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JANUARY 1999

The Liquid Earth

Landslides and other "ground failures" cost more lives and more money each year than all other natural disasters combined, and their incidence appears to be rising. Nevertheless, the government devotes few resources to their study -- and the foolhardy continue to build and live in places likely to be consumed one day by avalanches of mud

by Brenda Bell

(*The online version of this article appears in three parts. Click here to go to part two. Click here to go to part three.*)

WE live near Seattle, on Bainbridge Island, which is roughly the size of Manhattan but has a population of only

19,000. As in most small communities, news travels rapidly by word of mouth. We heard about the mudslide about four hours after it happened, on Sunday, January 19, 1997. Our friend Dave told us about it late that morning, as he scuffed his muddy shoes on the mat inside our front door, waiting to pick up his daughter from a sleepover at our house. It was raining -- not hard, but steadily. Almost twenty-six inches of precipitation had fallen since the beginning of the rainy season, in October -- 40 percent above normal -- and the ground had been slipping all around the Puget Sound area for weeks.

Dave said that the slide had demolished a house in Rolling Bay, a picturesque old neighborhood on the east side of the island, with sweeping views across the sound to the dark glitter of Seattle and the serrated backdrop of the Cascade Mountains. The house was one of about twenty squeezed onto a sliver of beach beneath a high cliff that parallels the Rolling Bay shore. It was owned by a couple who had been remodeling it while they lived in the basement with their children. Their living quarters were buried now, and rescuers were digging through tons of mud to find the family. It didn't look good, Dave said.

After he left, I yelled upstairs to our seventeen-year-old daughter, Anna. "Did you hear about that? A big mudslide over on Rolling Bay."

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"Rolling Bay? That's where I was baby-sitting last night." Anna had come home around midnight and told me how nervous the mother had been about leaving her children -- a three-month-old baby and his two-year-old brother -- with a sitter. Now, for the first time, I realized that we had not bothered to ask Anna where she had been. "Was the house on the water?" I asked.

"Yeah."

A tremor of alarm prickled the back of my neck. "Who were you baby-sitting for?"

"Mr. Herren -- you know, the biology teacher." Herren taught advanced-placement classes at the high school, where his exuberant teaching style, good looks, and long honey-colored hair made him a standout.

"Were they sleeping in the basement?"

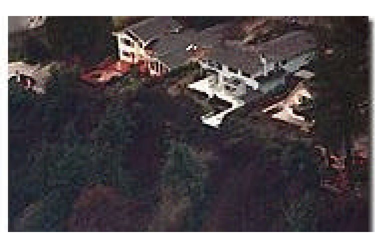
"Well, yeah. But it's not really a basement. They're just on the bottom floor."

That prickle again. I thought of my daughter giving the baby his bottle, hoisting the sturdy two-year-old onto her hip. They had watched the video *Babe* together just hours ago. I thought of cold gray mud smothering them all.

Anna went upstairs to call her friends, to find out if anyone knew anything. No one did. The phone rang once, and she had a brief conversation. Then her father and I heard her feet on the stairs. She took them slowly, one step at a time. Someone had heard something on the TV news, Anna said. *Step, step*. Her voice was matter-of-fact. They weren't releasing names, but they knew the ages of the children in the house. *Step*. *Step*. Anna stood at the bottom of the stairs, her expression strangely unreadable. "They were two years old and three months old," she said, and her words dissolved abruptly in a hard sob.

IT was still raining when I got to Rolling Bay Walk that afternoon. The sky was a flat, dead gray -- the same color as the water, and the beach, and the mud surrounding what was left of the Herren house. A portion of the top floor lay on its side, the windows framed in raw plywood and the roof lapped by the incoming tide. An orange excavating machine reached over mounds of weeping earth and shattered timbers, its segmented arm gingerly scooping up debris in the search for survivors. Emergency workers in raincoats and hard hats clambered around, but it was impossible to tell what they were doing -- or what they could do. There was no way to know what the three-story house had looked like. Save for the empty shell of the toppled roof, it was gone.

Despite the heavy equipment and a TV helicopter that hovered



Bainbridge Island, Washington: slide scar, and the remains of the Herren house on Rolling Bay Walk, January, 1997. (Photograph by Teresa Tamura, *The Seattle Times*.)

offshore, the scene seemed peculiarly quiet. The search crews had already found the body of Dwight Herren; when I saw a woman leading her search dog back to her van, I knew there was no hope for the others. Word soon passed among the bystanders that the rescuers were bringing out the body of Herren's wife, Jennifer Cantrell-Herren. A man standing next to me began to silently cry. The tiny forms of the two-year-old, Skyler, and the baby, Cooper, were recovered next. All had been sleeping in the same bedroom on the ground floor when the tremendous force of the mudslide crushed the house on top of them, killing them instantly.

