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Opposite: This photo shows coal tips in Aberfam, Wales where a landslide occurred. The overlay shows areas of slide activity.
What causes earthquakes and volcanism? How are mountain ranges formed? Why are there continents? The transformation of classical geology from a qualitative study of surface features to a quantitative science based on the fundamental laws of physics, chemistry, and mathematics is helping man arrive at answers to these and related questions.

In the past two years scientists have devised a comprehensive model for the dynamic behavior of the earth. In this model the crust of the earth is divided into a series of plates. The plates are segments of a sphere (fig. 1). These surface plates are created at oceanic ridges and destroyed at oceanic trenches. Each plate is rigid, but adjacent plates move with respect to each other. For example, the San Andreas Fault in California is the result of the movement to the northwest of the Pacific plate relative to the North American plate.

ORIGINS OF EARTHQUAKES AND VOLCANIC ERUPTIONS

The plate model explains the worldwide distribution of earthquakes. Earthquakes of large magnitude and deep earthquakes are associated with oceanic trenches. These earthquakes are the result of the downward movement of the oceanic crust into the earth's mantle. They lie along an inclined plane, and studies of seismic waves show that a cold, plate-like region, known as the descending crust, lies beneath the seismic zone. When the Great Alaskan Earthquake occurred in 1964, it was the result of the movement of the Pacific plate downward beneath Alaska.

Shallow earthquakes occur beneath oceanic ridges. The tensional character of these quakes is explained by the creation of new crust at the ridges and the continuous movement of the crust and upper mantle away from the ridges.

Through the use of this plate model, one can determine the rate at which strain is accumulating on major faults such as the San Andreas. As a result, the magnitude of an earthquake on the fault can be predicted. The time of its occurrence cannot, however, for the amount of strain that is required to trigger an earthquake is unknown.
The plate model also explains the worldwide distribution of volcanism. Most of the earth's volcanic eruptions occur on the continental side of oceanic trenches—for example, in Japan. This volcanism is attributed to frictional heating on the inclined fault zone associated with the descending movement of crustal material. The plate model also explains the type of lavas produced in volcanoes. The extensive volcanic activity associated with oceanic ridges is the actual origin of the oceanic crust. The crust is formed from the basaltic lavas that well up from the earth's interior in the vicinity of the ridge. The crust then moves away from the ridge as part of a plate (fig. 2).

Indeed, the creation of continents is a natural consequence of the downward movement of plates. Crustal material is scraped off the plate as it descends into the earth's mantle. The volcanic activity behind the oceanic trenches also contributes to the formation of continents. The Chilean coast, the Aleutians, and Japan are examples of regions in which new continental material is being created. The moun-
tain building that is going on in these areas is a direct result of the stresses associated with the interaction between adjacent plates.

CONTINENTAL DRIFT

Continental drift, too, may be explained by the plate theory. At one time South America and Africa formed part of the continent called Gondwanaland. (Evidence comes from matching rock type and age, mountain ranges, ancient fault zones, mineral deposits, and fauna along the coasts of these continents as well as from observing the fit which is obvious on any map.) A split occurred and an oceanic ridge formed. The oceanic crust created at this ridge spread laterally on either side of the ridge, creating the Atlantic Ocean. Today, this ridge bisects the Atlantic Ocean. The Red Sea represents the beginning of a new ocean as Africa drifts away from the Arabian peninsula.

With the theory of continental drift, many diverse phenomena can be explained—glaciation in India, oil in Alaska, tropical fossils in Antarctica. The Caledonian Mountains in Scotland and the Appalachian Mountains in North America were once connected. They were created before the separation of North America and Europe by a previous episode of plate movement. A study of past plate movements is similar to solving a jigsaw puzzle.

Today, most earth scientists accept continental drift as a geologic fact, but the theory of continental drift has not always been so well received. In the earlier part of this century Alfred Wegener proposed that continental movements were driven by gravitational forces. This explanation fell into disrepute during the 1930s and 1940s after Sir Harold Jeffreys showed that gravitational forces are many orders of magnitude too small to provide the required relative motion. In the last twenty years or so quantitative evidence supporting continental drift has been obtained.

At the time rocks are formed by the cooling of lavas they acquire a permanent magnetic field, with orientation
and intensity dependent on the earth’s magnetic field at that time. Systematic measurements made in relatively undisturbed rock sequences have given two principal results: the polarity of the earth’s magnetic field has undergone periodic reversals in the past, and the apparent magnetic latitude of a given area has varied continuously with time. From measurements made on a rock unit of known age, one can derive an apparent magnetic pole position with respect to that area at a specific time; measurements on rocks of different ages allow the derivation of a polar wandering path. Of particular interest was the discovery that contemporaneous positions of the earth’s magnetic pole, as determined from measurements on different continents, do not coincide (fig. 3). The difference between the pole positions found for North America and Europe can be explained by the relative movement between continents over long periods of time.

The conclusive evidence for plate motion was the correlation of magnetic anomalies adjacent to oceanic ridges with the reversals of the earth’s magnetic field. Measurements have shown a striped pattern of magnetic anomalies parallel to the worldwide ridge system. In 1963 Fred Vine and Drummond Matthews correlated the spacing of these stripes with the periodic reversals in the earth’s magnetic field. The correlation provided an accurate measurement of the velocity at which plates are moving away from the ridges.

**SOURCES OF ENERGY**

The assumption that segments of the earth’s crust are in relative movement forms the basis for a comprehensive understanding of geology. The geophysicist cannot be satisfied, however, until a rigorous theory for the cause of the relative motions is available. There must be an energy source for the energy dissipated in earthquakes and volcanic eruptions. Regardless of the energies associated with the formation of the earth, it is likely that the release of gravitational potential energy associated with the separation of the dense metallic core was sufficient to melt, or

Opposite page: It is postulated that at one time all the land masses of the earth were joined together on one giant protocontinent. Austrian geologist Eduard Suess called it Gondwanaland, after a province of rock in central India.

