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The Mystery of Mud

MUCH about mud is puzzling. Its flow behavior is complex, combining characteristics of solid and liquid matter. It can carry large boulders and other heavy objects for long distances -- a feat not entirely explained by the Archimedes principle, the buoyancy effect that allows a boat to float in water because it is lighter than the material it displaces. Big rocks weigh more than the mud they displace, so why don't they sink? Apparently mud holds them up by behaving as a porous solid, a sort of honeycomb that both supports solid objects and allows the flow of water. Only when enough water has seeped away does gravity gain the upper hand again, allowing the mixture of clay, rock, and sand to settle and harden into solid earth.

March, 1997: landslide damage on portions of U.S. Route 52, along the Ohio River Valley, after eight inches of rain fell in just two days. (Photographs by Aaron Mitten, Ohio Department of Transportation.)

Because spontaneously occurring debris flows are notoriously difficult to anticipate and observe in nature (nothing happens for years, and then it's over in a flash), scientists have carried out all sorts of experiments in an effort to understand how they work. They've loaded glass-sided flumes with a mixture of water and black and white sand, and recorded the movement of the sand grains with a high-speed camera. They've mixed wallpaper paste with coal slack, and PVC beads with water, to mimic the clay-sand-gravel slurry of mudflows. At the world's largest experimental landslide flume, in Oregon's Willamette National Forest, USGS researchers have slopped together truckloads of material similar to the composition of two of the biggest volcanic mudslides in recent geologic history: the debris flow from the 1980 eruption of Mount St. Helens, and the Osceola Mudflow that reshaped the face of Mount

Rainier 5,000 years ago. A much smaller experimental contraption is a mud-filled condom (size large, nonlubricated) that is set rolling down a plywood ramp to measure the rate of deformation -- how rapidly the latex ellipse loses and regains its shape, over and over.

Yet despite painstaking calculations of flow, stress, velocity, water pressure, and the like, a stubborn mystery still shrouds the flash point at which solid earth becomes semi-liquid. Does it happen incrementally -- one grain of soil breaks loose, then two, then four, then sixteen, in a logarithmic cascade -- or all at once? Does it start at the base, or "toe," of a slope (imagine taking an orange from the bottom of a pyramid at the supermarket) or at the top (growing like a snowball as it descends)? Once the process begins, is there any way to know what's happening and get out of the way? These were some of the questions that led me to Dave Montgomery, at the University of Washington's Quaternary Research Center. (The Quaternary period, which Montgomery refers to as the geological "here and now," began about 1.6 million years ago.) It turns out that landslides don't give up answers to any of these questions easily.

"We have lots of theories and very little data," Montgomery admits. There is evidence that some landslides, particularly those in sandy soils common in the Coast Range and the Puget Sound area, begin as a slower earth movement called a translational slide. In such cases rising pore pressure and subsurface deformation of the soil -- both detectable with carefully placed instruments -- could function as warning signals. But Montgomery doubts that the signals would be of much use. "If the delay is very short, which I think it is, then a warning may be pointless. Once a fairly large area starts to move, it happens fast. These things travel up to ten meters per second -- that's twenty-two miles an hour. By the time you hear them, you don't have time to get out of the way."

Like his colleague Bill Dietrich, Montgomery is a geomorphologist, someone who studies how landscapes change over time. In the past, geomorphology was less concerned with the mechanics of these physical processes than with the history and sequence of their occurrence. William Morris Davis (1850-1934), the most influential geomorphologist of this century, theorized that topography evolves over millennia according to a repetitive cycle analogous to youth, adolescence, maturity, old age, and eventual rejuvenation. For many decades his adherents viewed landscapes through the same wide-angle evolutionary lens. They examined a riverbank, for instance, not to understand the process of erosion but to figure out which phase of life the river had reached in the eternal cycle, and how that coincided with the geologic history of its surroundings.

