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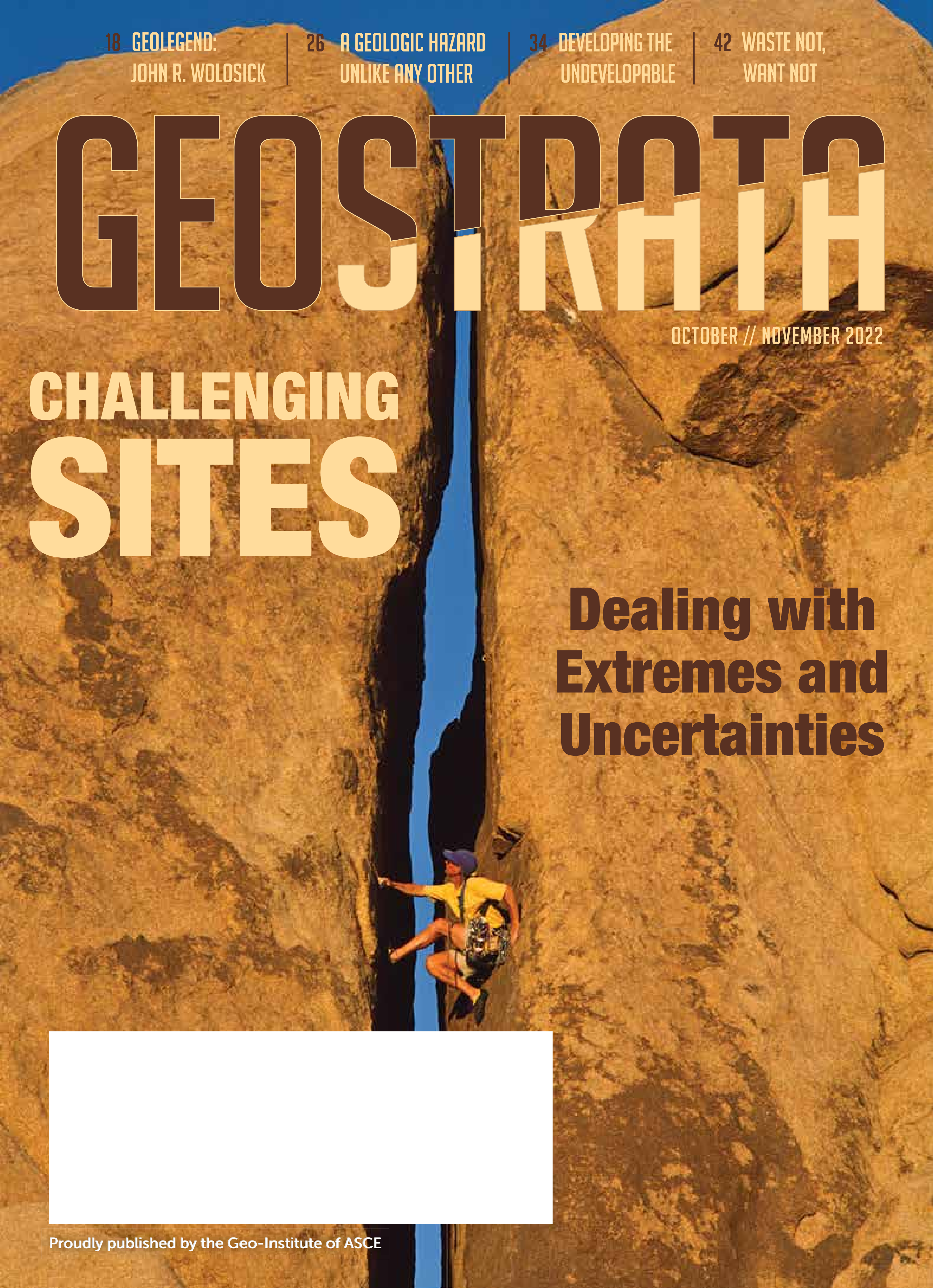

