# Rapid Recovery

By Joe Erwin, P.E., and Brian Fuller, P.E.

**After a major landslide closed a section of the iconic State Route 1 through central California's scenic coastal region of Big Sur, the California Department of Transportation swung into action. Relying on teamwork, innovative processes, and cutting-edge technology, Caltrans developed balanced solutions to restore access to this vital arterial as rapidly as possible while taking steps to protect the highway and its travelers from the effects of similar events in the future.**

To reopen State Route 1 as quickly and as safely as possible, Caltrans opted to construct a newly relocated highway across the body of the landslide. COURTESY OF JOHN MADONNA CONSTRUCTION

Where it passes through central California's scenic coastal region of Big Sur, State Route 1 symbolizes the ability of the California Department of Transportation (Caltrans) to design and construct infrastructure that strikes a balance with nature. Straddling a rugged coastline, the more than 70 mi long ribbon of pavement is world-renowned for transporting people to a most beautiful, tranquil, and serene place. Part of this natural beauty includes the dynamic landscapes, making every drive and bicycle ride a truly unique experience. Ever since the highway was completed in 1937, countless landslides and unceasing erosion have changed how the roadway traverses the coast. In 2017, nature offered another reminder of its mighty power with some of the most catastrophic storms in recent history, severely damaging the highway in the Big Sur region and closing it for more than a year. Within that same year, harsh weather conditions resulted in numerous emergency highway closures on State Route 1, cutting off critical access for those who lived on, worked on, or traveled along the Big Sur coast.

In January 2017, about 9 mi north of the Monterey—San Luis Obispo County line, sections of the State Route 1 embankment hundreds of feet above the ocean failed. Material falling onto the highway and a loss of supporting soil beneath the southbound lane resulted in the closure of that side of the highway at a location known as Mud Creek. Traffic was diverted to a one-way reversing lane on the remaining northbound side. Rock, mud, and debris continually slid down the mountainside above the highway and quickly became more than Caltrans's maintenance forces could address. In response, the department executed an emergency contract with John Madonna Construction Company Inc. (JMC), of San Luis Obispo, California, to maintain that section of roadway while keeping it open. JMC was selected for this work because the company happened to be constructing the final portions of a project just south of the Monterey—San Luis Obispo County line.

In May 2017, a massive landslide buried about 1,000 ft of State Route 1 beneath 160 ft of earthen materials. COURTESY OF JOHN MADONNA CONSTRUCTION

The winter roadwork at Mud Creek was repetitive and seemingly never ending. After clearing the highway by the end of a shift, crews would return to the site the next day only to discover the roadway covered in mud and rock again—as if no removal had occurred at all. From January to May 2017, the highway experienced intermittent closures while the work was conducted. In May 2017, ground movement at the site increased substantially and an approximately 0.5 mi stretch of the highway was fully closed to local traffic and emergency vehicles.

As Caltrans has done since the highway opened, its engineers, surveyors, planners, and maintenance forces used teamwork and innovative processes, along with cutting-edge technology, to develop balanced solutions to restore access to this vital arterial. Caltrans and its geotechnical consultant, the Grover Beach, California, office of Yeh and Associates Inc., assessed a series of smaller landslides within the Mud Creek complex. Historically, this location has experienced significant activity, including toe erosion, natural springs that translated debris downslope, and an undulating slide plane that daylighted at the approximate roadway elevation.

At one point in May 2017, a subcontractor foreman determined it was unsafe to continue working on the highway and demobilized all the construction equipment from the site. The final pieces of equipment were removed on May 19. The next evening, 50 acres of land and more than 5 million cu yd of earth broke free from the mountainside. With a thunderous roar—likened to an earthquake by a nearby resident—a new 15-acre peninsula was created. About 1,000 ft of State Route 1 was now buried beneath 160 ft of earthen material. The new 2,400 ft long coastline jutted out 550 ft into the Pacific Ocean (see "Major Landslides on Iconic Coastal Roadway Occupy Caltrans in Big Sur Region," Civil Engineering, July/August 2017, pages 16-17). Thanks to the expert judgment of the foreman, miraculously no one was injured or killed in the catastrophic landslide.