Farther up the beach the street was blocked by a recent slide, a small one that had not yet been shoveled away. Next to the roadblock a vacant house bore a notice that it was unsafe for occupation. Several such notices had been posted the previous year after a slide had destroyed another house. Why did people persist in living here, when the proof of disaster was all around them?

As darkness fell on Rolling Bay Walk, neighbors called for the Herrens' big Labrador, Henry. The dog didn't turn up, but other reminders of the family did. In the days that followed, detritus washed up on the beach -- ruined clothing, remnants of electronic equipment, shattered kitchen utensils. Tiny disposable diapers were half buried in the sand. A little parade of rusting Tonka trucks rested nearby. People put some of the items on top of a concrete bulkhead, out of reach of the tides. "For the father," a neighbor said, meaning Dwight Herren's despairing father, Vern, who walked the beach daily, trying to salvage what he could. A week after the slide I found a pair of broken binoculars, a shattered tape cassette, a packet of allergy medicine. I added them to the bleak collection. Nothing was left of this family's life but pieces of worthless trash.

The three-story house on the beach had been Dwight Herren's dream; he was building it with his own hands and the help of family members, who pitched in on weekends. He and his two brothers had grown up on a stony beach on the west side of the island, in the lee of a forested cliff much like the one at Rolling Bay, and Dwight wanted the same for his own sons. "He had an attraction to the sea, to the water," his father, an avid sailor, told me. "I have it too."

After Dwight received a master's degree from Cornell, he got a job as a marine biologist for the State of Washington, diving in water so cold that he wore two wet suits, mapping beds of geoduck clams and sea cucumbers. It was dangerous work, but he was careful. He believed utterly in himself, and that confidence was contagious. When Dwight and Jennifer bought the beach house, their fathers had voiced doubts. "We both advised them not to build there; it didn't look good to us," Vern Herren said. "But Dwight said those houses had been there for sixty or seventy years and nothing had ever happened."

A neighbor was watching when Henry was finally found. A crane unearthed the dog's corpse while clearing away the last remains of the house. "He was right under the house, in the place where he used to sleep," the man said. He spoke softly, his voice blurred with sadness, and he had to clear his throat.

Once the crane finished its dreary work, the scene looked as if no house had ever stood there, no dog had ever bounded to the front door, no children had been rocked to sleep within the walls. There was just another gap in the tattered bulwark of houses along Rolling Bay Walk, their backs to the treacherous cliff and their trusting faces fixed on the heedless sea.

Hazard Zones

LANDSLIDES are perhaps the most widespread geologic hazard, and, since they are a function of gravity, an intractable one. They play an essential role in the synchrony by which the uplifting continents are continually worn down, their sediments swept away and deposited somewhere else to start anew. They made their first known appearance in written history in 1767 B.C., when earthquake-triggered slides in China dammed the Yi and Lo Rivers. Peruvians have been well acquainted with terrible landslides for thousands of years, and have words to distinguish different kinds of them: huaico is a mudslide containing large and small rocks, llapana a smooth mudflow. Entire villages are easily lost to avalanches in the Andes -- 18,000 people were killed in a single slide in 1970, and a devastating series of mudflows claimed more than 20,000 victims in Colombia in 1985. The kind of slide that killed the Herrens is known to geologists as a debris flow -- a rapid collapse of the surface that is characteristic of slope failures in many parts of the world.

Tracks north of Seattle where, in January of 1997, mud swept a freight train into Puget Sound. (Photograph by Mike Siegel, *The Seattle Times*.)

Despite growing scientific knowledge about where and why landslides occur, the threat they pose continues to increase, for reasons familiar to students of ecological hazards:

increasing development in vulnerable terrain, global climate changes that exacerbate severe weather, and deforestation. The financial costs incurred by slides run into the billions of dollars annually in countries including the United States, Italy, India, and Japan. Poorer countries such as Nepal and Indonesia, with less development at stake, suffer great losses in human lives and productivity. Landslide casualties are usually lumped together with those of more-publicized natural phenomena: most of the victims of last year's earthquakes in Afghanistan, for instance, were killed when their homes were crushed by the avalanches of debris that followed the quake and its aftershocks. Similarly, mudslides were responsible for much of the death and destruction wrought by Hurricane Mitch in Central America this past November.

