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SOME ENGINEERING GEOLOGIC EFFECTS OF THE 1964 ALASKA EARTHQUAKE

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ABSTRACT

One of the greatest earthquakes of our time rocked southern Alaska on 28 March 1964 at 03.36 GMT. Its magnitude (M 8.3-8.6), duration (3-4 minutes), and extent (about 120 000 km^2) would have caused catastrophic damage in a region more heavily populated than Alaska. As it was, 130 lives were lost, and property damages exceeded $311 million.

So great an event holds unusual interest for engineering geologists, who are especially concerned about the effects of natural happenings on the works of man and of steps that can be taken to avert such effects in the future. Heavy damages throughout the meizoseismal zone were caused by direct vibration, ground breakage, subaerial and submarine landsliding, avalanching, ground compaction, tectonic subsidence and uplift, soil liquifaction, and seismic sea waves.

Anchorage, Alaska's largest city, sustained the most damage in absolute terms, although several small coastal communities were completely destroyed by sea waves. At Anchorage, damage was caused chiefly by landsliding and vibration. Much of the city rests on the Bootlegger Cove Clay, an estuarine-marine formation, that contains silty clays of low strength and high sensitivity. Dynamic failure of these clays and of interbedded sand layers led to large-scale landsliding in several parts of the city. Most of the destructive landslides moved primarily by translation, despite wide variations in size, appearance, and complexity. They slid on nearly horizontal slip surfaces in a zone of low shear strength.

INTRODUCTION

The Earthquake and its Immediate Aftermath

At 5:36 p.m., 27 March 1964, local time (28 March 1964, 0336 GMT), Anchorage and all southern Alaska within a radius of about 1 300 km of Prince William Sound were struck by perhaps the strongest earthquake to have hit North America within historic time. The magnitude of this great quake has been variously computed at 8.3-8.6 on the revised Richter scale. Its epicenter was about 129 km east-southeast of Anchorage near the head of Prince William Sound (fig. 1). Energy

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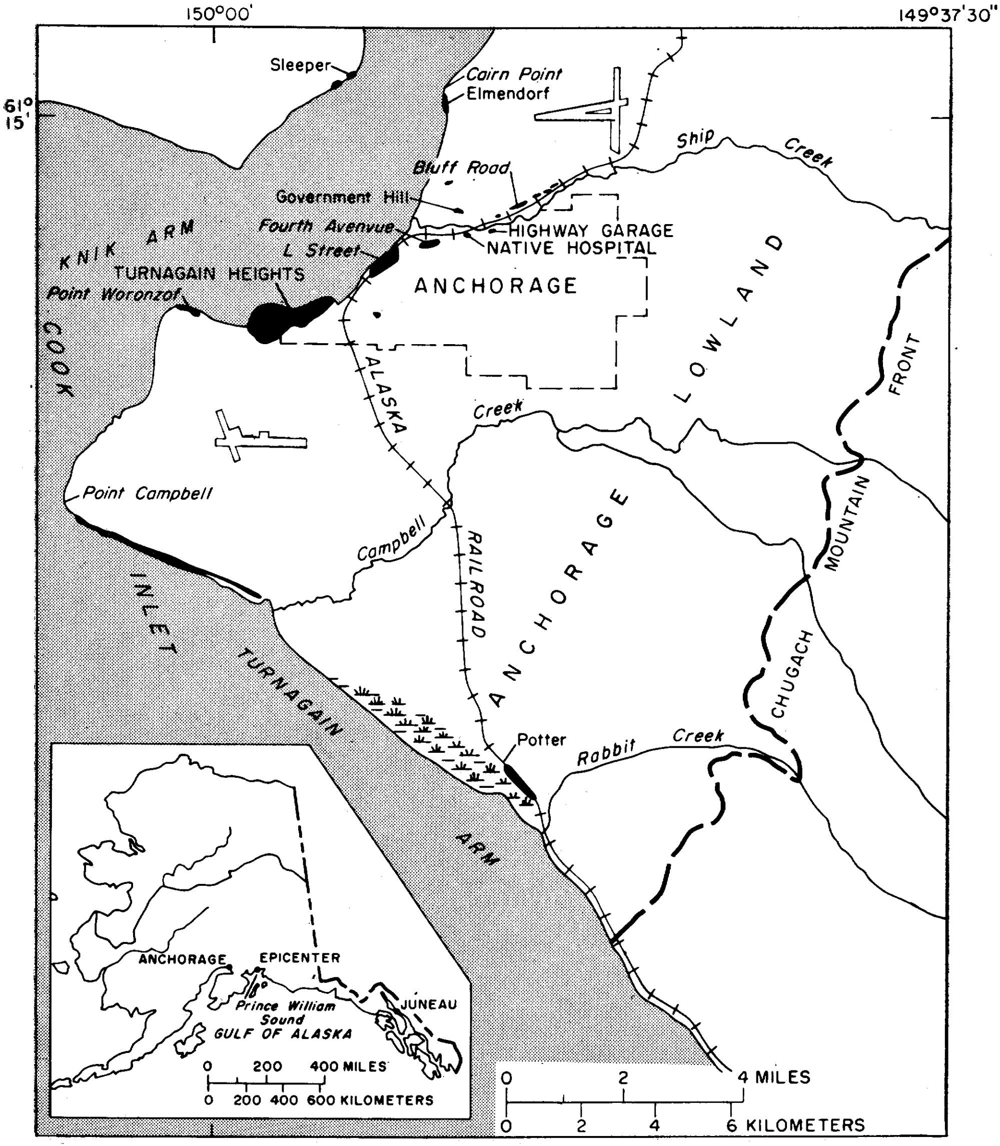