Although the Mud Creek slide was much larger than typical, it still behaved in a way that has been witnessed before. The perimeter slide areas, near the scarp and flanks, settled over time into a more natural equilibrium, while the main body remained relatively static. YEH AND ASSOCIATES

Afterward, Caltrans and its partners conducted site investigations. Certified engineering geologists from within Caltrans and from subcontracted consultants working on the project conducted the initial assessment. The team of geologists and engineers working on this assessment comprised some of the most knowledgeable and skilled experts in understanding major landslides, particularly those that have occurred along the Big Sur coast.

The first task was to establish a slide monitoring system and safety protocol for workers. After waiting several days for the secondary slides to slow to an acceptable rate so that personnel could be safe on-site, engineers began a comprehensive assessment by means of field mapping on foot and visual observation. Once the site had been deemed safe for construction equipment, engineers from Caltrans's Division of Construction coordinated the contractors' work and managed the daily operations. JMC began developing a series of access roads on the landslide to help further study and monitor the ground movement. IDS GeoRadar North America, of Golden, Colorado, installed and operated ground-based radar a few miles south of the landslide at a location known as Grey Slip. Eventually, the equipment was moved near the toe of the landslide once the access roads were completed. Drill rigs determined the landslide composition materials at key locations, and slope inclinometers were installed and read frequently. This information enabled the geotechnical engineers to characterize the subsurface site conditions.

Landslides, no matter how large or small, generally consist of the same features. The main body of the slide is the material that moved downslope. The scarp is the freshly exposed mountainside. Between these two features is the head of the slide. The crown of a slide is the material above the scarp, and the flanks are the soil on either side of the main body and scarp. The toe of a slide represents the outer limits of the main body, and in the case of a landslide into the ocean, it is the new shoreline. Although the Mud Creek slide was much larger than typical, it still behaved in a way that has been witnessed before. The perimeter slide areas, near the scarp and flanks, settled over time into a more natural equilibrium, while the main body remained relatively static.

From fall 2017 to winter 2018, several large storms in the northern Pacific Ocean caused large swells and breaking waves at the project site, hampering construction of the rock revetment at the toe of the slide. KYLE EVANS 2018

Concurrent to the monitoring and initial access road construction, Caltrans's Project Management Division quickly assembled a project development team to start the process of determining a permanent solution. The team included representatives from Caltrans's Division of Design, Office of Hydraulics and Stormwater Design, Division of Construction, Office of Geotechnical Services, and Maintenance Engineering branch within the Maintenance Division. Although already busy working on other projects, many of these groups were asked to set aside their normal work to help with this urgent effort. The team met both on-site and at the Caltrans district office in San Luis Obispo to determine strategies for highway restoration. During the first days and weeks after the initial slide, meetings were fast paced and frequent, as information poured in from various sources.

Because State Route 1 through Big Sur is one of the world's premier coastal scenic highways, novel approaches to landslides and other complex problems there are often required to maintain a roadway that many from all over the world have traveled to see. Caltrans evaluates landslide mitigation alternatives in accordance with the agency's 2004 Highway 1 Big Sur Coast Highway Management Plan. Developed in collaboration with multiple agencies and local partners, the plan provides guidance on how best to maintain the route through Big Sur. A subset of this plan offers specific guidelines for landslide management and storm damage response. Many of the techniques and methods for responding to landslides were developed by applying what were at the time the most innovative ideas or state-of-the-art technology. Other maintenance and response strategies within the plan resulted directly from lessons learned as part of previous projects to address landslides and the effects those projects had.


The main features of the completed project included a rock revetment at the toe of the landslide to control erosion, a new embankment built up from the revetment, and large earthen berms outfitted with a type of rock basket wall known as a Hilfiker wall to capture materials that travel downslope from the catchment above. COURTESY OF JOHN MADONNA CONSTRUCTION

For example, in 1983, a landslide totaling more than a million cu yd damaged the highway near Julia Pfeiffer Burns State Park, closing that stretch of the road for more than a year. At that time, the roadway was reopened by means of a team of bulldozers that shaved back the mountainside, pushing another 2 million cu yd of soil into the Pacific Ocean. Although the highway was reopened to traffic and the mountainside was stabilized, the sediment that was disposed of directly into the Pacific Ocean covered the sensitive marine environment. To this day, areas beneath the slide have not fully recovered, according to scientists from the University of California, Santa Cruz, and the Monterey Bay National Marine Sanctuary (MBNMS).