A month later, the track repaired. (Photograph by Ed Harp, USGS.)

The Japanese spend more than $4 billion annually in attempts to control debris flows and to respond to the disasters they cause. In a country that idealizes the harmony of nature, the scenic river systems near urban areas are trussed and choked by countless *sabo* dams, which trap mud and rocks sliding down from the mountains. An

American version of these dams is found in southern California, where Los Angeles County maintains a system of massive "flood control" breastworks to protect towns like Pasadena and Glendale -- not from rising water but from the boulder-laden debris flows that can rumble out of the canyons of the San Gabriel Mountains after a hard rain.

Ground failures of various sorts occur in every state; according to the National Research Council, they annually cause more deaths (twenty-five to fifty) and greater economic loss (roughly estimated at $1.5 billion) than all other natural hazards combined. Yet they get little public attention. Because there is no nationwide system for reporting landslides, hard statistics are difficult to come by: the last inventory of landslide hazards was completed in the 1980s by a geologist working for the U.S. Geological Survey who toured all fifty states (most of them in his own van) -- a 70,000-mile survey that took him three years.

Though the American West Coast is one of the most slide-prone regions in the world, other natural disasters there steal the headlines -- earthquakes, volcanoes, floods, wildfires. Debris flows are widely seen as cosmological misfires, freaks of nature, and as a result people tend to underestimate the risks they pose. Such misperceptions contribute to the general neglect of landslide studies by research entities including the USGS, which in recent years has been distracted by personnel cutbacks and congressional threats to eliminate the agency. "The USGS competes with the Forest Service as the most demoralized federal resource agency," says Bill Dietrich, a professor of geology at the University of California at Berkeley. "It came under attack from various political points of view -- it was no longer seen as so essential." Meanwhile, the agency has struggled -- unsuccessfully, its critics say -- to mount a comprehensive landslide-hazards program. "I don't think it's for lack of trying," Dietrich says. "It's for lack of getting people's attention."That struggle is reflected in the staffing of the USGS landslide group, which numbers only fifteen employees. Its annual budget of $2.4 million is dwarfed by the $49 million earthquake program, which has a staff ten times as large.

Compared with other geological hazards, landslide zones are very narrow, very specific, and relatively easy to avoid. Unfortunately, they're often also attractive places to live. The Puget Sound lowlands are a good example. Born of mud and ice, these unstable hills of sand, silt, and gravel were bulldozed and compacted by glaciers that obliterated much of the geological record before the Holocene. The jagged shoreline edges some of the newest real estate in the country, and some of the most coveted. But a third of it -- some 660 miles along the islands and mainland -- is composed of steep bluffs continually subject to collapse.

The Rolling Bay slide took about three seconds, scooping a narrow track only about three feet deep down the face of the cliff. The cumulative weight of even a shallow debris flow is enormous: in this case 2,000 tons of rocks, trees, and sodden soil landed with uncanny accuracy on the Herrens' house. It was all over before the couple next door, who were sitting outside in their hot tub, realized what was happening. There was a sudden giant exhalation -- *whumpf*! -- as the air was pushed out of the collapsing house. A forty-foot fir tree, its saucer-shaped root system intact, slid down the cliff and halted atop the wreckage, as erect as if it had been planted there. Seven houses down in the opposite direction another neighbor heard the noise and walked outside in her bathrobe to look around. She saw the shattered plywood walls on the beach, the mountain of mud, and the tree standing serenely. She heard no more sounds. "It was utterly still,"she later told me. "So still that I thought this must have happened the night before, and I just hadn't noticed."

When Dave Montgomery, an assistant professor of geology at the University of Washington, saw the front-page story in the newspaper the next day, he shook his head. "I looked at that picture in the paper," he told me afterward, "and I thought, My God -- here's a cliff that's been moving backward for 10,000 years. Why would you live below it?" Since the last Ice Age the cliff at Rolling Bay has not so much stood as retreated, retaining a steep pitch that teases the angle of repose -- the maximum angle at which a slope will hold fast. "Normal slopes tend to round over time. A steep, straight slope is something that is created and maintained by landslides," Montgomery says.