Figure 2. The movement of oceanic crust is represented by this schematic model. The cooling of the hot, ascending flow by conduction to the ocean establishes a cold, brittle, thermal boundary layer at the upper surface (A). Gravitational instability of this layer and the interference of the continental margin cause descending flow along an inclined fault characterized by seismic activity (B). Partial melting along the fault zone causes volcanic activity at the surface (C).
nearly melt, the entire earth between three and four-and-one-half billion years ago. Since that time the main source of heat has been radioactive decay of unstable isotopes of uranium, thorium, and potassium.

There must be a mechanism that converts this heat into motion. This conversion can only occur if the mantle behaves like a fluid. If a fluid is heated from below or from within in the presence of a gravitational field, motion will occur. Think of the overturning motion of a thick liquid heated on a stove or the upward motion of the air above a hot sidewalk. The radioactive heat-release in the mantle causes an overturning motion of mantle material that in turn causes the motion of the surface plates. The ascending flow occurs beneath oceanic ridges, the descending flow beneath oceanic trenches.

Convection cells in the earth's mantle were first proposed by Arthur Holmes in 1931 as a mechanism for continental drift. The concept that the oceanic crust is created at the oceanic ridges and carried away from the ridges on a convection cell was first proposed by Harry Hess in 1965 and is known as sea floor spreading.

The spreading rate of the ocean floor is 1–5 cm/year. This rate is of the correct magnitude to explain continental drift. The mean rates of slip on major fault zones are also in the range of 1–5 cm/year. Conclusive evidence supporting sea floor spreading has been obtained from cores of sediment collected from the ocean floor by the United States oceanographic ship *Glomar Challenger*. The sediments were found...
to be older the farther away from the mid-ocean ridges they were drilled. Furthermore, the surface heat flux at ocean ridges is as much as six times the average for ocean floors.

The continents float on the earth's mantle like blocks of wood on water. The roots of mountains sink into the mantle. When an ice load is applied, the continent upon which it rests is depressed. In the case of Greenland, the center is depressed below sea level. If an ice load is removed by melting, a rebound occurs. Scandinavia is still rising at about one centimeter a year as a result of the removal of the ice load left from the last ice age. These observations are completely consistent with the theory of a fluid-like mantle.

The thick crust of the continents is carried about passively on the convection cells in the mantle. Its mean density is too low and its thickness too great for it to participate to any significant extent in descending flow. It appears that a continental mass will ride a convection cell as far as the zone of descending flow; once there the continent either decouples from the flow beneath or stops the flow. In contrast, it appears that the thin, cold oceanic crust can readily be carried down into the mantle.

The postulate that the earth's mantle behaves like a fluid provides an explanation for the movement of plates and also explains other observed phenomena. However, an explanation for the fluid behavior of crystalline rocks is necessary. It is known that these rocks respond to the propagation of seismic waves like a solid. But the time
scale of continental movement is far removed from that of a seismic wave. Laboratory experiments have shown that a crystalline solid, which exhibits elastic behavior on short time-scales, will creep on long time-scales under the influence of a stress. Since the rate of strain for diffusion creep is proportional to the stress, the crystalline solid behaves like a Newtonian fluid. Quantitative calculations have shown that the fluid behavior of the earth's mantle may be explained by diffusion creep.

Using the theoretical expression for viscosity based on diffusion creep, it is possible to carry out numerical calculations for the structure of convection cells in the earth's mantle. These calculations have allowed the prediction of surface heat flux, topography of the ocean flow, and gravitational field anomalies. The predictions are in good agreement with observations.

THE NEW GEOLOGY

The new geology is a truly interdisciplinary field. Extensive research in geochemistry is necessary for knowledge of the materials in the earth's mantle and crust. Research in solid state physics is necessary for an understanding of deformation mechanisms. A knowledge of fluid dynamics is essential to the study of deformation processes.

The evidence gained from observations is essential not only for the testing of hypotheses and theoretical calculations but for the very make-up of any comprehensive theory. Seismic observations have been the primary source of information to date on the interior of the earth. Observations of variations in the earth's gravitational and magnetic fields must be explained. The heat flux to the earth's surface must be accurately measured both on continents and on ocean floors. The great range of surface data geologists have amassed from studies of surface features and rock types must be explained. A host of problems in the field of classical geology must be reconsidered.

Geophysical research has many practical applications. It may lead to the prediction and control of earthquakes and volcanic eruptions. It may help man determine the distribution of minerals and other natural resources on the earth. And it may help him vary the climate. The geophysics of the earth is certain to be one of the exciting areas of scientific research in the 1970s. It is essential to man's basic understanding of his environment, and engineers can play an important role in geophysical research.
Donald L. Turcotte is professor of aerospace engineering at Cornell. While a National Science Foundation postdoctoral fellow in the Department of Engineering Science at the University of Oxford in 1965-66, he was introduced to the problems of the moving earth by Ronald Oxburgh, a lecturer in geology and fellow of St. Edmund Hall at Oxford. Together they have published a series of papers relating geology and fluid dynamics. Professor Oxburgh has spent two summers at the Graduate School of Aerospace Engineering at Cornell.

In carrying out numerical calculations of mantle convection, Professor Turcotte has collaborated with Kenneth Torrance, assistant professor of thermal engineering at Cornell.

Professor Turcotte earned the Bachelor of Science degree in mechanical engineering in 1954 and the Doctor of Philosophy degree in aerospace engineering in 1958, both from the California Institute of Technology. He was awarded a Master's degree in aerospace engineering from Cornell in 1955. He joined the Cornell faculty in 1959 after serving for a year as an assistant professor of aeronautical engineering at the United States Naval Postgraduate School in Monterey, California.