FIG. 1. — *Map showing locations of earthquake-caused landslides in the Anchorage area, Alaska, with inset showing epicenter.*

was released, however, throughout a broad area south and southwest of the epicenter beneath and adjacent to Prince William Sound and the Gulf of Alaska. Vertical tectonic-level changes took place in an area of perhaps 200 000 km^2 (Plafker, 1965, p. 1686; 1969, p. I-8). Significant damage on land took place in an area of perhaps 130 000 km^2 (Grantz and others, 1964, p. 2). Marked fluctuations in recording water wells were noted in places as distant as Puerto Rico (Waller and others, 1965, p. 131); fluctuations were recorded in such places as England, Denmark, South Africa, Israel, and Australia (Vorhis, 1967, p. C1).

Eyewitness accounts of happenings at Anchorage during and immediately after the earthquake have been reported in many publications, both technical and popular. Much valuable information has thus been gained from the objective observations of individuals who were equal to the task. Calm detachment under such trying circumstances plainly is a rare and admired virtue. Some confusion and contradiction did appear in early accounts, because of the distressing conditions under which the observations were made.

The duration of the earthquake can only be surmised owing to the lack of strong-motion seismographs in Alaska at the time of the quake. At Anchorage seismic motions seem to have lasted 3 to 4 minutes, perhaps appreciably longer. Durations of this length were timed by people with wrist or pocket watches. Where localized ground displacements occurred, as in or near landslides, motions may have been felt appreciably longer, after strong seismic shaking had ceased. Steinbrugge (1964, p. 62) noted that persons at Anchorage were able to accomplish several time-consuming tasks during the shaking, including such things as leaving and reentering buildings more than once, or helping other individuals to escape, despite much difficulty in standing and walking.

Total earthquake damage to property in Alaska perhaps will never be fully known. The final total damage estimate, exclusive of personal property and loss of income, was about $311 million (Federal Reconstruction and Development Planning Commission for Alaska, 1964, p. 11). At least 130 people were killed, including 16 whose lives were lost by drownings in California and Oregon in seismic sea waves. Nine lives were lost in Anchorage where, in less than 5 minutes, more than 2 000 people, were made homeless. The loss of life was less in Anchorage than in some of the small coastal towns, where many people were killed by sea waves. But Anchorage, because of its much greater size, bore the brunt of the property damage; property losses were greater in Anchorage than in all the rest of Alaska combined.

Early estimates by the Office of Emergency Planning indicated that about 75 percent of the city's total developed worth was measurably damaged. Early estimates of total damage, however, tended to be larger than later ones. According to the *Anchorage Daily Times* of April 9, 1964, 215 homes were destroyed in Anchorage and 157 commercial buildings were destroyed or damaged beyond repair. Scores of buildings throughout Anchorage sustained damage requiring repairs costing many thousands of dollars.

The school system was hard hit. Fortunately, classes were not in session, so the buildings were empty. Early estimates of damage came to about $3.86 million. One school building was severely damaged and another was a total loss (fig. 2). Of the 26 schools in Anchorage, 20 were soon back in operation.

In downtown Anchorage about 30 blocks of dwellings and commercial buildings were destroyed or severely damaged, and many automobiles were struck by the falling debris. All high-rise buildings (of 10 stories or more) sustained moderate to severe vibratory damage, much of it in response to vertical shearing forces caused by oscillation. Many other multistory or large-area buildings were severely damaged.

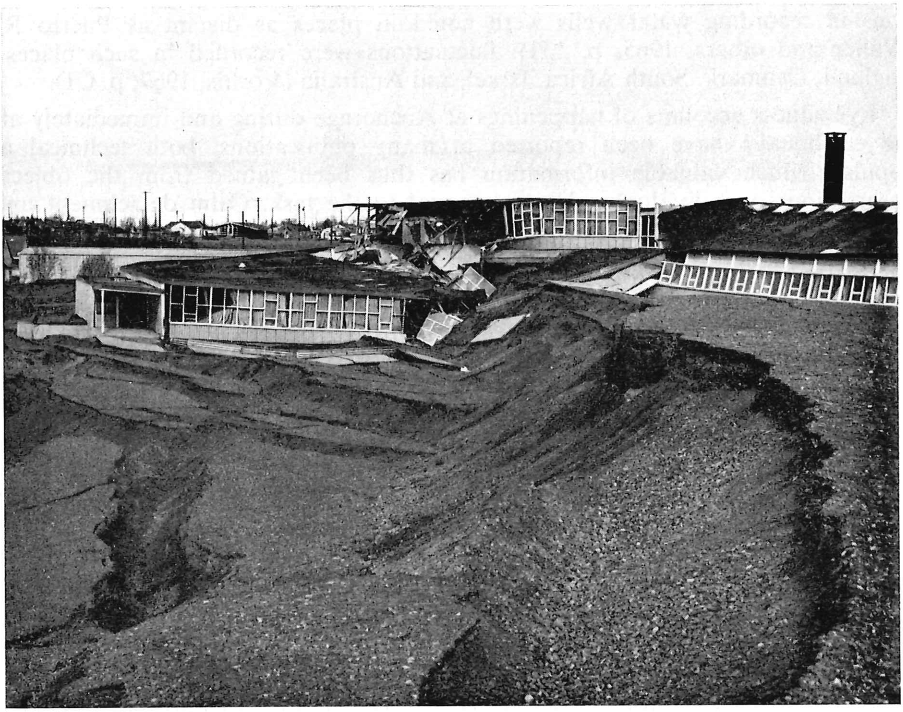


FIG. 2. — *Government Hill Elementary School, destroyed by landsliding.*

Water mains and gas, sewer, telephone, and electric systems were disrupted. Providentially, electric power failed at the onset of the quake. Although the loss of power might seem to be an added hardship to the stricken city, untold numbers of fires were probably avoided because of the lack of electric current in all the severed wires—and at a time, too, when water was unavailable for fighting fire. Anchorage spent the night of March 27 in total darkness, but the city has no fires and was prepared to deal with the many disrupted electric circuits when service was restored.

