small and large diameter borings. Borings were drilled with truck-mounted and track-mounted rigs and portable tripod rigs. Immediately after the failure, work hours extended into the night and weekends to allow rapid accumulation of subsurface data. Large diameter borings were downhole logged by geologists. A number of the small diameter borings included the installation of instrumentation consisting of slope inclinometer casings and piezometers. Representative samples of the soils encountered during the drilling and logging of the exploratory borings and test pits were obtained. Laboratory tests performed included moisture and density, Atterberg limits, gradation, direct shear, remolded direct shear and residual (ring) shear, specific gravity and chemical tests.

ANALYSIS

Stability analyses were performed using a 2-Dimensional Limit Equilibrium method. The XSTABL computer program was used for the analyses. Final runs included a Spencer's Analysis was performed to satisfy equilibrium conditions. The analyses included consideration of failure along the well-developed, sheared clay seam that defines the basal rupture surface of the October 3, 2007 landslide and a slightly deeper shear surface which is interpreted as an ancient landslide slip surface. These two surfaces are depicted on the geologic cross section (Figure 6). Final factors of safety were calculated using a Spencer's analysis which satisfies all conditions of equilibrium.

Rupture surface parameters (for the active landslide) were back-calculated using the configuration of the active landslide as delineated on the geologic cross sections assuming a factor of safety of 1.0. Strength parameters of phi = 25 degrees and c = 9.6 kPa were utilized in the analysis to represent landslide debris strengths with a lower (anisotropic) strength of phi = 20 degrees and c = 0 kPa in the range of 55 to 60 degrees from horizontal. Groundwater was not included in the back-calculations due to the absence of free water in the landslide before and after the failure event.

A rupture surface strength of phi = 9.7 degrees (zero cohesion) was obtained through back-calculation. This friction angle is somewhat higher than laboratory residual shear test results (using a modified Bromhead ring shear device, ASTM D6467) which yielded a friction angle of approximately 7.5 degrees (zero cohesion).

Two-Dimensional Finite Element Modeling was performed for evaluation of pier deflections along the east side of Soledad Mountain Road. Initial calculations were performed considering an open excavation within Soledad Mountain Road during removal of landslide debris. Theoretical deflections were compared with actual deflections measured by inclinometer casings within the shear pins for selection of modulus of elasticity values for retained landslide debris. Subsequent calculations considered the reconstructed roadway upslope of the shear pins and the downslope side of the shear pins both supported by landslide debris and unsupported to the depth of the rupture surface. The unsupported condition was considered in case future private property repairs included removal of remaining landslide debris.

The lower series of shear pins, above Desert View Drive Alley, were designed to resist lateral forces imposed by the remaining upslope landslide mass. Using a two-dimensional limit equilibrium stability analysis, resultant horizontal forces needed to achieve a factor of safety of 1.5 were determined and used to calculate the depth, size, spacing and reinforcement of the CIDH shear pins.