In addition to teaching an undergraduate course in thermodynamics and a graduate course in magnetohydrodynamics, Professor Turcotte participates in a freshman engineering program called "Meet the Professors." He is author of the text Space Propulsion (New York: Blaisdell, 1965) and coauthor of Statistical Thermodynamics (Reading, Mass.: Addison-Wesley, 1963). He is a member of the American Institute of Aeronautics and Astronautics, the American Physical Society, and the American Geophysical Union.
Hundreds of minor earthquakes are recorded each year, with no loss to person or property. But catastrophic earthquakes do occur and not infrequently. As yet we cannot predict when. In the past decade there have been major quakes in Morocco, Chile, Iran, Turkey, Yugoslavia, Venezuela, the United States, Japan, and the Philippines. They have caused the loss of thousands of lives and millions of dollars of property.

According to some ancient beliefs, Ruaumoko, the god of earthquakes, caused the quakes that shook the earth's surface. From early times, man has attributed the phenomenon of earthquakes to the supernatural. In the past thirty years, however, extensive measurements of quakes have provided more substantial evidence of their cause.

It is generally accepted that earthquakes are caused by the release of strain in the earth's crust. Slow movement of land masses builds up this strain. We know that land masses move because we have evidence that mountain regions are continuously moving upwards and downwards and that the middle of continents displace one way while ocean beds displace another. If people realize that the crust is very thin compared with the core of the earth, they should not find it difficult to believe they are on the surface of a deforming earth.

As land masses move, the stresses in certain locations of the bedrock become too high, and the rock ruptures or slips along existing faults (slip surfaces). This sudden release of built-up strain energy causes stress waves of various kinds that travel to the surface and along it. The best known fault is the San Andreas Fault near San Francisco.

Seismologists are busy monitoring and assessing the slow relative movements between the sides of known faults. They realize that absence of movement along portions of an active fault may mean that strain energy is being stored. This situation enhances the possibility of a major earthquake occurring. Some authorities think it may be feasible to prevent large earth-
quakes by triggering many small energy releases along active faults, thereby avoiding the build-up of large amounts of energy.

CAUSES OF STRUCTURAL FAILURES

The vertical and horizontal vibrations of the ground during an earthquake induce deformations in structures because they cannot follow such rapid motion. The inertia of mass of a structure resists motion. If a structure is unable to ride with the ground vibrations or cannot deform sufficiently, it will be damaged. Thus, it is the capacity of a structure to deform without failure that is of utmost importance in structural design.

Besides causing vibrations in the ground, earthquakes excite the ocean floor, causing tremendous ocean waves (tsunamis). These high waves travel very fast and hit the coasts of continents like a moving wall of water. They are another source of damage to buildings.

A structure does not have to be near an earthquake to be damaged by it. Responses of particular structures vary with their distance from the center of an earthquake. The stress waves travel in the earth's crust, and the frequency of vibration in the ground decreases as the waves travel away from the origin of the disturbance. In general, resonance conditions occur both in stiff structures (that is, ones with high natural frequencies) near the center of an earthquake and in flexible structures (with low natural frequencies) far from the epicenter. This fact must be considered when underground nuclear test devices are triggered away from cities.

Resonance of a structure also depends on soil conditions. For example, a basin of soft subsoil may respond to stress waves like a bowl of jelly responds to agitation; the soil's response strongly influences the vibration of the surface and the structures built upon it.

PREDICTING EARTHQUAKE OCCURRENCE

Before we can develop rational prediction theories and procedures for earthquakes, we need to have more measurements of stress waves at vari-
"A structure does not have to be near an earthquake to be damaged by it."

A number of experts believe that an above-average size earthquake is overdue in California. They share the opinion that "the sooner, the better," for their instruments are ready and many new, high-rise buildings need testing.

The most widely used scale for describing the intensity of earthquakes is the Modified Mercalli Scale. It assigns intensity numbers from 1 to 12 to earthquakes, depending on the amount of damage they cause and their perceptibility to humans. For example, during an earthquake of intensity 5
some dishes are broken, some objects overturned, and everyone feels the motion. An earthquake of intensity 8 damages most ordinary structures. Walls are thrown out of building frames. Some structures collapse. Heavy furniture may tip over. The Alaskan earthquake of March 27, 1964 had an intensity of 8.4.

In recent years, the United States Coast and Geodetic Survey has been installing many seismographs to record earthquakes. But the amount of financial support currently available for seismological and related research is pitifully low. As shown in figure 2, most of the recorded earthquakes in the United States occurred along the West Coast. Other areas do experience disturbances, though. It will require years of extensive research before we can predict with some degree of certainty the occurrence of an earthquake. (As shown in figure 3, nuclear reactor plants have been built in areas of major seismic activity. The effects of earthquakes on reactors will be discussed later.)

DESIGNING SAFER STRUCTURES

Structural engineers are faced with the task of designing buildings, bridges, water towers, and other structures to withstand earthquakes. Building codes, which are based on information gathered from experience and research, contain empirical formulas that specify the total horizontal force for which a structure must be designed. (The vertical forces are usually neglected since structures are much stronger in the vertical direction than in the horizontal.) Recent revisions of these codes have incorporated structural engineers' increased understanding of the dynamic forces experienced by various kinds of structures during ground disturbances. Forces affecting structural design vary greatly depending on the magnitude of earthquake activity in different regions. The United States has been divided into four earthquake zones, numbered from zero (no activity) to three (major seismic activity), (fig. 3.)

The basic philosophy in the design approach is to build structures that will
Bradfield Hall, part of the New York State College of Agriculture facilities at Cornell. It was built during 1965—68 and is designed to provide a completely controlled environment for experimental research in agronomy, biometry, and genetics. The dramatic, fortress-like structure contains considerable square footage on a small space on the agriculture campus.
experience very little damage from moderate-size quakes (which occur frequently) and will also withstand large quakes.