CHALLENGING SITES

Dealing with Extremes and Uncertainties

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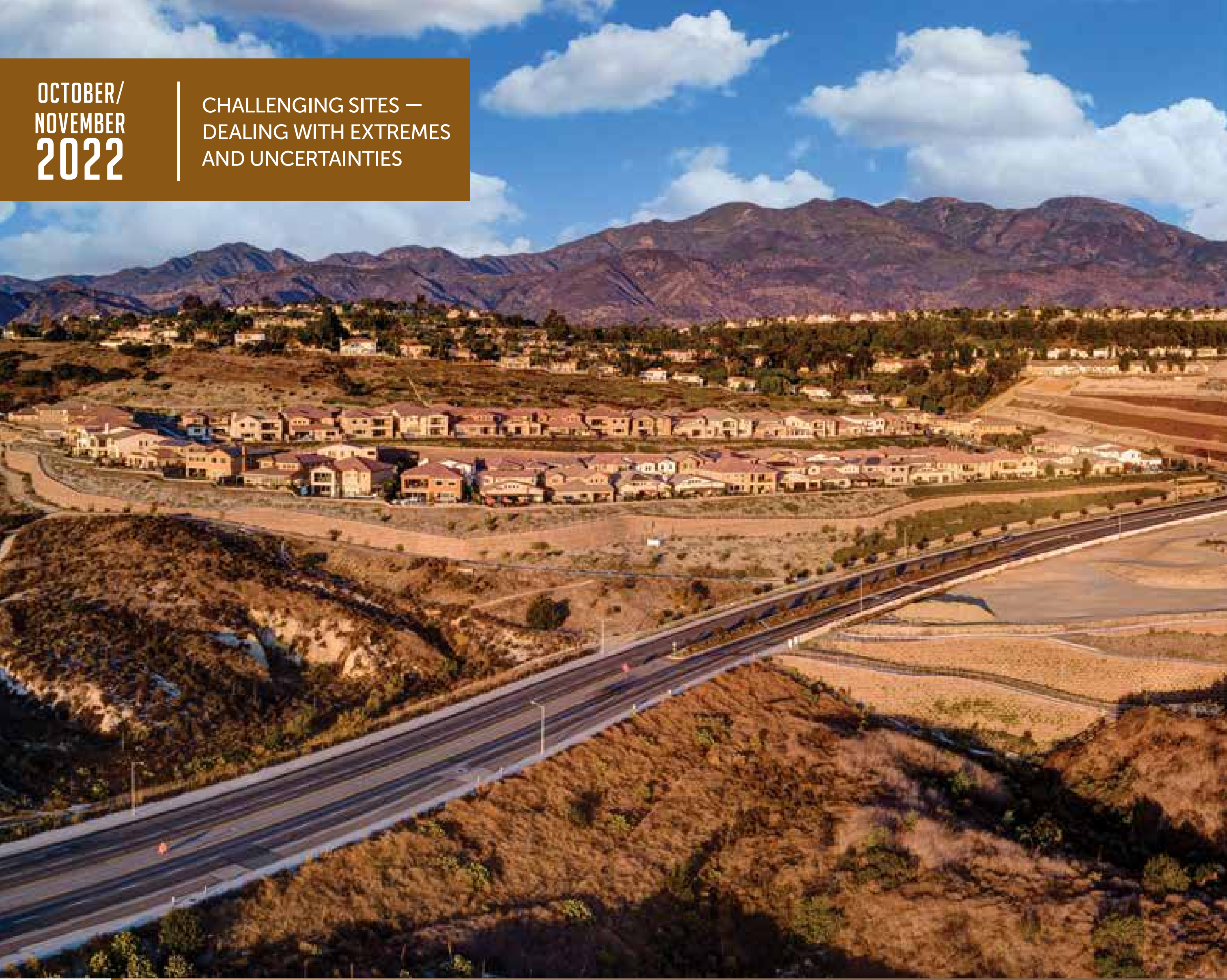

DEVELOPING THE UNDEVELOPABLE

Geotechnical Solutions for Complex Hillside Construction

By Rupert Adams, CEG

The Maginot Line: Perimeter mechanically stabilized earth walls at the Portola Center development. (Photo courtesy of John Carter.)