By the 1960s Davis's holistic view of landscape evolution had fallen out of favor, replaced by technical studies that generated "hard" scientific data. Landscapes began to be analyzed in terms of their smallest components; indeed, the history of an entire river basin could theoretically be read in the minute workings of a single feeder stream. Today geomorphologists focus almost exclusively on specific earth processes that can be observed and measured as they are happening. They assume that the earth's topography is continuing to evolve pretty much as it always has -- by a relatively small set of quantifiable mechanisms such as weathering, erosion, and sedimentation, which are basically the same everywhere, though they occur at different rates. These rates are critical to understanding how landforms evolved, and how they will continue to change. Thus data from a few sites can be used to predict what will happen over much wider geographic areas -- which is just what Dietrich and Montgomery are doing with computer models of landslide-hazard zones in the Oregon Coast Range.

One of their main sources of data is a clear-cut swale at Mettman Ridge, in the coastal foothills near Coos Bay, Oregon. Stripped of its timber, tilted precariously at 43 degrees, positioned to catch buckets of rain from Pacific storms, Mettman Ridge is classic debris-flow habitat. For nine years researchers swarmed all over the slope.

They punched hundreds of holes in the ground to measure pore water pressure, built weirs to capture and measure runoff, installed rain gauges and a sprinkler system to simulate storm rainfall, and set up sensors to track hydraulic movement through the colluvium and cracks in the underlying bedrock. They planned eventually to drench the slope until it failed, monitoring the slide with a bevy of instruments. It would have been a rare show -- seldom had a hillside anywhere been subjected to such intense scrutiny. But curtain time came early. In November of 1996 heavy rains in Oregon triggered hundreds of mudslides, including one that wiped out the installation at Mettman Ridge and brought the studies to a premature end.

Montgomery's reaction was sanguine. After all, he and his colleagues had picked the site because it was likely to fail. Though no one saw the slide happen, the instruments captured "a beautiful record of slide initiation," he says. "We got some fabulous data -- we're still ploughing through it." Among their early findings: a surprising amount of water moves rapidly through fractures in subsurface bedrock during high-intensity storms, playing a greater role in raising pore pressure than had been thought and creating "hot spots" that can fail. Because the fractures are hidden and infinitely variable, they cause problems for computer models that assume uniform diffusion of rainfall. "It makes it rather difficult to predict which of the most hazardous areas would actually go in a particular storm," Montgomery says.

Timothy Davies, a geological engineer at Lincoln University, in New Zealand, believes that debris flows are among the chaotic natural systems that are too complex to be predicted by current analytical methods. "It may well be the case that a theoretical solution to the prediction of debris-flow behavior is beyond human intelligence at present," Davies declared in a paper presented in 1997 at an international debris-flow conference in San Francisco. Yet the models developed by Montgomery and Dietrich appear to work reasonably well -- with 80 percent accuracy -- in the Coast Range. They're already being used to suggest "no-cut" zones for timber companies, whose clear-cuts have been widely blamed for the destructive mudslides that have plagued western Oregon in recent years. And with a little tweaking they could also be applied to the Puget Sound region, which has a similar climate and soil profile.

"We can tell pretty well where debris flows are likely to happen," Dietrich explains. "We can write equations that represent how water runs off a landscape and how that water can lead to destabilization of the soil mass, and put that in the computer on a numerical surface representing the landscape. We can then show the relative risk that there'll be some shallow landsliding that can generate debris flows that can take away fish habitat or hit housing." The models work best with digital topography produced by laser altimetry, an aerial technology capable of mapping subtle variations in terrain even when the ground is obscured by evergreen tree canopies. Slide risk is established by calculating the steady rainfall necessary to trigger a slide anywhere on the digital landscape. The less rain required, the higher the probability of slides.

In a scientific discipline once wholly dependent on fieldwork, technology has eased geomorphology's labor while expanding its reach. It used to take geologists months to put together landslide-susceptibility maps by hand, using plastic grids to overlay numerous factors -- a task that computers have rendered obsolete. Thanks to a USGS project on the Internet, geologists all over the country can monitor instruments embedded in slopes on the Highway 50 corridor in California and along the section of train track where the freight train was thrown into Puget Sound two years ago.