It has become clear in recent years that a considerable portion of the energy transmitted from ground motion to a structure is absorbed by inelastic deformations, cracking, and damping. A good design has to assure that the structure is ductile as opposed to brittle (that is, that it can deform inelastically without failure). Glass and concrete structures without steel reinforcement are examples of brittle structures. They shatter with little deformation. Most of the damage done to buildings during earthquakes has occurred in brittle structures or their components (such as brick walls).

Extensive research in the past decade has proved that most structures made of steel, concrete, timber, or masonry can be made ductile by proper design. Load-deformation curves of two concrete frames, one with proper steel reinforcement and the other with insufficient reinforcement, are shown in figure 4. As curve b shows, if confinement (lateral pressure) is provided, concrete can undergo a large amount of deformation without crushing. Confinement is usually provided by spiral steel bars wrapped around the longitudinal bars in concrete columns or beams. This steel cage restricts the transverse expansion of the member and postpones failure.

The seismic provisions of a new building code for California have introduced "ductile concrete." As shown above, concrete structural elements can be quite ductile and deform to a great extent without crushing. The work of members of the Structural Engineering Department at Cornell has contributed significantly to the study of ductility of structures. Professors George Winter, Floyd Slate, Richard White, and I have been involved in basic research on the ductility of concrete, reinforced concrete, and light-gage steel structural members.

Besides assuring the ductile behavior of structural elements (beams, columns, walls, tension ties), a good design must tie these elements together to prevent failure during vibrations. A number of high-rise buildings failed in Caracas, Venezuela, during the 1967 earthquake there because their walls were not tied to the structural frames.

Contrary to fears by laymen, it is very unlikely that a building would tip over during an earthquake. In fact, to my knowledge no major structure has ever toppled. When furniture is upset it is mainly due to the fact that the vibration of the floors in a building is quite different from that of the ground.

We still do not know enough about the strength and stiffness of structural assemblies. Research is under way here and at several other institutions to study this problem. Static and dynamic tests are being performed, and the changes in characteristics of these assemblies during vibration are being investigated. This work includes tests on small-scale models. Professor Richard White has been especially active in this area.

Valuable experience may be gained by studying the performance of structures during earthquakes. A comparison of the different kinds of damage resulting in differently designed struc-
The advent of the nuclear reactor has . . . given impetus to progress in earthquake engineering.

The San Andreas Fault near San Francisco, California.

The observance of the dynamic behavior of novel types of structural elements is especially informative because it provides data for future design procedures.

PROGRESS IN EARTHQUAKE ENGINEERING

Our capability to analyze the dynamics of complex structures has progressed astoundingly in the last decade. With the development of large computers, the detailed analysis of structures is becoming a routine procedure. This development has also altered our approach to teaching structural engineering and changed the role of the practicing structural engineer. He is no longer principally occupied with lengthy calculations but can spend his time and talents on innovation and the planning for entire building projects, not just individual structures.

The advent of the nuclear reactor has also given impetus to progress in earthquake engineering. Damage to a reactor plant would have far greater consequences than damage to an apartment building. Because of this danger, structural engineers have increased the precision and reliability of their seismic designs, under the close supervision of the Atomic Energy Commission. The manifold safeguards developed for the protection of reactors during earthquakes are unparalleled in the structural engineering profession. Reactor plants have been designed to continue operation during moderate-size quakes and to be shut down safely in the event of a major earthquake. The worst that could happen would be that the reactor would melt. Even then no harmful leakage could penetrate its containment vessel.

Other types of modern structures, such as skyscrapers with light curtain-walls, structures with precast elements (such as Montreal’s L'Habitat), tall towers, and huge liquid storage tanks, also pose challenges to the structural engineer. With the continuous emergence of novel structures, it is essential that architects consult structural engineers at the beginning of new projects to assure that structural feasibility and
Above: The diagram shows the circular and straight line tunnels burrowed under an athletic field on the campus to house part of Cornell's 10 CeV synchrotron. The circular tunnel is about eleven feet in diameter and approximately half a mile in circumference. The $11,298,000 synchrotron was financed by the National Science Foundation.

Efficiency are considered. Architects and owners must balance the extra cost of earthquake-resistant design with the probable frequency of earthquakes and the cost associated with repairing damage. With the help of computers and vigorous research on the behavior of structures, we should be able to design common and exotic types of structures to resist earthquakes.

Peter Gergely has been a member of the College of Engineering faculty since 1963, when he received the Doctor of Philosophy degree in structural engineering from the University of Illinois at Urbana. Born in Budapest, Hungary, Professor Gergely attended the Technical University in Budapest for two years before transferring to McGill University in Montreal. He received the Bachelor of Science degree in applied mechanics from McGill in 1960 and the Master of Science degree in civil engineering from Illinois in 1962. He became an American citizen in 1968.

Professor Gergely has supervised research at Cornell on various aspects of cracking in reinforced concrete, thin-walled steel hyperbolic paraboloid shells, anchorage systems in prestressed concrete reactor vessels, and computer analysis methods.

During the fall term, he was on sabbatical leave and was employed by the Pittsburgh-Des Moines Steel Company in Pittsburgh, where he worked on the design of steel shells and pressure vessels and on the seismic design of components for nuclear reactor facilities. His consulting work has involved computer analyses, seismic design, finite element analyses of nuclear containment structures, and design of shell structures.

He is a member of the American Society of Civil Engineers, the American Concrete Institute, the American Society for Engineering Education, and the International Association for Bridge and Structural Engineering. He is an active member of several national technical committees and is a registered professional engineer in New York State.
What causes landslides?

Erosion, that is to say, landslides are caused by the steepening of slopes and by water. The strength of soil materials is primarily determined by what is called the effective stresses in the ground. This means that the actual force between the clay, rock, or sand particles determines the strength. If water gets between the particles it produces uplift, in an Archimedean sense. The force between the particles is reduced, and the shear strength then decreases. That is why water is such an important aspect of landslides.