Not all residential development projects are created equal. Some projects require significantly more patience and fortitude by the developer than others to successfully navigate from land evaluation to sale of the last parcel and home sale. Geotechnically straightforward sites within 50 mi of Southern California's coastline that are large enough to accommodate at least 500, single-family homes, have become a rare and expensive commodity. Increasingly, developers must now consider land previously deemed unsuitable or too expensive for large-scale residential development. Successfully solving the equation of land acquisition, development planning, grading, and home construction has now become an increasingly complex computation.

The 200-acre Portola Center development, located in the eastern reaches of the City of Lake Forest near the Whiting Ranch Wilderness Park, is one such site that necessitated careful navigation of a plethora of geotechnical obstacles that hampered the developer and design team. Situated under an approach path to the former El Toro Marine Corps Air Station, the site is characterized by geologically complex, east-west trending ridge and canyon topography epitomizing the west-facing foothills of the Santa Ana Mountains. The site remained largely undeveloped until circa 1990. Partially graded for commercial use contemporaneously with other residential and infrastructure projects following the City's incorporation in 1991, the site languished for several decades, becoming a de facto recreation area for local residents.

A zoning change finally opened the door for residential development, and the early phases of site evaluation and development planning began in earnest in 2010. The approximately 200-acre site is divided into three gated communities, colloquially referred to as the Portola Northwest, South, and Northeast. Although separate communities, all three are underlain by the same set of complex geologic conditions that provided the primary driving force behind a shared design goal: how to physically and economically counterbalance adverse geologic conditions to develop something that was previously considered undevelopable?

Figure 1. Slickensided remolded clay on a hard siltstone bed at the base of a backcut failure headscarp during buttress excavation.

Many Hazards... One Focus

Engineering design, and the analyses on which it's based, is only as good as the input parameters. A clear understanding of site geology and geologic hazards is crucial to the creation of an accurate model for use in making design decisions. Like any site in Southern California, consideration must be given to potential geologic hazards that may affect the site, such as strong seismic shaking, landslides, liquefaction, settlement, corrosivity, and expansion potential. Many of these hazards impacted the design of the development; however, slope stability issues inherent to the Puente Formation, the geologic formation underlying the entire development, were most challenging to evaluate and mitigate.

The Puente Formation, a contemporaneous cousin of the more well-known, landslide-prone Monterey Formation, is a middle to late Miocene-age marine sedimentary unit consisting of interbedded sandstone and highly fissile siltstone and claystone. Known for its diverse paleontological assemblage and high diatomaceous content, certain members of the Puente Formation also possess an infamous association with pervasive, remolded, bentonitic clay seams. Thought to be derived from chemical alteration of pyroclastic material, remolded-clay seams have a consistency ranging from well-worn shoe leather to toothpaste, making them an unwelcome bedfellow for a hillside development project. Coupled with a westerly dip of 18 to 32 degrees resulting from complex tectonic folding, faulting, and uplift during the last 4 million years, and pre-Holocene extensional faulting on the nearby Cristianitos Fault, the remolded-clay seams, or "bedding parallel shears" in slope stability parlance, were identified as the geologic hazard du jour from a geotechnical engineering design standpoint.