Coming Full Circle

GEOLOGISTS used to spend their lives just mapping stuff," Jonathan Stock, a graduate student at the University of California at Berkeley, told me as we slogged on foot toward the Mettman Ridge site one summer day. "Now you have to have quantitative skills. And you have to be sort of a naturalist -- to look at the natural world and see all the forces affecting it." Along with Montgomery and another graduate student, Kevin Schmidt, of the University of Washington, we clambered over huge bleached logs that lay tossed about like pickup sticks in the dry streambed. Occasionally the geologists would bend over to knock off a piece of log for carbon-dating, to determine how long it had been since a previous slide dropped and buried it here. The 1996 debris flow had dumped mud, gravel, wood chips, pieces of lumber and PVC pipe, and rocks of all sorts and sizes in the narrow channel. Foxglove and thimbleberry had already taken root.

Stock knew the area well. In the course of his research on stream-channel erosion he had crouched in the sandstone streambed and painstakingly measured the depth of 20,000 minute grooves where flakes of rock had been gouged out by the debris flow. Up above, at the scarp of the slide, Schmidt had dug up thousands of roots and pulled them apart to measure their tensile strength. He's studying the relative resistance of various plants and saplings to breaking and shearing, and the extent of the role that vegetation plays in slope stability. Tree roots anchor colluvium to bedrock and increase the angle of repose. Mature evergreens blunt cloudbursts that trigger slides, deflecting and absorbing rainfall before it hits the ground. However, there's a countereffect: vegetation promotes thickening of the soil, which over centuries adds weight and loosens the grip of root systems on bedrock. "Steep slopes, particularly steep wet slopes, fail in natural environments all the time," Montgomery says. "It's just that the frequency changes after logging." Some studies suggest that it increases as much as tenfold.

Earlier we had viewed Mettman Ridge from a four-seater aircraft that rose above Coos Bay and its sawmill-turned-casino, a smelly mountain of wet sawdust at the Weyerhauser export center, and cargo ships waiting to take wood products to Asia. We passed over cold sloughs and sand dunes and veered toward the emerald foothills. In the velvet maze of ridge and swale the study site appeared as a thin brown gash. The geologists snapped photos as the plane banked in nauseating circles. It seemed a curious undertaking: nine years of probing this insignificant patch, measuring the water that trickled through its veins, testing the tensile strength of its tree roots, studying 20,000 scratches in the streambed.

Why do you do this? I asked Montgomery. "I enjoy worrying about stuff that nobody else cares about," he said cheerfully. In a way that few could have predicted twenty or thirty years ago, the current focus on process studies and computer modeling is bringing geomorphologists full circle, leading them to reexamine William Morris Davis's idea of the long-term topographical life cycle. "Now we're standing back from single hillslopes and looking at whole systems," Montgomery said. "We're not focusing so much on the individual parts. You do an entire watershed analysis instead of studying a single streambed for years. I'll go back to Coos Bay for two or three more years. But it's mostly over."