One gets the idea that landslides are caused by man as well as by nature. Is this true?

Oh, yes. When man starts to build highways or dams—anything that involves either cutting into a hillside or constructing a road—he's liable to upset the equilibrium and start a landslide. This is equivalent to the erosion problem of increasing the steepness of the slope.

What are the forces that hold rock, clay, and sand particles together?

If we can confine ourselves for the moment to nonrock, that is to say, things that aren't stuck together with some sort of glue, then there is something called friction. Mind you, friction is a word we don't really understand, but it depends on the normal stress on any sliding surface, so the strength of the material depends on the normal stress. In some clay shales there are forces that hold the particles together, but in the long term, due to weathering, the magnitude of these forces decreases and landslides may occur.

Are there particular areas in the world where landslides occur with great frequency?

Yes, in those areas where the topography is steep and in all areas where active erosion is going on.

What do you mean by active erosion?

Where streams are cutting down, increasing the depth of the dents in the land. Slides occur to a very marked degree in places which have undergone
recent uplift. For example, in some parts of Scandinavia the land has been rising as a result of the ice removal from the last ice age. As the land rises, the streams are cutting down to a new base level, the valleys are getting deeper, and landslides are occurring.

Are landslides related to areas with high seismic activity?

Only in so far as the forces imposed by the earthquake produce a weakening of the material. You see, the significant period of oscillation for earth rumble is about one half a second. There can't be a lot of movement in half a second if the ground strength is not affected. There are difficulties if the shaking process during an earth rumble reduces the strength of the soil. For example, it may shatter rock and then rocks fall or, in a particular case of loose sand, vibrations can lead to an increase in pore water pressure. When the earthquake is gone, there is a higher pore water pressure left; this reduces the shear strength of the material and landslides can occur. A number of landslides occurred in Alaska after the 1964 earthquake there.

Are there means of predicting when slides will occur? Are they related to stress levels in the ground?

I think it's not so much a question of stresses as a question of the relationship among the angle of shear of the material, the slope, and the pore water pressure. The most common cause is a sudden increase in pore pressure, which can be measured. But measuring everywhere is impossible. If there is a certain place one is concerned about, measuring the pore pressures and taking steps to reduce them if they are too high can very often prevent a slide from occurring.

Where do the worst conditions for landslides prevail?

The worst conditions are in areas where there have been landslides before. The strength of the material has been permanently reduced. Many of the problems in highways, as far as landslides are concerned, occur when roads are placed on top of old landslide debris or cuts are made in places in which there have been landslides.

What's important here is that very often it is not the steepest slopes that are the most dangerous. In the landslide process gullies are formed where landslides have occurred and these act as drains. So, on the steepest slopes, which are better drained, one finds the pore pressures are lower, and these slopes are often more stable than the gentler slopes. I remember some years ago a pipe line was built up a hill in England. The engineers chose a route which was the gentlest way up the hill but it happened to be on top of an old landslide and it started to move. In another case in India, the penstocks in a hydro plant were taken down a gentle slope that happened to be the site of an old landslide. Again, movement occurred.

Are people in public works not as knowledgeable about landslides as they might be?

Firstly, I think it's very clear that they're not. Secondly, I think the aerial photograph even in 1970 is not used nearly as much as it should be. Aerial photos can give us a bird's eye view of the terrain, and even with limited
Diagrams 1 through 3 above show how some rockfalls are caused. In 1 differential weathering of bedrock is illustrated. The top two layers consist of limestone, sandstone, lava, or other materials resistant to erosion, but the bottom layer consists of shale, tuff, or volcanic ash, making an easily weathered bed. In 2 jointed homogeneous rock is shown. It can be weathered by frost to produce wedging. In 3 hydrostatic pressure acts on loosened blocks of jointed homogeneous rock to cause rockfall.

Diagrams 4 through 6 illustrate some varieties of slump, which causes many of the landslide problems facing highway engineers. A slump is a slide in which the moving mass is not greatly deformed; movement takes place along internal slip surfaces. In 4 base failure in non-homogeneous material is shown. The surface of rupture follows the bed of very soft clay. In 5 a slide beneath some fill on the side of a hill is shown. The slip is controlled by the weak soil on which the hill was placed. Diagram 6 shows failure within the fill on the side of a hill.
experience we can see why the topography takes its particular form. Once we understand that, we know if landslides are likely to occur and what sort of precautions we'll have to take or if rerouting will have to be done.

Aerial photographs aren't expensive, are they? Why aren't they used more often?

Oh, no. They're very cheap. It's just that people don't appreciate the importance of them. Some years ago I got involved in a highway project in Africa. This was not a landslide problem but a problem of building a road across a swamp. From the aerial photographs it was clear that there was a route for this road on hard ground. I talked to the chief engineer of public works and asked him, "Why didn't you look at the aerial photos?" He replied, "We can't afford to have a man trained." I said, "You can't afford not to have a man trained."

It has been pointed out that there are no permanent remedies for landslides and that man can only provide a delaying action. Any comments?

No, I don't think that's true. As I perhaps mentioned before, given a long enough period of time the topography is in equilibrium with the climate. The climate as I define it is not just so much annual rainfall, temperature, and evaporation. It's the microclimate at a point in the ground, and man can modify this. As I said before, the most important single feature in the stability problem is pressure in the water in the ground. Drainage can reduce this pressure and thereby help maintain stability. Conversely, the pore water pressure can be increased by foolish acts, thus precipitating a landslide. This sort of thing happens very often in California, where a lot of the people live in semiarid areas. When new housing developments are put in, people like to have lawns and, from what I gather, they put eighty inches of water on their lawns each year. This raises the ground water table and causes landslides.

Suppose the Ithaca area were landslide prone. Would the likelihood of landslides occurring be greater in summer than in winter?