Geologic Unit/Material	Density (pcf)	Cohesion (psf)	Friction Angle (deg)
Compacted Fill/Engineered Fill (Qcf/Afe)	120	500	28
MSE Wall Backfill (MSE)	120	500	32
Alluvium (Qal)	120	500	23
Terrace Deposits (Qt)	120	300	29
Puente Formation-Soquel Member (Tps)	125	400	33
Puente Formation-Soquel Member (Tps) [Seismic]	125	800	34
Puente Formation-Soquel Member (Tps-slt)	115	400	33
Puente Formation-Soquel Member (Tps-slt) [Seismic]	115	900	30
Puente Formation-La Vida Member (Tplv)	115	400	33
Puente Formation-La Vida Member (Tplv) [Seismic]	115	900	30
Puente Formation-Soquel Member/La Vida Member along Bedding (Tps-slt/Tplv along bedding)	115	250	24
Bedding Plane Shear (BPS)	115	30	9
Bedding Plane Shear (BPS) [Seismic]	115	125	12

Table 1. **Summary of soil properties used for slope stability analyses at Portola Center Northwest, South, and Northeast.**

Modeling… Clay?

Evaluation of the slope stability hazard posed by the remolded-clay seams within the interbedded siltstone and claystone members of the Puente Formation began during the early design phases of the project. Fieldwork included drilling and logging 91, small- and large-diameter borings and excavating 42 test pits. Structural-geologic data collected during downhole logging of large-diameter borings and geologic data gleaned from older reports from surrounding neighborhoods were distilled to create over 50 geologic cross-sections for slope-stability analysis for the proposed development — a lot by any measure. Due to the inherent difficulty in accurately tracing geologic features that are often as thin as a few sheets of paper over long distances, it was very difficult to determine an exact count of BPSs affecting project design. BPSs are comparable to sliced Swiss cheese: continuous, but not necessarily present at all boring locations penetrating the same stratigraphy. In the end, 12-14 near-continuous BPSs were identified, ranging in thickness from paper thin to about 2-in. (Figure 1).

Despite the comprehensive, upfront geologic analysis, the investigative process did not end with commencement of grading and construction activities. The geologic model was regularly updated throughout construction as transient grading-related geologic exposures were evaluated and investigated, providing information crucial in refining, resizing, and repositioning stabilizing buttresses and shear pins. In all, a total of 34 additional large-diameter borings were drilled and logged during grading, in areas previously inaccessible without earthmoving equipment, or at elevations well below pre-grading topography, to examine stratigraphy beyond the reach of borings drilled from original site grades. The client's support of supplemental investigation and analysis resulted in a reduction of buttress depth and volume on several occasions.

The Cycle of Stability

When afflicted with the uncomfortable triad of large-volume cut and fill grading, multitiered wall/slope combinations, and unfavorable, westward-dipping geologic structure, slip-sheeted with numerous remolded-clay seams, the prescribed analytical approach was a heavy dose of block- and rotational-mode stability analyses. Material shear strengths for the on-site geologic units (Table 1) were derived from a robust testing program of undrained direct

Figure 2. **Shear pin construction along the northern boundary of Portola Northwest, adjacent to Whiting Ranch Wilderness Park.**

shear testing performed on approximately 40 split-barrel samples selected to represent the on-site soil types. For comparison, shear tests were also performed on selected block samples collected from test pit excavations. For remolded-clay seams, estimated strengths were evaluated through shearing of fully softened paste mixes and by comparing Atterberg limit values and clay fraction grain-size analysis with tabulated data from the literature.

These material strengths were utilized in the geologic cross-sections compiled using investigation and construction mapping data. Rotational and block slope stability analyses were performed using limit-equilibrium methods available in common commercial software. The analysis considered the BPS shear strength and geometry to calculate the factor of safety for the proposed wall/slope configurations and the most adverse geologic structure in a given area.

If either the calculated static or pseudo-static values of FOS was less than 1.5 and 1.1, respectively, stability buttresses were designed to interrupt remolded-clay seams at varying depths until calculations indicated the proposed slopes possessed an adequate FOS. In the most complex case, a single buttress was stepped at various intervals over a horizontal distance of approximately 1,200 ft, to interrupt five different BPSs. Where limited by property boundary conditions, existing off-site improvements, or because excavation to exposure depths was impractical, shear pins were evaluated to determine the design resistance needed to increase the FOS to an acceptable level (Figure 2). Grid lengths for the proposed MSE walls were increased where necessary to increase the FOS for potential failures through or behind the reinforced zone.