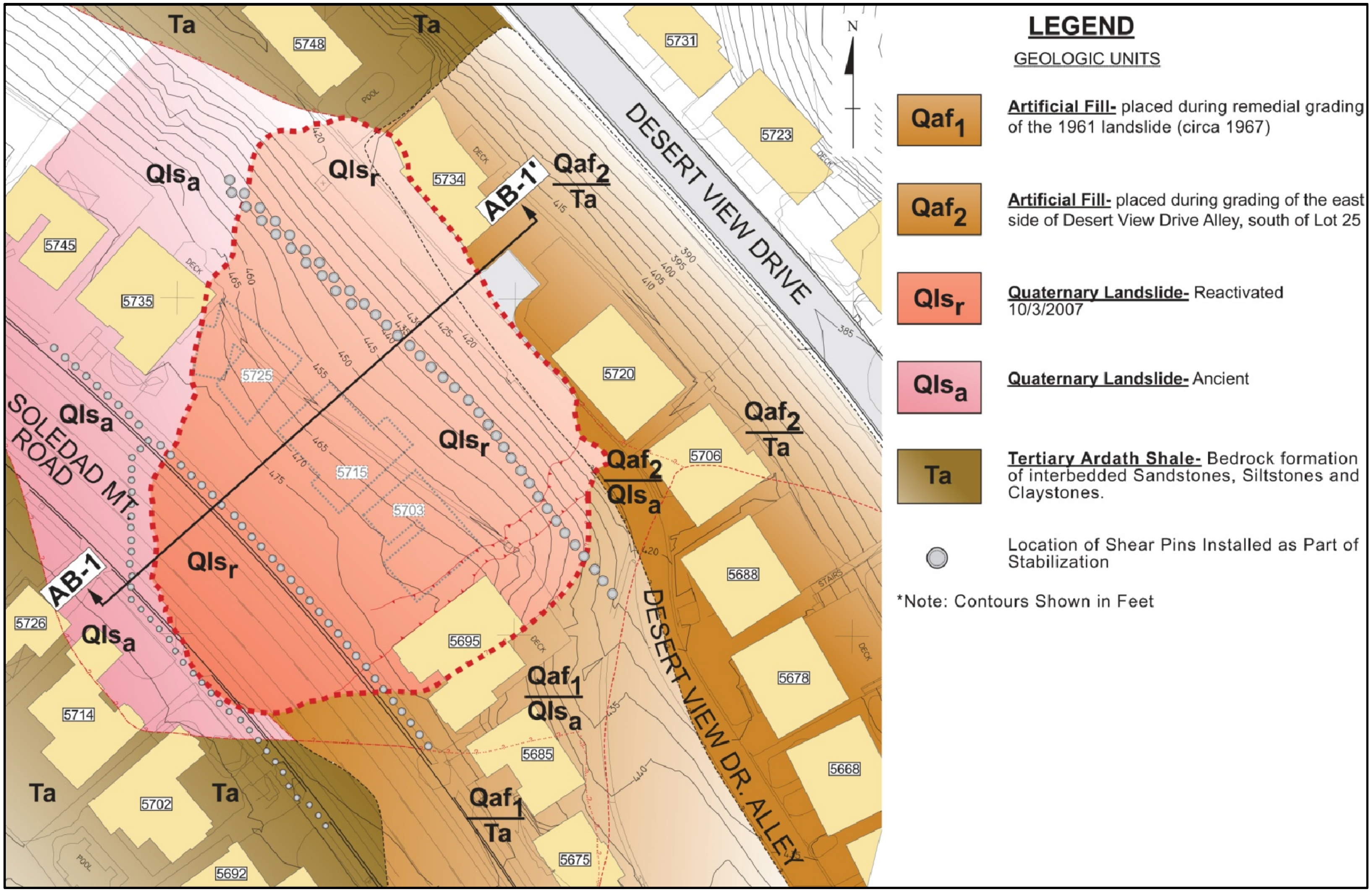

FIG. 5. Geologic Conditions Prior to Repair

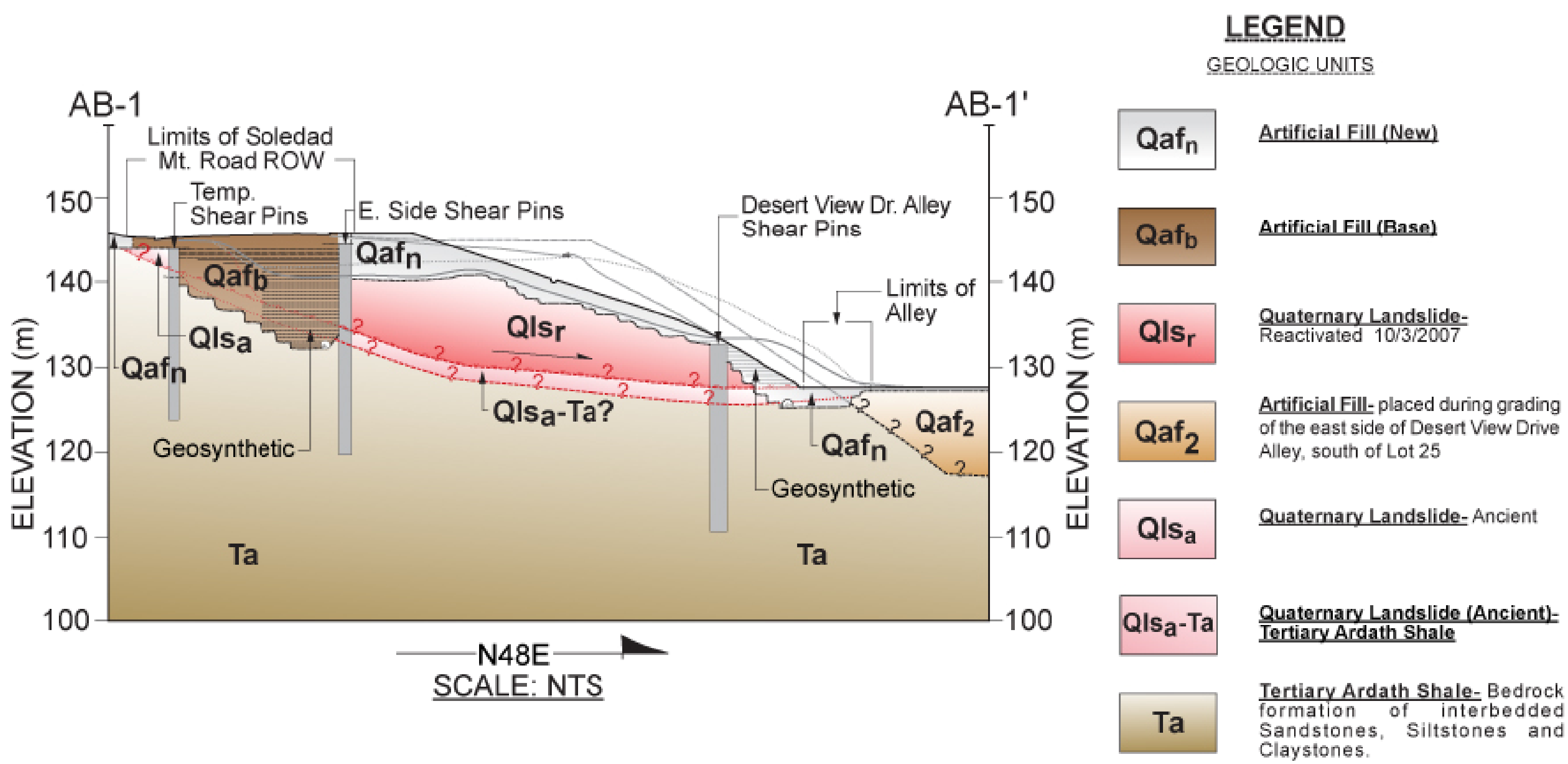

FIG. 6. As-Built Geologic Cross Section

STABILIZATION

Installation of stabilization features are pictured on Figure 7. Slope stabilization and repair of the Soledad Mountain Road Right-of-Way included installation of 75 CIDH re-bar reinforced concrete shear pins, 1.1, 1.2 and 1.4 meters in diameter, installed in two phases. The initial phase of shoring installation occurred along the west and north sides of the landslide mass, and consisted of 37 CIDH shear pins, 1.1 and 1.2 meters in diameter. This phase of shoring was designed for two primary purposes: to prevent westward expansion of the headscarp and associated damage to private property and to allow safe excavation of landslide debris within the right-of-way which would be hindered by existing shear surfaces. The second phase of shoring was installed along the east side of the Soledad Mountain Road Right-of-Way, and consisted of 38 CIDH shear pins, 1.4 meters in diameter. The purpose of this phase of shoring was to provide long-term slope stability of Soledad Mountain Road, to provide safe working conditions during removal and replacement of landslide debris and to support the temporary grade separation that existed between finished grade on the restored right-of-way and the ungraded private lots to the east which had dropped approximately 4.9 meters during landsliding.

FIG. 7. Roadway Stabilization (Looking North)
Photo From Geo-Tech Imagery Intl.

Panel walls with a maximum height of 4.9 meters (top of wall set 1.1 meters below finish grade) were designed between the shear pins to: provide additional retention of soil materials immediately beneath the road and sidewalk grade, allow shallow excavations adjacent to the east side of the right-of-way without impacting the property on the opposite side of the right-of-way and to allow backfilling and compaction against the shear pin wall as part of proposed stabilization efforts.