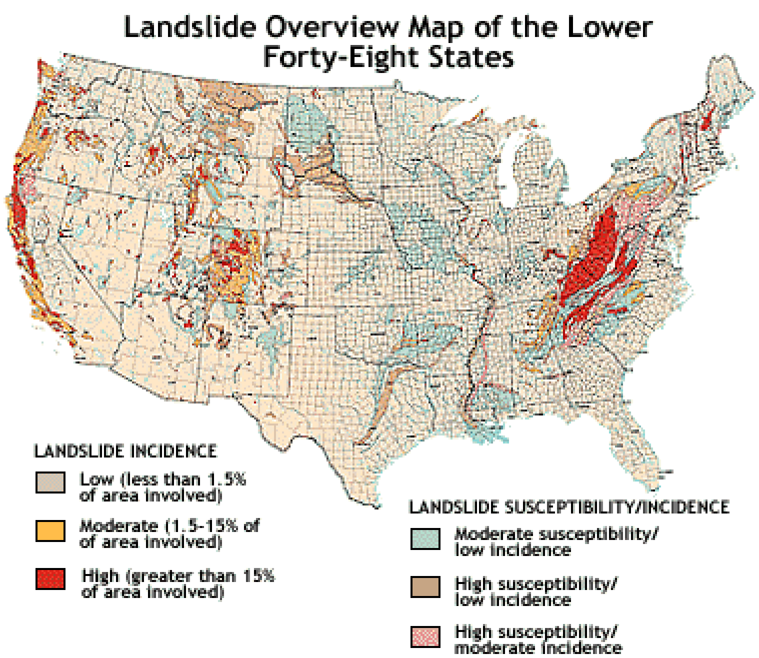
Montgomery signaled to the pilot that they had enough pictures. Mettman Ridge, which generated the data for half a dozen Ph.D. dissertations, including Montgomery's, faded into the distance.

Maps

BROAD-shouldered, long-armed, and alarmingly fit at sixty-five, Jerry Thorsen seems as firmly rooted to the ground as a post oak. A geologist who once traveled around Washington for the state Department of Natural Resources, he now works as a private geological consultant specializing in slope analysis. Since the wet winter of two years ago he's had no dearth of clients. Scrambling up and down muddy cliffs choked with bracken, Thorsen tossed me tips for reading the bluffs: a vertical stripe of alders all the same size conceals an avalanche scar; evergreen trees growing at strange angles are a bad sign; a flattened bench, or shelf, partway down a slope is a terrible place to put a house, because it was created by slide action.

In the 1970s Thorsen helped to map 2,000 miles of convoluted shoreline in and around Puget Sound for the Department of Ecology. The resulting atlas identifies the

660 miles with unstable slopes, and records evidence of both old and recent slides -- an invaluable if incomplete source of geological information. "We didn't have time to walk every beach, crawl up the bank, and go through the jungle," Thorsen says. "But it was our best guess at the time." The atlas should be required reading for every owner or prospective buyer of waterfront property, but it's out of print now. Years ago a supervisor at the Department of Ecology decided they were taking up too much room, and had a truckload taken to the dump. Though local planning departments still have copies, few citizens ask to see them.



USGS Open-File Report 97-289, by Jonathan W. Godt.

In the spring following the Rolling Bay slide geologists reconnoitered the shoreline from the air for the Federal Emergency Management Agency. On at least a third of the coastal bluffs there was evidence of active or recent landsliding. A notorious example is Magnolia Bluff, where several houses on a sagging bench are falling awkwardly toward Elliott Bay. Tour buses sometimes stop to view the progress. This is a slow-moving, deep-seated slide area that also spawns rapid debris flows. Magnolia has been a money pit since the 1930s; the Work Projects Administration spent one million Depression dollars to hand-dig a network of drainage trenches as much as a hundred feet deep on Magnolia and several other bluffs. The drains still work, but they haven't stopped the debris flows.

The public tab for landslide damage in Seattle from the 1996-1997 storms is $35 million. The city hopes to recover $19 million from FEMA and federal highway funds, thereby spreading the cost of mudslides -- like floods in the Midwest and hurricanes in Florida -- to the rest of the country. "Where does it end, and to what extent should the general taxpayer accommodate the interests of folks who choose to build in risky locations?" Margaret Pageler, a Seattle city councilwoman, asks. California has created special entities called geological hazard-abatement districts that enable property owners in specific locales to levy their own taxes to deal with landslide hazards. There are no such funding mechanisms yet in Washington. Seattle and other local governments are often caught between homeowners who blame (and sue) the city for drainage conditions that exacerbate slide activity, and other citizens who question why all taxpayers should bear the high cost of building and maintaining infrastructure to serve the relative few who live in unsafe areas.