Roads and railroad facilities were badly damaged. In the downtown area, many streets were blocked by debris, and in landslide areas, streets and roads were completely disrupted. Differential settlement caused marginal cracking along scores of highway fills throughout the Anchorage Lowland. In the Alaska Railroad yards, landslide debris spread across trackage and damaged or destroyed maintenance sheds. Cars and equipment were overturned, and car shops were damaged by vibration. Along the main line of the railroad, bridges failed, fills settled, and tracks were bent or buckled; near the south margin of the Anchorage Lowland, several hundred feet of track was carried away in an area that has had a long history of repeated sliding.

Facilities at the Port of Anchorage, including docks and equipment, were damaged by seismic vibration and ground cracks. Nearby oil-storage tanks were damaged, and large quantities of fuel oil were lost.

Landslides caused the greatest devastation in the Anchorage area. Great slides occurred in the downtown business section (Fourth Avenue slide), in the lower downtown business and residential area (L Street slide), at Government Hill, and at Turnagain Heights. Less devastating slides occurred in undeveloped or unpopulated areas.

Capricious damage was caused by ground cracks. Cracking was most common behind the heads of landslides, but it was also prevalent throughout the lowland in areas underlain by clay or silt or artificial fills on muskeg. Differential compaction was a common cause. Cracking was minimal in areas of thick ground moraine.

Technical Literature

A very extensive technical literature on the Alaska Earthquake has accumulated in the 10 years since the event. This great earthquake, perhaps, has been the most thoroughly studied and best documented earthquake in history. Numerous articles on the varied aspects of the earthquake have been published by Federal and State agencies, professional and technical societies, educational institutions, and private consulting firms. The most comprehensive source of information is a series of 8 monographic volumes published by the National Academy of Sciences, Washington, D.C., dealing with *Geology, Seismology and Geodesy, Hydrology, Biology, Oceanography and Coastal Engineering, Engineering, Human Ecology,* and *Summary and Conclusions.* These volumes contain many articles reprinted from earlier-published sources, such as the U.S. Geological Survey's Professional Paper series and other less readily accessible sources. The present paper for this colloquium is based mainly on a report published in the U.S. Geological Survey series (Hansen, 1965) and reprinted in the National Academy of Sciences series.

EARTHQUAKE EFFECTS

Direct Seismic Effects

Most of the more spectacular structural damage in the Anchorage area resulted from secondary causes such as landslides and ground cracks triggered by seismic vibration. Structural damage due directly to seismic vibration was subordinate to other damages in terms of total property and financial loss. Nevertheless, the cumulative vibratory damage was impressive. The extent and amplitude of vibration was dependent partly on geologic factors such as foundation and subfoundation conditions. Other things being equal, vibration was more intense and damage was greater in areas of thick unconsolidated deposits than in areas of bedrock. Examples of this rule are too numerous and too widely recognized to need documentation. Virtually all the severe vibratory damage to buildings in the Anchorage Lowland was in areas underlain at some depth by Bootlegger Cove Clay, a soft, sensitive estuarine deposit that was largely responsible for landslide damage also (Miller and Dobrovolny, 1959, p. 35). The term "Clay" as used here refers also to fine-grained sediment that contains much silt-size material and is not necessarily clay in a petrographic sense.

Only the highlights of the vibratory damage are summarized here. The distribution and character of this damage were unusual. Probably few buildings in the Anchorage area were totally undamaged, but many blocks of homes and small commercial buildings received only cursory damage and sustained virtually no damage to structural members, frameworks, or foundations. On the other hand, many multistory buildings and buildings having large floor areas sustained significant structural damage; several such buildings were total losses and some required major repairs.

Steinbrugge (1964, p. 58-72) ascribed the selectivity of the effects to the great magnitude of the quake and the distance of Anchorage from the epicenter: "The ground motion at Anchorage did not appear to contain significant short period motions which has been commonly observed in epicentral regions of destructive shocks." "This damage pattern appears to be attributable to the distance that Anchorage was from the epicenter, with the longer period ground motion having a dominant effect at this distance."

In general, most small buildings outside of landslide areas withstood the effects of the earthquake remarkably well. The low loss of life is, in some measure, the result of the low susceptibility of smaller structures to the long-period vibrations that racked the area.

Small wood-frame buildings outside areas of ground displacement were generally little damaged. Also, most unreinforced masonry walls and chimneys withstood the shaking well. Most interior wooden-stud walls sustained only minor nonstructural cracking. Outside of areas where the ground itself was cracked, most foundations of poured concrete or hollow concrete block were not damaged. Most house windows were unbroken, and many objects even remained standing on shelves indoors.