Actually, the spring is the most likely time, when the snow is melting. Another time is when local freezing at the surface prevents the water from getting out and therefore increases the water pressures behind the zones where freezing occurs.

What can be done to reduce the problem of serious landslides?

The first thing to do is to identify the potential slide area and look at the economics of the operation. That is, how much would have to be spent to prevent a landslide from occurring and is it worth it? Or is it easier to move the facility somewhere else? But it may not be a question of whether or not it's economical when you consider the social value of what you're trying to protect.

How does one stop a landslide?

On a small one some sort of retaining wall can be used. In a landslide of any appreciable size, you have to remember, the forces involved are enormous—there are thousands or even millions of tons of material, and the stability de-

"The most common cause (of landslides) is a sudden increase in pore (water) pressure . . ."
pends on the shear strength of the material all the way along the slide zone. Really, the only way to stop a landslide is to employ nature and lower the pore water pressure that has reduced the shear strength of the material. Of course, slopes can be flattened to some extent, but this can involve removing enormous amounts of material.

What about the pipes one sometimes sees stuck in steep slopes?

Sometimes horizontal drains are put in to drain the water out. And in rock slopes, rock bolts can sometimes be used. A rock bolt increases the stresses and forces on the material, thereby increasing its strength and holding it up. But by and large, it’s better to rely on utilizing the internal forces of a material for increasing its internal strength than to try to put up some external device to hold it back. Very often a wall has been put in and the landslide didn’t know about the wall and went straight over the top. Then there is a problem.

Do building codes take into account the hazards of landslides, particularly in residential construction?

In theory, yes. For instance, in Los Angeles County there are rules about how steep slopes can be. But it’s nearly impossible to lay down rules that are applicable to everything, for some materials are only stable in a very flat slope and others are only stable in a very steep slope. So, to lay this down in a code is extraordinarily difficult. All you can really do is make sure you get competent engineering advice. I was looking at some problems in California just a little while ago where a house had been placed on compacted soil. The bylaws say that the slopes of the soil should not be steeper than one and one-half to one. Well, the engineers had complied with the bylaws, but the slopes slipped. They were made of clay and there were lawns on top of them, and the lawns were watered. I don’t think this kind of problem is amenable to bylaws.

Is that area popular for landslides?

I think California has top rating for landslides in residential areas. For the most part, there are sedimentary rocks with sandy members and clayey members and these are folded and contorted. Where there is an orientation of the beds that is favorable to landslides, there is trouble with the clay beds. This has got to be recognized in the early stages of planning because very often people move in with the bulldozers and make a shape that suits the landscape architect and doesn’t suit the geology.

You mention landscape architects. Are they knowledgeable in general or concerned about the characteristics of landslide areas?

I think they are concerned but I don’t think they are very knowledgeable.

Are there any particular kinds of projects that are especially prone to landslide problems?

Highways going through hilly country present a problem. There are overall requirements of line and grade for the highway and, if the topography doesn’t suit, engineers are forced into cuts and fills and have to be very careful. Dams, of course, pose some very nasty problems because during the building of a dam the water regime is changed. One
very bad state of affairs is when the water in the reservoir is drawn down. You might think of it like this: the water gets into the rock and soil around the reservoir and when it is drawn down quickly it can’t get out. The water pressures in this material are then high. These draw-down failures can be very serious. A spectacular example is in Franklin D. Roosevelt Lake behind the Grand Coulee Dam. There, the walls of the reservoir are composed primarily of glacial materials of all kinds, and there’s a draw-down regularly every year.

There have been literally thousands of landslides.

The other problem, of course, is downstream of the dam, because as the level of the water is raised it gets into the hillside and has to come out somewhere. This can change the ground water regime and cause landslides downstream of the dam.

Are there instances where rises in the ground water regime cause undermining of the dam itself?

There is the problem of internal erosion, which has occurred under some dams. Undermining occurs where the water comes out, washing out materials. One must be terribly careful when designing dams that this won’t happen. That is, one has to make sure that the water can go through the dam, under the dam, around the sides of the dam, and come out safely. More and more, drainage wells downstream of the dam are used to control pressure in the water. The quantity of water flowing is really not of great significance from the stability point of view, provided it
doesn't wash material away. But the water must not cause undermining and it must not cause piping, internal erosion, or landslides. After all, one cannot contemplate the failure of a dam.

Do geologists and civil engineers work together to determine the danger of landslides before building?

Yes, they work together. They have to work together. Before they carry out any large project they have to understand the geomorphology of the area. From an engineering point of view they have to know quantitatively about the strength of materials and what will happen to them. By and large, geologists are not very much concerned about the numbers, but it takes a team approach to understand the history of a material, how it got there, and why it looks as it does. Once geologists and civil engineers understand these things, they can begin to think about how it will stand up to any changes they might impose on it and its environment.

Do builders consider land slippage more today then previously? Are we getting more sensitive to landslides?

One of the things that is making people more conscious of landslide danger is the legal claims that are being pressed at the moment, especially in California. They are a major headache for engineers giving advice in these areas. The engineers are liable should anything go wrong. The Federal Housing Administration is very concerned about the problem too. A congressional committee has been looking into it because there have been problems with FHA-guaranteed loans in housing areas where there have been very substantial landslides. Congress wants to know why FHA was giving these loans if there were going to be landslides and what all the engineers and geologists on their staff were doing.

Are there any professional organizations that attempt to watchdog the earth movers?

Not as such. All professional engineers involved with soil mechanics and all engineering geologists are clearly concerned about the problem of landslides, but I'm not sure just what you mean by watchdog.

Is there an American Society of Civil Engineers committee on the subject?

The Association of Engineering Geologists is very concerned. As you know, I presented a paper at their conference on this subject. The purpose of the conference was to see how local authorities, engineers, and geologists could work together to (a) make the best use of the geological environment, and (b) prevent disasters.