In the stormy weeks before the Herrens were killed, Seattle newspapers carried many reminders of the dangers of steep slopes: a man's house was destroyed beneath him as he rode it into the water like a ship's captain; a mudslide slammed into a freight train and threw it into Puget Sound, from the same tracks where an Amtrak train carrying 650 passengers had passed only two hours before; city officials spent $900,000 in a Sisyphean effort to stabilize a sagging section of Seattle's Magnolia Bluff, where a half dozen homes were losing their precarious perch. These stories were read not as cautionary tales but as entertaining anecdotes about life in the rainy Northwest.

"We all live with risks," Dietrich says. "But we have some sense of those risks. Most people have *no* sense of the landslide risk. You don't live through a landslide at your house very often. Now, we have places that we can easily identify that were formed by periodic debris flows. I would never live in one of those places. You couldn't pay me anything to live there. If that's the case, then how do I inform a person who's thinking of living there, or is already living there, enough to realize the decision they're making?"

Continued...

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Illustration by Bryant Wang

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Just Sitting There, Growing Trees?

THE earth comes unglued for a variety of reasons, but there is usually a single triggering event. The largest, most catastrophic debris flows are caused by earthquakes and volcanic eruptions -- hence the prevalence of landslides throughout the Pacific Rim and the mountainous regions of China, the former Soviet Union, and Central Europe. But most often the culprit is simply water -- in the form of rainfall, snowmelt, or river flow. Thus there have also been spectacular slides in Iowa and in the placid river valleys of Quebec. Pittsburgh and Cincinnati, constructed on loose sediments cut by river systems, incur some of the highest landslide costs in the United States.

Aftermath of the 1995 La Conchita landslide, in southern California. (Photograph by Robert L. Schuster, USGS.)

Perhaps the most common medium for landslides is colluvium -- basically particles of weathered rock in the process of becoming soil. Mature soils settle out into homogenous layers, called horizons. If colluvium stays still long enough, it may form horizons too. But on unstable hillsides it remains young and restless, a poorly sorted conglomeration of silt, sand, pebbles, and rocks.

Colluvium covers most of the ground surface in humid temperate zones and semi-arid mountainous areas. It is ubiquitous in the western United States and the Appalachian Range, from Maine to Alabama. Along the California and Oregon coasts tectonic stress has shattered the sandstone-and-shale bedrock of the Coast Range, and frequent ocean storms have accelerated the weathering of the rock. The result is a mantle of loose, cruddy dirt --

pre-dirt, if you will -- that produces some of the best forests on earth. Colluvium appears to be just sitting there, growing trees, but over hundreds and thousands of years it is on the move, and the direction of its movement is always downhill. It trickles into narrow gulleys, or swales, which form distinctive tracks running straight down the steep foothills. These natural sluices also catch water draining off the hilltop ridges. Colluvium may accumulate for millennia in a swale, until it is washed out by a debris flow into the valley below and the cycle starts anew.

The angle of repose for colluvium slopes averages 35 degrees but varies widely. There are thickly forested 45-degree slopes in the Oregon Coast Range that appear stable, and 26-degree hillsides in the San Francisco Bay area that have failed catastrophically. The stability of the glacially compacted bluffs on Washington's Puget Sound is sorely threatened beyond 33 degrees, especially when conditions are unusually wet. The overall incline of the cliff at Rolling Bay is just under 40 degrees.

The first axiom of debris flows is that where one has occurred, others will inevitably follow. But nobody knows when. Water must enter the soil not only in sufficient but also in correctly timed amounts. Typically what is required is a long saturation period followed by intense bursts of rain concentrated in just a few hours or days. Water passes rapidly through surface material until it hits bedrock or clay, creating a saturated zone as it fills the pores between solid particles. Rising pore pressure creates a buoyancy that effectively reduces the stabilizing friction of the colluvium on the slope beneath it. At some point gravity overcomes the natural inertia, and the soil mass breaks loose, sliding down the less permeable surface below.

Or maybe not. The debris-flow scenario depends on numerous factors: soil depth and composition, the kind of vegetation and the size of tree roots, subtle variations in slope shape, road cuts, drainage pipes, incongruities in underlying bedrock, even the presence of small animal burrows. Water can collapse a slope after traveling beneath the surface from miles away. Vibrations from trains are suspected of triggering debris flows. And sometimes there seems to be no particular cause. The 1978 Bluebird Canyon landslide, near Los Angeles, which caused $15 million in property damage, had no obvious triggering event. In June of 1993, 75 acres of Ontario farmland suddenly liquefied and clogged the South Nation River, creating the great Lemieux landslide. In September of 1997 a man sitting at a bar in Port Angeles, Washington, was crushed to death when a mudslide destroyed the building. The area had had no appreciable rain for months.