Vibration badly crippled the public utilities. Many such structures were crippled by multiple causes, however, and it would be pointless to try to assign any one cause to any one effect. Many utility poles for power or telephone lines leading into Anchorage were broken by a whip-lash action caused by seismic vibration; taut wires were broken in tension at the same time (Eckel, 1967, p. B 18). In some places transmission lines and poles were damaged by shifting and liquifaction of the soil. Electric power failed throughout Anchorage at the onset of strong ground motion. Heavy damage to some power stations overloaded other undamaged parts of the generating system, which, in turn, tripped automatic shut-off devices.

Ground Cracks and Compaction

Some areas were much more vulnerable to cracking than others were. Frozen muskeg in and bordering swamps was very susceptible. Man-made land in former muskeg areas, reclaimed either by draining or by filling directly over muskeg, was exceedingly susceptible to cracking. Lowland areas underlain by silty clay and outwash were very susceptible also, whereas highland areas underlain by ground moraine were not.

The most severely cracked ground was adjacent to landslides or within slide areas where cracks were caused by tension directly related to sliding. Much structural damage in build-up areas was caused by such ground cracking. At Turnagain Heights, for example, severe cracking extended at least 670 m back from the head of the landslide, completely through the residential subdivision, badly damaging scores of houses (fig. 3).

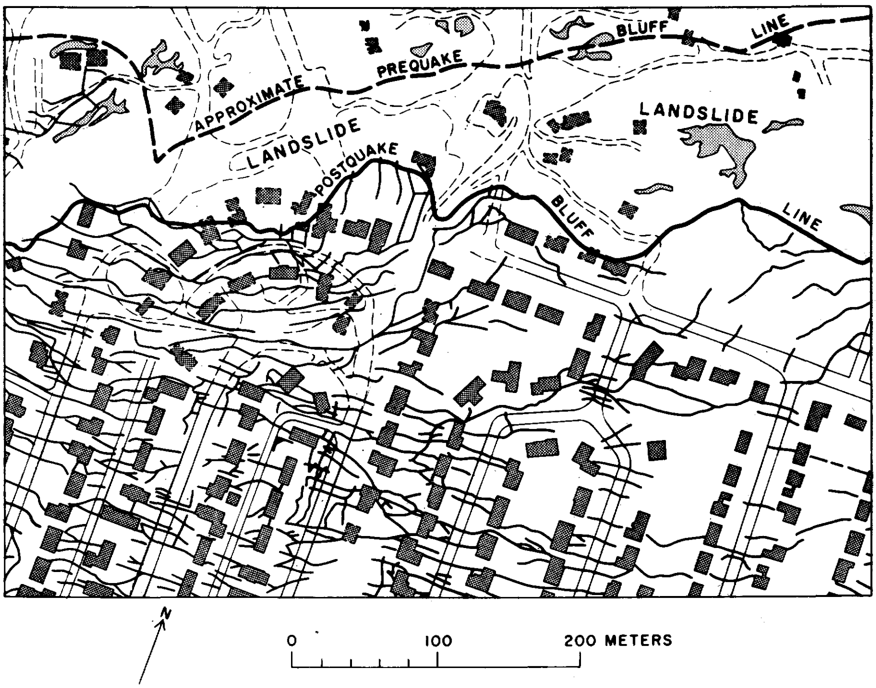


FIG. 3. — *Map showing the pattern of ground cracks at Turnagain Heights. Part of the landslide is at the top of the map (from Hansen, 1965, pl. 1).*

On sloping ground, cracks generally formed subparallel to the slope, owing to differential compaction, lateral shifting (lurching) under the influence of gravity, tension, and rupture. Along streets, highways, and railroads, alternate cuts and fills had a distinct pattern of fractures: fills that compacted under the vibratory stress of the earthquake were cracked adjacent to the fill-cut contact; some fills, including precompacted ones, dropped several inches and required costly repair.

Preexisting zones of weakness in the ground were particularly susceptible to cracking. Some cracks followed backfilled utility trenches, for example, or backfills around building foundations. In such places, the ground separated near the contact between the fill and the preexisting ground. Consequently, underground conduits for water, gas, sewer, telephone, and electric power utilities were severed at these places. Buildings constructed partly on fill were damaged by cracking between the fill and the adjacent ground. Trees were split by cracks that passed through their root systems.

Reportedly, many ground cracks opened and closed with the rhythm of the earthquake. Such action may help explain the extensive damage some cracks caused. A pulsating fracture would cause more damage to a superincumbent structure than would a fracture that merely opened.

Sand Boils and Mud Fountains

Sand boils and mud fountains are transient or short-lived features commonly produced by strong earthquakes where ground breakage occurs. They were wide-