The slope stability evaluation process for the Portola project was somewhat of an analytical Möbius strip: a never-ending cycle of engineering evaluation to model subtle changes in geologic structure diligently recorded by the engineering geologist. At steeper dip angles within the formational units, a change of one or two degrees in dip on a geologic cross-section can have a profound effect on the FOS, buttress width, MSE wall reinforcement length, and/or shear pin design loads. For example, detailed mapping of a broad synclinal fold identified in initial buttress excavations often resulted in substantial increases to future buttress widths, when updated geologic cross-sections depicting variable dip angles measured on different sections of the fold limbs were reanalyzed. To design for the uncertainties, the most geologically onerous portions of the site were represented in cross-section using modal dip angles projected over wider areas to strike a suitable balance between engineering conservatism and constructability. This approach was augmented by keyway excavations that were typically wider and deeper than necessary to facilitate safe and efficient operation of excavation equipment. In the end, close coordination between the design team and near-real-time slope stability analyses were pivotal in evaluating if the finished product had been properly engineered to reflect the underlying geologic and as-graded conditions, which in many cases differed from those conceived during initial project investigation phases.

Figure 3. A typical day of buttress grading… another backcut failure along a remolded clay seam during buttress grading on Portola Northeast. (Photo courtesy of John Carter.)

Backcuts and Buttressing

The obvious consequence to a project design using tall MSE wall/slope combinations to reform steep, westward-sloping terrain into level building areas is a substantial change to the mass balance of the site. Dramatically changing the mass balance using a methodology designed to create maximum buildable space atop far-from-ideal geologic conditions is akin to playing geologic Jenga, i.e., it's risky. So, to come as close to eliminating the risk of slope instability in the project design as practical, heavy investment in geotechnical stabilization measures was necessary to offset potential failure along multiple, steeply dipping remolded-clay seams… the proverbial "banana peel" of Tertiary marine sedimentary formations. The result was 16 separate stability buttresses requiring remedial grading on the order of 1.25 million cu yds, and one single- and one double-row of vertical shear pins constructed in 60-in.-diameter drilled shafts extending up to 65 ft in length (Figure 2).

The challenge of backcutting the landscape for construction of stability buttress and shear pins was a "downhill" struggle. In some cases, as many as five BPSs were exposed in cut slopes before the target buttress depth was reached. Cuts 2H:1V or steeper were typically unstable, and planar failures along remolded-clay seams occurred almost daily (Figure 3). Flatter 3H:1V backcuts approximating dip slopes were attempted to improve excavation stability and safety, but even those occasionally failed. Buttress slot-cutting techniques were used to limit the size of potential backcut failures above the deepest keyway excavations (Figure 4). In the end, preventing backcut failures proved futile, so a two-steps-forward, one-step-back grading procedure became the norm. In the most extreme case, one section of a buttress keyway was approved by studying UAV footage rather than the tried-and-true method of digging for remolded clay with a geologic hammer. Other safety measures included biweekly reading of slope inclinometers installed atop buttress backcuts and dedicated safety personnel to watch for signs of impending slope failures.