Nearly all the slides in Seattle in the winter of 1996-1997 took place in zones mapped as unstable twenty-five years ago; none damaged buildings constructed under new, more rigorous ordinances adopted in 1990. However, development is still permitted, with restrictions, on slopes as steep as 45 degrees -- far more leniency than most Bay-area jurisdictions allow. "Saying no is a huge issue -- it's a really hard thing to do," says Kate Janeway, a Seattle attorney and an expert in natural-hazard law. "Public officials see themselves assailed by developers, their lawyers. They probably say yes more than they should. The best way to say no is to have the maps that do it, parcel by parcel -- maps that make it clear the area is so unstable we won't allow anything on them. Let's all agree to shut the door."

What Do You Do?

THE gloomy wet spring did nothing to dispel the sense of unease that lingered on Bainbridge Island long after the Rolling Bay slide. The idea of being swallowed up by the earth is profoundly unsettling. At first people had disturbing dreams -- dreams of mud. They awoke at night to the malevolent sound of rain. With newly critical eyes they examined the waterfront houses of strangers. How close was the house to the cliff? Were the trees leaning? What caused those suspicious bare spots? For a time, envy abated.

Related link:

• **"Landslides Triggered by the Winter 1996-97 Storms in the Puget Lowland, Washington," by Rex L. Baum, Alan F. Chleborad, and Robert L. Schuster (1998)**
A USGS report on the Bainbridge Island landslides and others in the Seattle area at around the same time.

February, March, April, May. The rain kept coming. It was the wettest year on record in Seattle. Roads closed, pipelines exploded because of shifting soil, more railroad tracks washed out, more buildings slid down hills. In March a mudslide shattered another house on Rolling Bay Walk. No lives were lost -- the beach was empty by then, so plainly unsafe that its occupants had fled. Of twenty-one houses, seven had been destroyed or badly damaged in a year's time. Six more were red-tagged by the island's building official as unsafe for occupation. Residents of most of the rest are strongly advised to evacuate when more than an inch of rain falls in twenty-four hours on saturated ground. After each disaster residents had nursed the hope -- incomprehensible to outsiders -- that it would be the last. The March landslide "kind of finished the neighborhood off," Mary Clare recalled as we sat at her kitchen table. She was still limping from a leg injury that she had suffered during one of the evacuations from her home on Rolling Bay Walk.

Clare and her former husband bought their beach house in 1982. No one told them about the slides that had been occurring sporadically for decades. (Such disclosure isn't required by law in Washington real-estate transactions.) "We knew there had always been some sloughing off," she said. "Not until the 1996 slide [when a house was destroyed five doors away from her own] did I find out it was dangerous." That year Clare took out a second mortgage and began to buttress her house against the moving cliff by rebuilding the foundation, stiffening the walls with plywood, and pouring so much concrete on the ground floor that it now resembles a dam -- which, in a sense, it is. The bedrooms are on the top floor, overlooking the water, as far away from the face of the bluff as possible. The lower structure is a rigid box, engineered not to withstand a slide but to enable its occupants to survive one. Donald Tubbs, who mapped Seattle's hazardous slopes back in the 1970s, when he was a graduate student, and has been the geotechnical consultant for Rolling Bay's residents, says, "The house would move as one piece. It's what we call graceful destruction -- it fails in a relatively benign way." Tubbs recommends that other houses be retrofitted in the same way.

Part of a retaining wall behind the Herren house still stands. The slide jumped right over it. To provide effective protection to the dozen properties most at risk, a wall would need to be twenty feet high and an eighth of a mile long, and would cost about $1.5 million, Tubbs says. That's $125,000 per owner. Another way to minimize slide risk is to cut away the face of the hillside entirely and stack a multi-story building against it, so that the structure functions as a retaining wall. "You can do that only with expensive construction," he says. "If you're Bill Gates, you can do it." Tubbs was a consultant for Gates's new $60 million house, which sprawls across a hillside on the shore of Lake Washington.