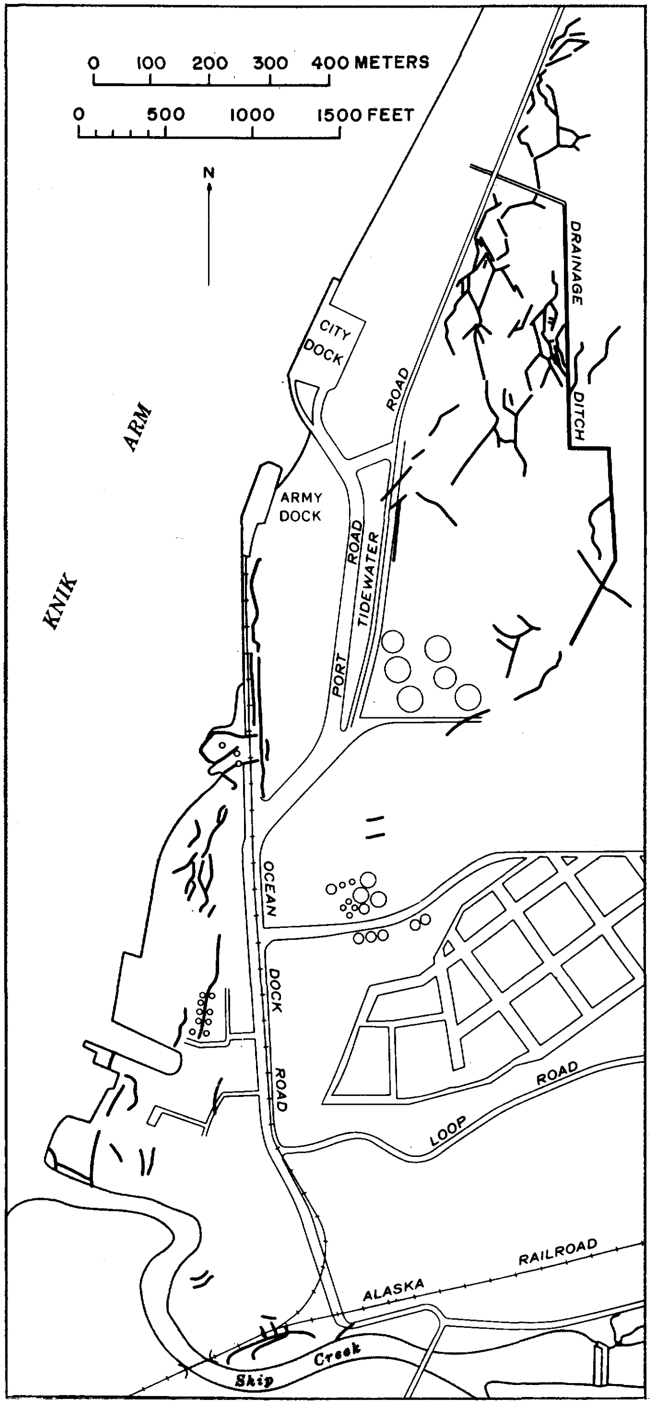


FIG. 4. — *Ground cracks, Port of Anchorage and vicinity. Many of these cracks spouted mud, particularly those east of City Dock. Base by City of Anchorage, Office of City Engineer.*

spread in the damage zone of the Alaskan earthquake. Mud fountains were produced where the water table was shallow and where frozen ground overlying saturated, unconsolidated sand or silt was cracked by the earthquake.

In the Anchorage area mud fountains or sand boils were abundant (1) on or near to cracked tidal flats adjacent to Knik Arm, especially in the vicinity of the Port of Anchorage at the mouth of Ship Creek, (2) in association with some landslides, (3) around the shores of ice-covered lakes, and (4) in other settings of fractured ground (fig. 4).

Various processes related to the earthquake may have caused fountaining. Some fountains seem to have been caused by compaction of unconsolidated saturated sediments, accompanied by ejection of the interstitial water up through ground cracks. Some fountains may have been caused by the passage of compressional seismic waves through the ground. The association of sand boils with some landslides suggests a causative relationship, whereby spontaneous liquifaction of interlayered sand, brought about by a rise in pore-water pressure consonant with the vibratory motion of the quake, may have contributed to failure of the ground and to the ensuing sliding (Seed and Wilson, 1973, p. 120).

Three large sand boils, one covering about 300 m^2 of ground, formed just east of the Turnagain Heights landslide. These boils seemed to have resulted from the spontaneous liquifaction of saturated sands forced to the surface by collapsing overburden. Similar smaller boils were ejected near the toe of the Fourth Avenue landslide.

On most large frozen lakes the ice was severely cracked near shore in a peripheral zone perhaps 80-160 m wide. Seiche action induced by the earthquake probably was the principal cause (Waller, 1966, p. A 5). Fountains of water were ejected from some of these cracks, and where the lake bottom was shallow, mud was extruded also. Such mud deposits, on the ice or snow, were clearly visible on aerial photographs filmed shortly after the earthquake.

The economic effects of sand and mud ejections in the Anchorage area were minimal, although in some other localities, considerable damage was caused by sediment forced into the insides of buildings (Coulter and Migliaccio, 1966, p. C 31; Waller, 1966; Waller and others, 1965). Damages caused by ground cracks themselves, however, generally exceeded the effects caused by the sediment ejected from the cracks.

Landslides

Landslides were the most spectacular manifestations of earthquake damage at Anchorage, and they occurred in many places (fig. 1). The slides took many forms in several types of earth materials. The most destructive ones, in terms of property damage, resulted from failures in the Bootlegger Cove Clay. Serious failures, however, also occurred in glacial till, delta deposits, tidal sediments, and dune sands.

Evidence of landsliding in the Anchorage area was abundant prior to the Alaska earthquake. Several localities had histories of sliding that dated back to or before the settlement of the city—the evidence was both historic and geologic. Previous sliding had taken place under conditions of static as well as dynamic (earthquake) loading. Some slopes where landslides were triggered by the earthquake were only marginally stable at the time of the quake, and slope failures on a modest scale under static load conditions were in progress more or less continuously along some bluff lines. Miller and Dobrovolny (1959, p. 104) described areas of past landsliding and warned of possible landslide dangers in the event of an earthquake. The triggering of large-scale landsliding at Anchorage by an earthquake as great as the Alaska earthquake of March 1964, therefore, should not have been surprising.