Walls, Walls, and More Walls

To satisfy the incongruent economics of maximizing developable space for single- and attached-family structures with planning requirements such as stormwater detention, affordable housing, open space, and the need to flatten the steeply sloping terrain for home-building purposes, the project required the design and construction of

Figure 4. **Slot-cutting to reach keyway elevations. Benching and placement of fill in the recently completed slot behind the water truck (foreground). Collapse of excavation sidewall along a remolded clay seam daylighted in the next keyway slot (background). (Photo courtesy of John Carter.)**

an abundance of walls. Many wall types were utilized:

- Concrete masonry walls up to 16 ft in height
- Drilled pier and grade beam supported walls
- Soil nail walls with geogrid-attached block facing
- Sixty-two separate MSE walls

The MSE wall has become a ubiquitous design element in many projects because of its:

- Construction economics versus other wall types
- Versatility in spanning large elevation breaks (an attribute for hillside development)
- Ability to conform to the natural landscape via myriad block color combinations, patterns, and block planting options

Individual MSE walls varied in height from a few feet up to approximately 30 ft, totaling almost half a million sq ft stretched over 36,000 lineal ft (Figure 5). The longest single MSE wall was approximately 2,200 lineal ft. Multiple uniaxial geogrid strengths were used in the design, ranging from Mirafi 3 XT up to 24 XT.

Constructed almost exclusively using nonlinear, freeform layouts with sloping backfill in single, double, triple, and quadruple wall/slope configurations, MSE walls and 2H:1V fill slopes spanned elevation breaks up to 100 ft in some areas (Figure 5). Aesthetically, perimeter MSE walls were often constructed with repeating plantable block courses to soften exterior project exposures with landscaping. The success of plantable MSE walls was mixed, owing to the amount of irrigation necessary to keep the plants alive during hot, dry California summers. Near vertical, nonplantable walls were often chosen for interior project areas to maximize lot depth on higher elevation view lots.

Large-scale construction of MSE walls at Portola presented a few unique challenges. For example, it was sometimes difficult to temper the desire for rapid wall assembly while striving to achieve the basic tenants of MSE wall construction: good drainage, consistent compaction throughout the reinforced and retained zones, and most importantly, geogrids installed nearly flat, under tension, and without wrinkles. Stuff that's simple, but often overlooked in lieu of production and construction schedules. This meant that policing the basic tenants of MSE wall construction was a full-time job to keep expected levels of settlement and/or top-of-wall rotation in line with engineering estimates.

Another factor making MSE wall building at Portola more complicated

Figure 5. **Construction of a three-tiered MSE wall/slope combination (foreground) and ongoing buttress excavation (background). (Photo courtesy of John Carter.)**

than for small-scale, single-tiered MSE wall construction was the need to achieve symbiosis between the wall contractor and the grading contractor, particularly for walls where increased geogrid embedment, beyond the lengths required for the wall design, was necessary for global stability. Monitoring precise placement of "select" backfill in the reinforced zone and "nonselect" backfill over extended geogrids behind the reinforced zone was often more about mediation than inspection.

It's All About Teamwork

It's hard to imagine another development project with a more complex slope stability paradigm, although one will almost certainly be found as development stretches further from the coast to absorb the panoramic hillside views of Southern California. Although clearly not impossible, development projects of this type are not for the faint hearted. If one takes the "if we knew then what we know now" position, it's doubtful that any projects as geotechnically complex as Portola would make it further than a set of architectural renderings depicting happy California residents strolling through the well-manicured landscapes of planned communities.

Still, there's one key factor in the success of geotechnically complex projects, one that makes developing the undevelopable possible, and that's consistency of personnel. Not just of the design team — although picking a core team of engineers, geologists, and contractors with experience and expertise in equal measure is vital — but also of the management team. Having client representatives who are insightful enough to embrace an "adapt and overcome" attitude in concert with enforcing the linear constraints of construction scheduling often means the difference between success and failure of challenging projects. After all, backcut failures along remolded-clay seams rarely happen on schedule! GS

RUPERT ADAMS, CEG, is a senior engineering geologist at Geocon Incorporated in San Diego, Calif. Working in the San Diego area, he focuses on residential and commercial development projects. He has participated on several complex slope-stability projects in the last 25 years, including the Ocean Trails (Trump National) Golf Course project, and the Mt. Soledad Landslide repair. He can be contacted at *adams@geoconinc.com*.