Do landslides cause more deaths than snow avalanches?

Probably more in the long run. Snow avalanches usually occur in areas of fairly low population density. But you will remember that only a few years ago there was a big landslide in a coal tip in Wales that killed over a hundred school children. And in Chile from time to time there are big mud flows that come down and wipe out villages.

Are there any analogies between snow avalanches and landslides?

There is an analogy between snow avalanches and a certain kind of landslide that occurs in the very sensitive clays. In both, once a movement starts, the structure of the material tends to collapse. In the clays there is a very high pore water pressure and a low shear strength. In the avalanches, where there is very loosely packed snow and the shearing movement tends to cause it to compact, a very high air pressure builds up. In effect, the snow comes down floating on air pressure. The avalanche accelerates because it has an excess of disturbing force over resisting force.

In your professional experience, what is the most dramatic landslide you've seen?

I think one of the more dramatic was the one that happened about eighteen months ago just outside the city of Albany in the Albany clay.

Could you elaborate on that a bit? That is one I know nothing about.

There are legal problems involved here so I can't say very much. The Albany clay was laid down in the Pleistocene Period in the Hudson Valley. It is a laminated clay. There are layers of clayey material, layers of silty material, and layers of sandy material, and some of the clay layers are rather sensitive. That is, they lose a lot of shear strength once shear deformation starts. The slide suddenly took off and moved a distance of one-hundred feet in a matter of minutes. About half a million cubic yards were involved. The dissipation of a lot of kinetic energy left a very tumbled mess of everything.

Where does the definition of a landslide end and that of rock erosion begin?

In rocks the strength of the joints and discontinuities are of overriding importance. It doesn't really matter how
strong a piece of rock is if it's got joints in it because it fails along the joints. Now, even in very soft soils there are microscopic joints, but the strength of the joints and the strength of the soil are very much the same. I think it's all a question of degree, and the form these things take depends on the relative strength of the material between the joints and the strength in the joints. The major problem is that water pressure gets in the joints and this pushes the rocks out or, by uplift, enables them to slide.

What are some examples of research currently under way in the area of soil stabilization?

If we take a very pessimistic view of life and think that we have to design against what we call the residual shear strength (that is, the strength that a material has after it has undergone very large deformations), then everything would be hopelessly expensive. The real problem in this area is to make an economically feasible engineering assessment. One of the major problems in the soils area is to decide just what the *in situ* shear strength of the material is. We can't do this by laboratory testing. This has now been established. We can only do it by a study of what goes on in the field. The field is really the laboratory for landslides. A lot of the work involves trying to understand the field process and why the laboratory tests we do make normally overestimate the strengths of the materials *in situ*.

Are there any instrumentation techniques useful in these tests? Or are they primarily observational?

They have to be observational because the scale is so large. We have to
understand what's happening—from the topography, the water pressures, whether movement is going on or not—and, in effect, work backwards. We can detect movement quite readily by slope indicators placed in a casing in the ground. We can run an indicator down and get information on the slope of the casing at any depth and integrate up from the bottom, getting a displacement curve. This is used to check where movements are occurring and what their magnitudes are. We can measure large movements in other ways.

While you've been at Cornell, how has interest in the whole area of soil engineering grown among students? Is interest greater today than it was five years ago?

I would say so, yes. Soil engineering is part of the more general problem of the environment. Soil engineering is a little odd in that we can't idealize our problems into elaborate, mathematical, computer-oriented models. The whole thing is so complex. The central problem is really to find out what is going on in the field. This is a painstaking process. Quite a lot of work is being done on finite element analyses of landslides. We have to make an awful lot of arbitrary assumptions on stress-strain relationships and geology and in time this kind of analysis will help, but at the moment I don't think we can really solve problems this way. The most difficult thing, really, is to find out what is there and what are the processes that have gone on up to this point.

I think that at the present stage we are not using the technology we have nearly widely enough. This is true for quite a lot of areas of man's activity. To some extent I think the best contribution that can be made in the next few years is not pure research as such but getting across to civil engineers and geologists what we know, what we can do, and what we can't do about landslides.

David J. Henkel is chairman of the Department of Geotechnical Engineering in the School of Civil Engineering. Before coming to Cornell in 1965 he was professor of soil mechanics at the Indian Institute of Technology in Delhi for two years. He served as lecturer in civil engineering at the Imperial College, London, from 1949 to 1963.

Professor Henkel received the Bachelor of Science degree in engineering from the University of Natal in Durban, South Africa, in 1941 and the Doctor of Philosophy degree in civil engineering from the University of London in 1958. He has been a consultant to public authorities and private firms in England, Africa, India, and the United States. His consulting work has been focused on problems in soil stability and foundations.

He is a member of the Institution of Civil Engineers (Great Britain), the American Society of Civil Engineers (ASCE), the Geological Society of London, and the United States Committee on Large Dams. He serves on several ASCE committees and is vice chairman of the program committee for an ASCE specialty conference to be held at Cornell June 22-24, 1970. The title of the conference is "Lateral Stresses in the Ground and the Design of Earth-Retaining Structures."

Professor Henkel is leaving Cornell at the end of this term to assume a position as consulting engineer with Ove Arup and Partners, London.
Crystal defects, operations research modelling, airphoto interpretation, probing with x rays, semiconductor electronics, environmental case studies, bionics and robots, fruit and vegetable harvesting, surface physics—a list of upperclass courses? No, just a part of the diet of Cornell's introductory course for freshman engineers.

Engineering 104 is set up to give students a view of the many dimensions to engineering research and practice. Three hundred freshmen take it in a term. During two lecture periods each week guest speakers, who may be Cornell faculty members or practicing engineers, discuss a variety of topics. Recently, Raphael Littauer, professor of physics, gave a lecture on the design and operation of the University's 10 GeV synchrotron. Professor William H. Erickson, associate dean of engineering and coordinator of the course, gives several lectures on the engineering design process.