EARTHSLIPS ALONG TURNAGAIN ARM NEAR POINT CAMPBELL

Structurally, the simplest slides were in the bluffs facing Turnagain Arm south-east of Point Campbell (fig. 5). There, a thin cover of wind-blown sand and slope wash had been loosely anchored to the steep face of the bluff by an overgrowth of trees, shrubs, and grasses. The entire superficial mat slumped downward a few inches to several feet along the full length of the bluff from Point Campbell to Campbell Creek, a distance of about 6 km. Locally the slumping was more intense, and the face of the bluff was laid bare from top to bottom. Southeast of Campbell Creek, minor slumping and cracking extended along the bluff to the tracks of the Alaska Railroad near Potter, where slides destroyed trackage and embankments.

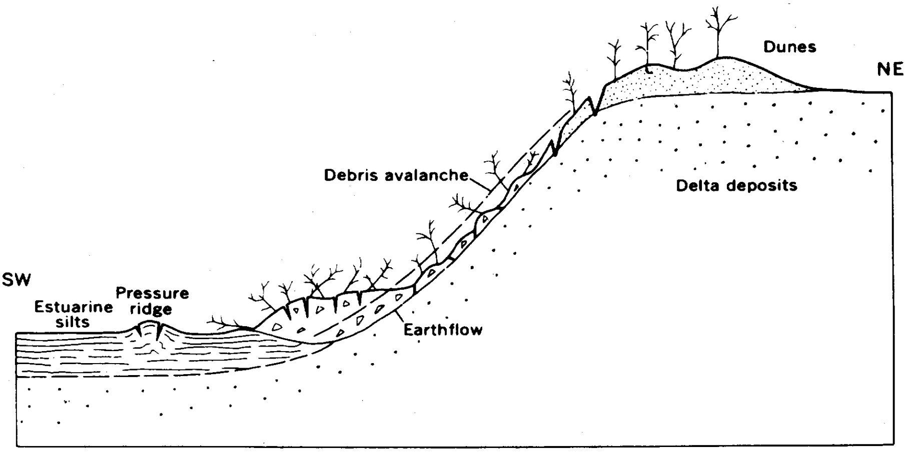


FIG. 5. — *Diagrammatic section near Point Campbell, showing mode of failure along bluff line overlooking Turnagain Arm. Bluff is about 75 m high.*

Between Point Campbell and Campbell Creek, the earth either slid en masse, as a shallow nonrotational glide, or it disintegrated into blocks and fragments, as a debris slide or avalanche. All intermediate steps are represented. The velocity of motion probably was rapid, because of the height and steepness of the slope and the granular incoherent character of the material.

ROTATIONAL LANDSLIDES

Rotational landslides were caused by the earthquake at half a dozen localities in the Anchorage area. Although some of the slides were large and spectacular

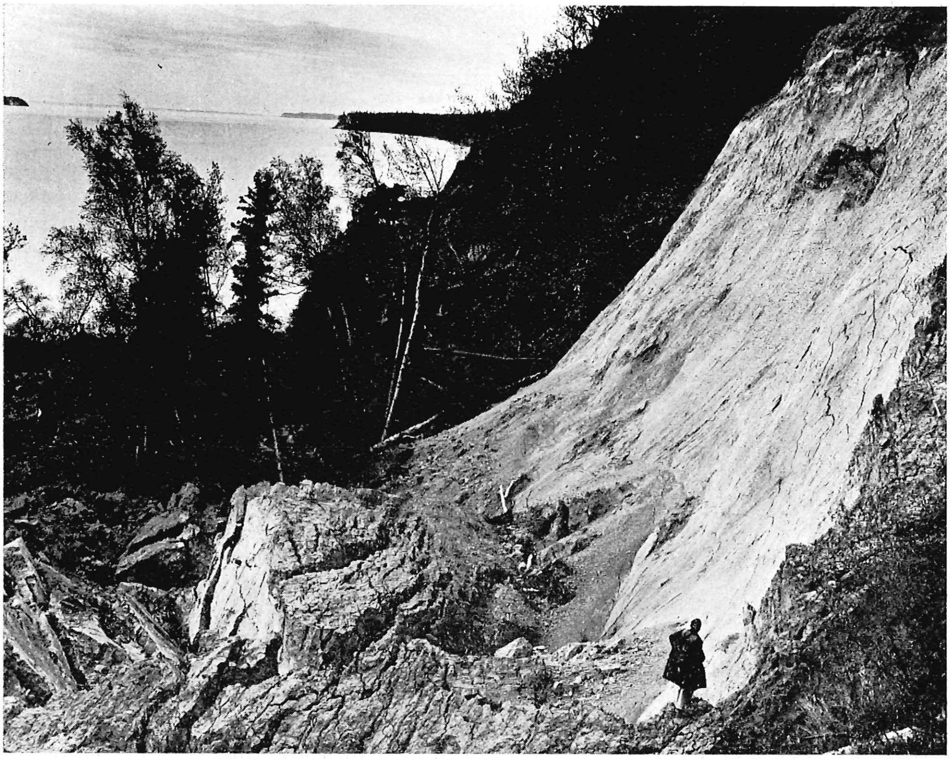
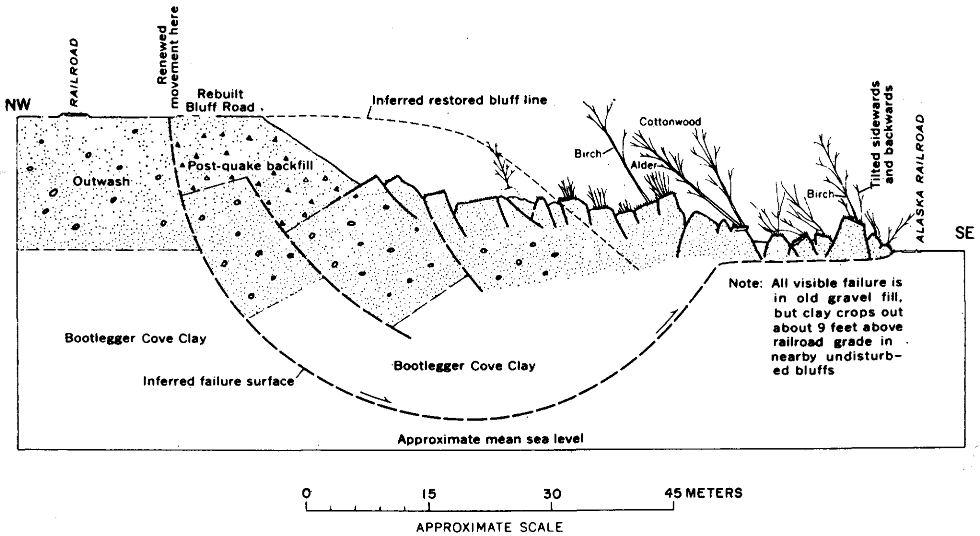