There are basically two kinds of landslides: slow and fast. The latter are more likely in loose, coarse material like sand or colluvium; most clay soils stick together better and are less prone to rapid movement. Large, deep-seated slides, in which the dislocation originates far below the face of a slope, tend to occur more slowly than shallow debris flows, which are more deadly. Because a few growing seasons will cover the tracks of shallow slides, their telltale scars are harder to spot. Slide-prone slopes may remain hidden for generations until revealed by the perfect storm. For instance, it took geologists most of this century to grasp how vulnerable the San Francisco Bay area is to debris flows. "We had always considered it a southern-California problem," Ray Wilson, a landslide expert with the USGS, says. "Then we got this storm in 1982."

In January of that year a Pacific front stalled over the Bay area, dumping as much as twenty-four inches of rain. The steady downpour was punctuated by intense cloudbursts that reminded Wilson of his home town near Houston, where tropical deluges are commonplace. In San Francisco they precipitated the largest natural disaster in the region since the earthquake of 1906, causing thirty-three deaths and nearly $300 million in property damage. When the weather cleared, aerial photographs identified 18,000 debris flows in the ten counties around San Francisco Bay.

For most of California's history the periodic slides in the Coast Range took place far from populated areas. But when suburban development pushed out into the foothills, in the latter half of this century, it spread into the serpentine valleys beneath the swales. Seventy percent of the slides in 1982 took place in the swales.

The 1982 storm spawned volumes of research papers and forever altered geologists' understanding of the northern-California landscape. But it was also instructive for what it revealed about human nature. Jerry Weber, a consulting geologist in Santa Cruz, says that our "collective disaster memory" goes back only two years, even when lives have been lost. Even when those lives were next door. "People cannot focus any longer than that unless they're directly involved," Weber says. As time passed after the 1982 storm, the horror of the slides faded from memory -- and so did the idea that they might recur. When Santa Cruz County officials ordered two dozen houses removed from a dangerously unstable area where ten people had perished in a slide, homeowners fought the action and sued to reoccupy their dwellings. One turned away inspectors at gunpoint.

The Oddstad Tragedy

ONE of the most publicized debris flows of the 1982 storm occurred on Oddstad Boulevard, in Pacifica, a town of 37,000 people south of San Francisco. Mud with the consistency of wet concrete poured down a hillside in a 1970s subdivision, smashing two houses and trapping three small children inside one of them. Rescuers shoveled through the wreckage for thirty-six hours, hoping the children had survived in a pocket of air. They hadn't. Cal Hinton, a Pacifica city councilman who was the fire chief at the time, helped to dig out the bodies. "I remember taking the blanket off them. They'd been in bed asleep. They were still clean underneath, no blood or anything. I don't remember what the autopsy said, whether they were crushed or smothered. I imagine it was a combination."

The two lots where the houses had stood remained vacant for years. Ray Wilson often passed by on his way to a hiking trail at the end of Oddstad. One day he noticed a FOR SALE sign on one of the properties. By 1998 new houses had been built on both lots and sold to new owners. This did not seem to be a noteworthy event in Pacifica. The last newspaper story on the Oddstad tragedy was written years ago. The parents of the dead children divorced and moved away. Deflection walls have been built behind the new houses; dirt and vegetation have been scraped from the hillside, and subsurface pipes are in place that are supposed to collect water before it can cause more slides.

A legacy of the 1982 storm is Pacifica's policy requiring expert review of new construction on problem sites like these. These sites are common in Pacifica -- as might be expected in a town bounded by earthquake faults, a mountain range, and cliffs that are sloughing into the sea. But despite the precautions being taken, the San Francisco consulting geologist Robert Wright is uneasy. "I spent about five years of my life studying that slide," he says, "and I'm personally uncomfortable with rebuilding houses there. You just don't put homes in the mouths of swales if you can help it. It's just too risky."

There are "hard" solutions to landslide risk -- debris dams, retaining structures, graded slopes, elaborate drainage systems, even, in Japan, a $210 million highway overpass that coils improbably around a large slide area. Geoscientists argue that "soft" solutions like zoning and building codes, which rely on simple avoidance, are cheaper and safer in the long run. San Mateo County, which permits only one living unit per forty acres in geologically hazardous areas, probably has the strictest such ordinances in the country. But they don't apply inside Pacifica and other San Mateo towns, where local governments say "maybe" to developers far more often than "no." Saying no is especially difficult because slides occur so erratically, over such long intervals. New developments notwithstanding, the question persists: What should be done about dangerous places where people already live?