The *Big Sur Coast Highway Management Plan* embodies Caltrans's efforts to learn from the past and features context-sensitive solutions for managing landslides by means of various strategies, including:

- avoidance: realigning the highway with either a long-distance bypass or a tunnel
- stabilization: removing any potentially unstable materials
- protection: constructing retaining walls or protective barriers
- management: maintaining the highway with smaller crews removing lesser amounts of dirt and debris

Often, unstable slopes require a combination of mitigating strategies. The extremely large area of the Mud Creek landslide and the rugged, steep terrain of the Big Sur coast highway obviated the use of traditional avoidance and stabilization as feasible engineering alternatives. Improvements considered and analyzed included realignment with a bypass or tunnel, removal of the remaining slide mass, and construction of retaining walls, viaducts, and bridges. All were deemed unsuitable to the site conditions for various reasons, including the absence of bedrock to tie into or the time it would take to plan and complete construction. During an emergency project to reopen a closed highway, the preferred solution often strikes a balance between cost, constructability, and schedule. Ultimately, the strategy devised by Caltrans for addressing the Mud Creek landslide involved a combination of protection and management, in this case by constructing a newly relocated highway across the body of the landslide.

At the Mud Creek site, the rock basket walls were built up to about 25 ft in face height, dramatically improving the ability of the above-roadway catchments to protect the new highway below. COURTESY OF JOHN MADONNA CONSTRUCTION

Constructing infrastructure within a marine environment is challenging, particularly at the highly active site of a recent major landslide. The project team had to consider active rockfall, rapid erosion of the toe, and steep terrain in designing the new highway as well as how best to protect future travelers.

Caltrans Design used Civil 3D software, from Autodesk Inc., of San Rafael, California, to model the landslide's surface and develop iterations of the proposed solution. Lidar data delivered by Caltrans surveyors was used to form a digital terrain model. Because the contractor was working so quickly and the topography was changing as new access roads and areas were cleared, lidar data were delivered multiple times so that the final location and elevation of the new highway could be based on the most current site information. Caltrans used the model of the existing surface to optimize the design of the highway.

Staff from the geotechnical services, construction, and design offices worked with the contractor to develop and analyze multiple iterations of the highway design. The highway design's first few iterations called for a massive excavation above the highway on the northbound side to create a bench for the roadway at the north end. However, this plan was adjusted as the work progressed, so as to expedite construction and to include additional features designed to assist future maintenance efforts and further protect the traveling public.

The steep, rugged slopes created by the landslide proved challenging for the contractor, while the variability of the Franciscan Formation complicated excavation and earthwork efforts. The Franciscan Formation is a mixture of hard, resistant rocks of varying types and sizes, randomly distributed in a highly sheared, weaker matrix. Materials encountered ranged from low-strength clay to very hard metamorphic rock that required blasting, presenting daily challenges to crews attempting to complete the proposed excavations and embankments. Additional challenges involved the immense scope of earthwork to be completed at the site and the need to ensure that all grading locations remained safe for workers and equipment.

Erosion caused by ocean wave action resulted in a steady retreat of the toe of the slide. To stanch this erosion, the contractor installed a rock revetment at the toe of the landslide. Extending for more than 2,000 ft along the new coastline, the revetment consisted of a trapezoidal structure made of rock that was keyed into the newly formed beach 6 ft below sea level and built to heights of 40 ft at the most exposed limits. Because of the large sizes of the required rocks, some of which weighed as much as 8 tons, the semi-trailer trucks used to haul the rocks could transport only two at a time. Overall, about 200,000 tons of rock would eventually be placed to build the revetment, which was designed by Caltrans staff. Coastal environment expert Gary Griggs, Ph.D., a distinguished professor of earth sciences at the University of California, Santa Cruz, provided input on this effort.

Once the revetment was built, the project team decided that the massive cut planned to be made at the north end of the site would not be needed. Instead, the highway could be founded on a new embankment built up from the revetment. To provide more outside width on the southbound side of the highway, the embankment was designed with an inclination ranging from 1.5:1 to 1:1. The extra width would be used in the future to stockpile slide material and store equipment. Additionally, the extra width could also be counted on to reduce the energy of future landslides by enabling large debris flows and runoff to flatten and spread, rather than remain in a more concentrated flow that would have more energy and thus more potential to incise into the new highway and embankment.