FIG. 6. — *Large slump on west side of Knik Arm near Sleeper. Headwall scarp at right —foreshortened in this view—is more than 80 m high.*

(fig. 6), most of them caused no damage to improved properties, because they happened to take place in undeveloped or nonurban areas. One group of rotational slides at Bluff Road, however, destroyed a section of highway, and another group, at Potter, destroyed a section of railroad. Rotational slides occurred on the outer edges and slopes of bluffs where the soil-strength profile presumably was nearly uniform throughout the height of the bluff and where, therefore, the most probable mode of failure was rotational. Translatory failures, rather than rotational failures, took place where the soil-strength profile was characterized by a subhorizontal zone of very low strength intervening between zones of higher strength.

BLUFF ROAD

Several rotational slides gave way along the south-facing bluff line of Ship Creek, between Bluff Road and the tracks of the Alaska Railroad (fig. 7). The broadest failure there extended about 390 m along the bluff in four separate but connected slumps. These slumps would have been very destructive if they had failed in a built-up area. As it was, the outer rim of the bluff dropped about 12 m, rotating backward 15°-30° and destroying about 200 m of highway along the rim of the bluff. The toe of one slump flowed across the tracks of the Alaska Railroad



Note: All visible failure is in old gravel fill, but clay crops out about 9 feet above railroad grade in nearby undisturbed bluffs

FIG. 7. — *Sketch section through rotational slide at Bluff Road.*

but caused no damage. Two months after the earthquake, minor settlement was still evident at the heads of the slides in places where the road had been rebuilt.

Most of the visible landslide material was coarse outwash gravel, but failure in the Bootlegger Cove Clay probably was the chief cause of sliding. Bootlegger Cove Clay was exposed along a line of springs 3 m above the base of the slope of the bluff just west of the slides, and it must have extended under cover of colluvium into the slide area (Trainer and Waller, 1965, fig. 3 B). Its loss of strength under the vibratory motion of the quake must have contributed to the failure of the slopes below the bluff and to the flowage of material from the toe of the slides.

POTTER

Along the Alaska Railroad at Potter several kinds of earth material were involved in complex failures that involved earthflowage from the toes of slides and rotational slumping at the heads. These slides were investigated by McCulloch and Bonilla (1970, p. D 72) shortly after the earthquake, and the following account is based on their report. Glacial till forms the top of a bluff back of the slides and forms most of the exposed face of the bluff. The till rests on outwash that in turn lies on blue clay, silt, and fine sand which, perhaps, is equivalent to the Bootlegger Cove Clay.

The slides at Potter consisted of elongate slump blocks rotated backward and broken into many pieces toward the base of the slope. Severe ground cracking extended along the bluffline a distance of about 2 000 m. About 470 m of railroad trackage was carried away by slumping. Many pressure ridges were as far as 500 m beyond the foot of the bluff, but most of the larger ones were within 120 m. They were formed by pressures probably transmitted horizontally from the toe of the slides through the frozen upper layers of the tidal silts.

McCulloch and Bonilla (1970, p. D 72) concluded that sliding was caused by flowage of material near the base of the bluff. Flowage may have been initiated there or in the adjacent tidal sediments of Turnagain Arm, which had underlain part of the railroad embankment fill. The overlying material and the trackage were carried away in the process. Some sections of track were carried laterally as much as 42 m.

TRANSLATORY SLIDES

All the highly destructive landslides in the built-up parts of Anchorage were of a single structural-dynamic family, despite wide variations from slide to slide in size and complexity (fig. 8). All moved chiefly by translation rather than rotation.