Following shear pin installation, landslide debris in the Soledad Mountain Road Right-of-Way was removed during a three-slot, phased construction process, and replaced with compacted, engineered fill consisting of geosynthetic reinforced Caltrans Class II aggregate base. Voids were left between piers as fill was brought up to allow mobilization of tensile strength in the geosynthetic. Voids were later filled with gravel backfill. At the base of the fill, subsurface drainage was installed to provide keyway drainage. 150 mm perforated, Schedule 40 PVC pipe surrounded by 1.9 mm washed rock wrapped in filter fabric was tied into a solid, fuse-welded 200 mm HDPE outlet pipe installed and grouted in a sub-horizontal boring. The subdrain outlet was discharged through the east side of the excavation towards Desert View Drive Alley. The curb line, grade and finished road grades were restored to their pre-failure configuration.

Slope stabilization and repair of the Desert View Drive Alley Right-of-Way included installation of 44, 1.8 meter diameter, CIDH re-bar reinforced concrete shear pins, installed in two phases. High driving forces required installation of a double row at the north end below 5725 and 5735 Soledad Mountain Road. The weight of the re-bar reinforcement cages and long reaches required for placement necessitated the use of a 450,000-kg crane set up between two homes on Desert View Drive Alley and supported on a 2.7-meter thick, elevated, reinforced-earth mat.

Following shear pin installation, landslide debris on, and immediately to the west of Desert View Drive Alley Right-of-Way was removed during a phased, three slot-cut construction process, and replaced with compacted, engineered fill consisting of geosynthetic reinforced on-site soils. The central portion of the landslide mass remains on private property between the Soledad Mountain Road Right-of-Way and the Desert View Drive Alley reinforced fill. Subsurface drainage was also installed to provide keyway drainage. 150 mm perforated, Schedule 40 PVC pipe surrounded 1.9 mm washed rock wrapped in filter fabric was tied into a solid, Schedule 40 PVC outlet pipe.

CONCLUSIONS

The Mount Soledad area is known for unstable slope conditions caused by landslides of ancient origin that were unrecognized during early developments in the 1950’s and 1960’s and by sheared bedding planes with out-of-slope dip components caused by tectonic folding. The October 2007 landslide is considered reactivation of an ancient landslide that is identifiable in pre-development aerial photographs. The failure is interpreted to be “block-glide” on a pre-existing ancient landslide rupture surface. The landslide is similar in character to a previous block-glide landslide that occurred immediately to the south in 1961.

Grading was performed on the properties within the recent landslide limits in at least two episodes circa 1961 and 1967. Grading of the subdivision (1961) resulted in removal of materials at both the head and toe of the aforementioned ancient landslide. The grading did not include extensive stabilization such as construction of an earth buttress. Although flattening of the descending slope from the head of the landslide (Soledad Mountain Road) to the toe of the landslide (Desert View Drive Alley) occurred around 1967, the resulting configuration did not result in a significantly more stable condition.

No evidence of significant free water or saturated soils was discovered above the basal rupture surface of the landslide immediately before or after the failure. This observation combined with the occurrence of the failure during a relatively dry period indicates that groundwater was not a contributing factor in the failure. However, years of landscape irrigation and rainfall infiltration may have contributed to softening of the rupture surface.

The catastrophic failure that occurred on October 3, 2007 was the end result of long term creep that was evidenced by displacement along the northern margin of the landslide within the street starting at least as far back as March 2007. Although not originally attributed to landsliding, distress features described in an August 14, 2007 geotechnical report suggest that noticeable landslide distress at 5725 Soledad Mountain Road may have been occurring at least 3 ½ years prior to the catastrophic failure.

Soledad Mountain Road and Desert View Drive Alley in the area affected by the October 2007 landslide have been successfully stabilized by installation of 119 CIDH shear pins and geosynthetic reinforced fill. Future reconstruction on the private properties affected by the landslides will require special foundation and utility design and/or re-grading to address potential displacement issues in remaining landslide debris.

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