Erosion remained a concern during construction of the revetment. Along with continually reducing the land available for the realignment of the highway, erosion also would damage nearby marine habitats, including that of the black abalone, a protected species. Black abalones are a type of mollusk, or sea snail, found in rocky intertidal zones along the Pacific Coast of North America from California to Mexico. Coastal areas all along Big Sur are considered ideal black abalone habitat—cracks or crevices along a rocky coast that have low amounts of sediment—but the few miles north and south of Mud Creek were considered particularly pristine. However, erosion caused by wave action at the toe of the landslide began causing sediment to cover the rocky coastline and form sandy beaches, which suffocate black abalones.

Under emergency conditions, Caltrans biologists and other scientists worked with scientists from the MBNMS and other regulatory agencies to rescue black abalones from the encroaching sediment. The scientists entered the intertidal zone north of the landslide, where sediment was slowly drifting. They physically removed the abalones from the rocks, loaded them into special containers, and then safely transported them to more suitable habitat farther south of the project location, far away from the effects of the sediment of the landslide. After this initial rescue effort, Caltrans's monitors continually updated the MBNMS, as well as the California Coastal Commission and other regulatory agencies, on the progress being made on the projects and the changing physical conditions at the site. One condition of the emergency response entailed not physically placing any soil or materials beneath the mean high-tide line. Also, no harassment of marine wildlife could occur as a part of the reconstruction efforts. Environmental monitors hired by JMC to work for Caltrans acted as the eyes and ears for regulatory agencies, ensuring them that construction staff upheld these commitments on-site.

Concerns about potential damage to the highway caused by rockfall from the scarp prompted the project team to include protective elements as part of the design. A natural bowl or catchment had formed between the head of the main body and the bottom of the scarp. The project team improved this catchment by constructing large earthen berms on top of the head of the main body. A berm in its simplest form is a long, raised mound of soil. At Mud Creek, where everything is on a massive scale, these berms were more than 100 ft wide and 200 ft long measured at the top, towering 180 ft above the proposed realigned highway. Two rock-basket walls were added on top of the berms to further increase the capacity of the large bowls created by the landslide. Commonly known as a Hilfiker wall, these retaining walls were built with steel wire that is welded together to form mats. Rock is backfilled on top of each mat in lifts or horizontal sections. Another mat is placed and backfilled, and the process repeats until the wall is at the desired height.

At the Mud Creek site, these walls were built up to about 25 ft in face height, dramatically improving the ability of the above-roadway catchments to protect the new highway below. The walls stretch the entire length of the berms but with a gap between them to accommodate runoff and debris anticipated to flow down Mud Creek. To facilitate periodic maintenance of the catchments in the future, two maintenance access roads were graded with a series of switchbacks from the highway to the top of these walls. These roads, which are slightly more than 15 ft wide, enable such heavy equipment as long-reach excavators and dump trucks to ascend to the top of the wall. From there, excavators will be able to reach into the the natural bowl and transfer the material to the dump trucks.

Drainage features were installed at the site to line up with the existing and newly constructed overland drainage flow lines where they pass down the face of the slide and along the new highway. Caltrans engineers worked with the contractor to provide designs that could handle the anticipated flows but also prove constructible in this challenging work environment. Aligned with the gap between the two berms above the highway, a 63 in. diameter main culvert now channels flows from Mud Creek under the roadway. Additionally, a catchment ditch was installed at the highway grade, along the northbound side, with depths of up to about 10 ft. This catchment was constructed for ease of future maintenance as well as to further protect from landslides. A rock check dam sits near the gap between the berms to prevent large debris from Mud Creek from entering the culvert.

The roadway below the north end of the north flank cut is protected from rockfall by means of a combination of cable- net drapery and double-twisted wire-mesh drapery. The drapery system is 440 ft high by 240 ft long and secured by a series of ground anchors secured into the mountainside. The primary ground anchors are 0.75 in. thick galvanized cable drilled to depths of 12 ft and held in place by cement grout. Designed by Caltrans engineers, the drapery system is located on the north end of the site, where the at-grade catchment is limited by the roadway geometry. Elsewhere, the highway is protected with wide catchment ditches designed to contain rockfalls and debris flows.

As mentioned previously, the design of the roadway alignment and profile was reworked numerous times to avoid destabilizing cuts or to accommodate new features, based on frequent input from field engineers, Caltrans Design engineers, and the contractor. Final Civil 3D files were sent to JMC's subconsultant—Take-off Professionals, of Phoenix—and the files were processed and loaded into the contractor's grading equipment, helping expedite further the finished highway grading. The team had worked hard to optimize the design and get the highway open as quickly and safely as possible.