Each term the students in the course form small groups to work on a project. This year they were asked to examine the pros and cons of a proposal to illustrate strength of a structure, students meeting with Professor Arthur H. Nilson of the Department of Structural Engineering were asked to design and build a cardboard model spanning 24 inches between points of vertical support. The winning model was to be that one carrying the maximum load at midspan before collapsing or deflecting in excess of 3/4 inch. At last count, Professor Nilson's model had withstood 500 pounds.
to limit transportation in cities to electric vehicles in order to reduce air pollution from the internal combustion engine. They heard Wally Rippel give his views on the development of electric vehicle technology. Mr. Rippel designed the engine in the winning car of the 1968 Great Electric Car Race between Caltech and M.I.T.

Every other week the engineering students study CUPL, Cornell's computing language, during two-hour workshops. On alternating weeks they break into small groups during these periods to meet with professors whose interests match their own. Known as the "Meet the Professors" program, this portion of Engineering 104 is very popular with the students. It gives them a chance to get to know two professors during the term on a more informal basis. They meet with faculty members in seminars or labs, becoming familiar with the kinds of work being done in different engineering fields. Over thirty professors participate in this program, and some of their meetings with students are captured on these pages.
1. Associate dean of engineering William H. Erickson presents a lecture on the principles of engineering design.

2. With Professor Ralph Bolgiano of the School of Electrical Engineering freshmen formed a seminar to discuss engineering in today's society. Some of the questions they considered were (a) What is the nature of engineering today? and (b) What are the social responsibilities of engineers?

3. Two students operate a 400,000-pound testing machine in Cornell's structures laboratory while Samuel J. Errera, associate professor of structural engineering, checks the calculations of others who have recorded strain and deflection data.

4. John Silcox, associate professor of applied physics (pointing), and Jacques Gosselin, a graduate student, discuss their research on superconductivity with freshmen.

5. Professor Richard D. Black of the Department of Agricultural Engineering and students bleed air from a mercury differential manometer in preparation for an experiment to determine the characteristics of various measuring procedures.
Below: The chalk, talk, and hand waving of Professor Eraldus N. Scala (Department of Materials Science and Engineering) are augmented by laboratory visits.

Upper right: Students examine an experimental apple harvester while Professors Gerald E. Rehkugler (in suit) and J. Robert Cooke (in shirt and tie) of the Department of Agricultural Engineering explain how it operates.

Lower right: Professor Neil M. Brice of the School of Electrical Engineering discusses probing the atmosphere. He uses a loudspeaker powered by a Hi-Fi amplifier to show how the atmosphere can be sounded.
Above: The design and performance of a lunar soil sampler developed at Cornell are explained by Professor Robert L. Wehe of the Department of Mechanical Systems and Design.

Opposite: Professor Paul L. Hartman of the Department of Applied Physics discusses the use of the devices shown for spectral isolation and photo detection of light produced by electrons in rarefied air.

Below: Roger L. Geer, professor of mechanical engineering, demonstrates how a finished pair of right- and left-handed gears function as compared with the spur-toothed type.
Upper right: Freshmen interested in the Field of Electrical Engineering receive instruction from Professor Paul D. Ankrum before performing an electronic-circuits experiment.

Right: Principles of electromechanical energy conversion can be demonstrated by a compact, motor-generator-inertia-wheel system. Professor Simpson Linke of the School of Electrical Engineering explains the operation of a transducer that simultaneously measures instantaneous shaft torque and speed.
The following publications and conference papers by faculty members and graduate students of the Cornell College of Engineering were published or presented during August, September, and October 1969. The names of Cornell personnel are in italics.

• AEROSPACE ENGINEERING


• AGRICULTURAL ENGINEERING


• APPLIED PHYSICS


- CHEMICAL ENGINEERING


- CIVIL ENGINEERING


—. 1969. Structural Decisions for Consistent Reliability Allocation. Paper read at 83rd Annual General Meet-

- COMPUTER SCIENCE


• ELECTRICAL ENGINEERING


• MATERIALS SCIENCE AND ENGINEERING

24 August 1969, Stony Brook, New York.


**MECHANICAL ENGINEERING**


Darling, R. S., and McManus, H. N., Jr. 1969. Flow patterns in circular...


• OPERATIONS RESEARCH


• THEORETICAL AND APPLIED MECHANICS


Public concern for the impact of man's behavior on his environment is now widespread. Noise; solid, liquid, and gaseous pollution; and reckless exploitation of natural resources are all getting the attention they demand. With all this attention directed to the spoils of rampant technology, however, it is easy to overlook the equally destructive influences naturally induced phenomena have on the earth's surface, the effects of volcanism, landslides, and earthquakes in particular. Although highly sophisticated force measurement techniques have been devised, scientists are still unable to predict when an earthquake, landslide, or volcanic eruption will occur. Yet these natural processes account for thousands of deaths and millions of dollars worth of property damage every decade.

Geophysical research surely has as much relevance for maintaining the well-being of the environment as research on the wastes problems of modern-day technology. Using principles of fluid dynamics, Professor Donald L. Turcotte explains the phenomenon of continental drift. His article explores the ramifications of the plate theory as an explanation for worldwide distribution of earthquakes and volcanism.

Naturally occurring phenomena such as these provide a major impetus for structural engineers and architects to devise safer and more economical structures for the earth's surface. In his article, Peter Gergely suggests that the advent of nuclear power has contributed heavily to a growing interest in seismic design. Another worrisome natural occurrence are landslides. While several landslides have originated in recent years from the development of marginal land for construction purposes, there is much work being done on research in soil stability and on the development of preventive techniques. In his interview, David J. Henkel, chairman of the Department of Geotechnical Engineering, explores the phenomenon of landslides and some techniques to control them.