A landslide-warning system would at least alert residents when slide conditions were developing. "Even if you're in an area that in 1982 would have been a deathtrap, you're really only in danger for a few days a decade -- usually at night," Ray Wilson says. "You can broadcast a warning over the weather radio that advises people when they need to leave. If they choose to stay -- well, God bless 'em and keep 'em." In 1986 in the Bay area the USGS set up the nation's first warning system, employing a two-step rainfall threshold that correlated with high debris-flow activity. The first threshold was a seasonal accumulation of eleven inches, normally reached a few weeks after the winter solstice. The second threshold was any single storm that exceeded 30 percent of the local mean average precipitation. By monitoring a network of seventy-five rain gauges and several piezometers (which measure pore pressure in the water table), the USGS knew when rainfall was approaching dangerous levels, and issued warnings so that residents of risky areas could evacuate. There was talk of expanding the system to Los Angeles County. But when the agency downsized, in 1995, the program was abruptly canceled. "The whole thing cost peanuts -- maybe fifty thousand dollars a year," Wilson says. "We got all kinds of good publicity, and it really raised public consciousness. My worry is that people have forgotten all about it now."

Torrential rains brought by last winter's El Niño weather pattern produced what Wilson calls "a bumper crop" of debris flows along northern California's coastal hills, from Big Sur to Mendocino. As the geologists had hoped, slide activity appeared to correlate with their rainfall-threshold calculations. It also coincided with severe landsliding in southern California, raising concern that increasingly frequent heavy weather (there have been three strong El Niños and two weaker ones in the past sixteen years) will cause more debris flows than ever before. Even so, nothing yet compares to the scores of deaths and the tremendous damage wrought in the Coast Range by the storm of 1982. And after all this time a critical question remains unanswered. Why did the hillsides -- 18,000 of them -- suddenly fail in unison?

"I've always had this idea," Robert Wright says, "that when you have an Oddstad and it decides to go off, it's owing to something happening in the ground on a very small scale. I think the answer might be in microscopic changes brought about by weathering processes that change the nature of how the particles behave. On Oddstad there were several swales that did not fail in 1982. They had the same materials, the same rainfall, everything was the same -- except something was not. The swale that did fail had sat there for maybe eight thousand years. There's no way there haven't been rainstorms bigger than that in all that time. It went through maybe hundreds of them and didn't fail. Why then? We don't know."

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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."

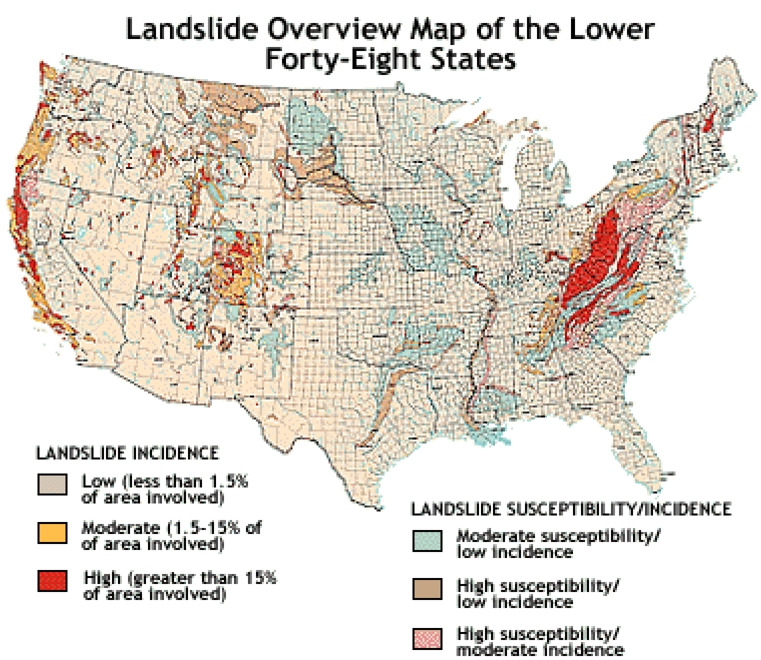
Montgomery signaled to the pilot that they had enough pictures. Mettman Ridge, which generated the data for half a dozen Ph.D. dissertations, including Montgomery's, faded into the distance.

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.

The online version of this article appears in three parts. Click here to go to part one. Click here to go to part two.

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Illustration by Bryant Wang

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