The weakened bluff at Rolling Bay is now at great risk for more slides. Tubbs suggests that the remaining large trees be removed to eliminate the potential damage they could cause as projectiles; Dave Montgomery vehemently disagrees, arguing that removing them would further destabilize the cliff. No matter how one looks at it, the situation here is bleak. Assessed values on Rolling Bay Walk have plummeted by more than 90 percent; what used to be a $300,000 house is on the tax rolls at $11,000. "I can't sell the house -- I can't give it away," Clare said. "I still owe all this money." She has spent $130,000 to fortify a house that she has to leave during rainy periods. "After all this work," she added, "I still may not be protected from a slide as large as the one that hit the Herrens."

"There are probably a thousand homes built on some sort of filled beach at the bottom of the bluff," says Hugh Shipman, a coastal geologist with the Washington Department of Ecology. "They're not all as close to the toe of the slope as Rolling Bay, but some of them are. What do you do? You can't buy everybody out." Along with many of his colleagues, Shipman initially thought the

Rolling Bay disaster would galvanize public agencies into dealing with the problem -- perhaps by implementing stricter building codes or growth-management policies, or mapping the hazardous areas more precisely. Now he's doubtful that anything will change.

Hopes faded for a FEMA buyout of Rolling Bay when it became clear that the cost -- $3.2 million to buy the houses, tear them down, and clean up the beach -- was too great, exceeding the hazard-mitigation funds available to any single jurisdiction as a result of the series of storms officially known as Presidential Disasters 1159 and 1172. FEMA funds have been used to bail out Washington farmers living in floodplains, but not people threatened by mudslides. Ironically, one of the reasons is that slides are too destructive. The premise of hazard mitigation is that it makes more sense to buy up properties than to pay for repairs again and again, but shallow debris flows tend to eliminate structures entirely. They leave nothing to repair.

Though privately underwritten landslide insurance is now impossible for Clare and her neighbors to obtain, federally subsidized flood insurance does cover certain water-caused landslides. In such cases the viscosity of the debris flow is critical: the agent of destruction must be so liquid -- about the consistency of a thick milkshake -- that it cannot be shoveled. In other words, it must have the unique attributes of mud.

Because the Rolling Bay slide satisfied that criterion, the Herrens' insurance paid for the loss of their home. What was not anticipated was that no one would survive to collect the money.

Dwight Herren's family has established a scholarship in his name for promising science students at the local high school, and the city of Bellevue, where Jennifer Cantrell-Herren worked as an urban planner, has dedicated a park playground in her memory. From boyhood Dwight was passionate about science; as an adult he was a deeply committed teacher, devoted to learning of all kinds. Jennifer, a staunch environmentalist, started Bellevue's recycling program. People now wonder how this intelligent, loving couple, so attuned to the earth and the sea, could have risked all for the sake of a view. But many others are making the same potential mistake. "There's nothing to say it couldn't have happened to any of a thousand other houses along Puget Sound," Donald Tubbs says.

The battered beach at Rolling Bay still reeks of sadness; it is impossible to imagine that the pall will ever lift from this particular shore. "Look this way and it's beautiful," Clare says, gazing at the gentle surface of the bay, sheltered from prevailing winds by a promontory called Skiff Point. "Look that way" -- she inclines her head toward the fortified rear of her house -- "and there's that sort of funny twist. That hidden danger."

The vacant lots will probably not be rebuilt; there's not enough room at the toe of the cliff to meet current standards. Still, memories are short. Events have proved that. As long as houses remain on the beach, as long as the views beckon, people will be tempted to push their luck. There could come a day -- not soon, but someday -- when the worry here is forgotten, when parents and their children sleep peacefully again in their brave houses by the water.

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Brenda Bell has written for the *Los Angeles Times Magazine* and *Utne Reader.* She is at work on a historical novel set in the Southwest.

Illustration by Bryant Wang

The Atlantic Monthly*; January 1999; The Liquid Earth; Volume 283, No. 1; pages 58 - 72.*

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