During the winter, from late 2017 until early 2018, concerns arose that the site would sustain more slides or drainage issues, possibly forcing the project team to return to the drawing board. Thankfully, the rainy season, which runs from October to April, was drier than the previous year, with only one storm that had a significant effect on the project. The March 2018 rainstorm triggered debris flows at the southern end of the landslide at Mud Creek and on the north flank. Ultimately, this event was helpful in planning the design of drainage features, catchment ditches, and roadway geometry and provided knowledge for use in future maintenance of State Route 1.

From fall 2017 through the winter, several large storms in the northern Pacific Ocean caused large swells and breaking waves at the project site, hampering construction of the rock revetment at the toe of the slide. During high tide and on days with larger swells, excavators and equipment were struck by the remains of breaking ocean waves, and in some instances work had to stop until the waves reduced in height and the tide lowered. One of the larger swell events occurred in October 2017, when some of the completed sections of the revetment were overtopped by the waves. Before this incident, the initial revetment design was proposed to be 26 ft tall. However, the swell and resulting waves prompted a design modification in structural height to 40 ft in the sections of revetment most exposed to the energy of the Pacific Ocean.

When constructing a highway into the side of a hill, engineers try to balance the amount of excavation into the hillside with the amount of embankment placed adjacent to existing slopes. In this way, the amount of imported or exported material is minimized and construction costs are reduced. As previously mentioned, the highway on the north end of the project originally was going to be situated on a bench created by means of an excavation into the north flank. However, because this excavation was no longer needed to create width for the highway and an embankment was instead used to support the realignment on the north end, the project needed to import material. Geotechnical engineers identified Grey Slip as a potential borrow site because it is the location of a previous landslide and is just 2 mi south of Mud Creek. Before any importing work began, Caltrans staff assessed the site to ensure that no sensitive biological, historical, or cultural resources were present. Material from Grey Slip, along with material from other locations within the project limits, was used to build the massive 250 ft tall northern embankment. In the end, 250,000 cu yd of material was imported. The new embankment was constructed as wide as possible to help dissipate future slide energies and protect the new embankment against damage from debris and mudflow. An added benefit is that the wider bench provides more room for temporary stockpiling in future storm events or slides.

Innovation and technology played crucial roles in the efforts to reopen the highway as quickly as possible. An automated total station and monitoring station were used to continuously monitor the slide nearly in real time. Solar arrays and satellite Wi-Fi enabled on-site communications not previously available to Caltrans at this location. By monitoring slide movement and accelerations in ground movement, IDS GeoRadar helped ensure construction safety during the preliminary stages of the job. The lessons learned at Mud Creek and the technologies used on this job will be applied in the future as part of efforts to address other large and challenging landslide projects along the Big Sur coast and statewide.

The embankment was completed in July 2018, and final grading and paving followed shortly afterward. The highway was opened to traffic on July 18, 2018, a little more than a year after the landslide closed it. The effort was truly one of teamwork and collaboration. Every member of the team, from those within Caltrans to the private and public partners, helped with the project's success. Crews with JMC worked seven days a week, at least 12 hours per day, from January 2017 until mid-July 2018. The total project cost of $54 million included all payments to the contractor for labor and materials as well as the cost of Caltrans personnel. Caltrans Construction staff highly commends JMC and its superintendents for their ingenuity, dedication, and hard work.

Overall, the public has warmly welcomed the project's completion. Residents can now use the highway to travel again, and the need for a two-hour detour south of the town of Gorda has ended. Central Coast business and economic interests are also pleased with the new roadway's ability to facilitate the movement of goods, services, and people. The many international visitors to the Big Sur area also appreciate that the iconic highway has reopened along the entire Big Sur coast and that life there is returning to normal.

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**Project Credits**

**Owner and designer** California Department of Transportation
**Geotechnical consultant** Yeh and Associates Inc., Grover Beach, California
**General contractor** John Madonna Construction Company Inc., San Luis Obispo, California
**Geotechnical monitoring** IDS GeoRadar North America, Golden, Colorado
**Modeling** Take-off Professionals, Phoenix Modeling Take-off Professionals, Phoenix