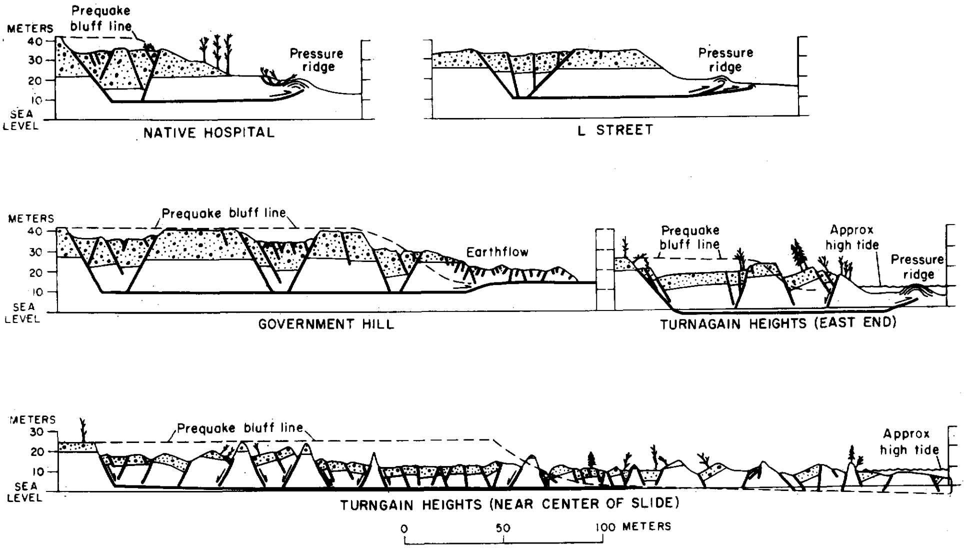


FIG. 8. — *Cross sections through some translatory landslides, Anchorage, Alaska.*

They slid laterally on nearly horizontal slip surfaces following drastic loss of strength in previously weak sensitive zones of the Bootlegger Cove Clay. Slides in which the slid mass was practically intact could be classed as "block glides"; those in which the slid mass underwent appreciable disruption are probably best classed as failures by lateral spreading (Varnes, 1958, pl. 1). Between these limits, all gradations of form were represented—not only from place to place but also in time. Structurally the "L" Street slide was the simplest and the Turnagain Heights slide was the most complex. The Turnagain Heights slide must have begun as a simple though highly transient block glide, or perhaps as several such block glides, arising independently along the bluff line. As sliding progressed, the Turnagain Heights slide deteriorated rapidly into a complex failure involving simultaneous translatory, sideward, and rotational motions (fig. 9). Its predominant motion, however, remained translatory. Destruction to property in the several

FIG. 9. — *Severe ground disruption caused by Turnagain Heights landslide. Original land surface intact, upper left. Knik Arm of Cook Inlet, upper right.*

FIG. 10. — *Private homes demolished by Turnagain Heights landslide. Seventy-five houses were destroyed in this slide; dozens more were severely damaged.*

slides was caused by tilting, wrenching, warping, and disruption of structures over the cracked, collapsed, and compressed zones of the slides (fig. 10). In undistorted parts of some slides even large buildings were little damaged despite horizontal ground translations of more than a meter.

Translatory slides are less common than rotational slides. They have, therefore, received less attention in the literature. Examples startlingly similar to those at Anchorage, however, have been reported and described from Scandinavia where the Pleistocene history has been comparable in many ways to that at Anchorage. (See Odenstad, 1951.)

Earthquake-triggered landslides accompanying the great New Madrid, Mo., earthquake of 1811 also seem to have been very similar to the slides at Anchorage. The physical setting of the slides was analogous to that at Anchorage (Fuller, 1912, p. 48, 59-61).

The Chilean earthquake of 22 May 1960 triggered three large landslides at Lago Rinihue, 65 km east of Valdivia in central Chile. The descriptions of Davis and Karzulovic (1963, p. 1407) indicate that these slides resembled the Turnagain Heights slide in form, size, and mode of failure. Translatory movement predominated; rotational movement was subordinate.

Geologic Setting

All areas of translatory sliding in Anchorage had the same general geologic environment. All were underlain at various depths by Bootlegger Cove Clay that had zones of low shear strength, high water content, and high sensitivity. All surmounted flat-topped bluffs bounded on one side by steep slopes. In all areas, the Bootlegger Cove Clay was overlain by outwash sand and gravel. Outwash deposits, however, had no critical part in the sliding. Failure was confined to thin zones of sensitive clay, silt, and sand within the Bootlegger Cove Clay.

Several geologic variables acting in concert with earthquake shaking probably caused failure in the several slide areas. They include: (1) the height of the bluff above its base, the slope angle of declivity of its face, and perhaps the ground-plan configuration, (2) the soil-strength profile, including consistency, dynamic shear strength, and sensitivity, and (3) water content and liquid limit of the soil at the critical depths below the ground surface. Some of these factors seem to be interdependent—the height, slope, and ground-plan configuration, for example, may have influenced the water content of the soil which in turn influenced the consistency.

Geometry and Mode of Failure

Translatory slides of the Anchorage area varied widely in size, shape, and internal complexity, but they all conformed to a single basic geometric form (fig. 11). In plan, each slide was bounded laterally by a series of crescentic tension fractures, which also marked the outer wall of the outermost graben. Other tension fractures—bounding potential slide blocks—commonly extended headward, outside the slide proper, scores of hundreds of meters beyond the bounding fractures. At Turnagain Heights, numerous crescentic tension fractures extended back through the subdivision as much as 660 m beyond the head of the slide. Had the earthquake lasted longer, sliding undoubtedly would have retrogressed back into that area. "Retrogression," as applied to landslides, means a headward expansion of the slide.

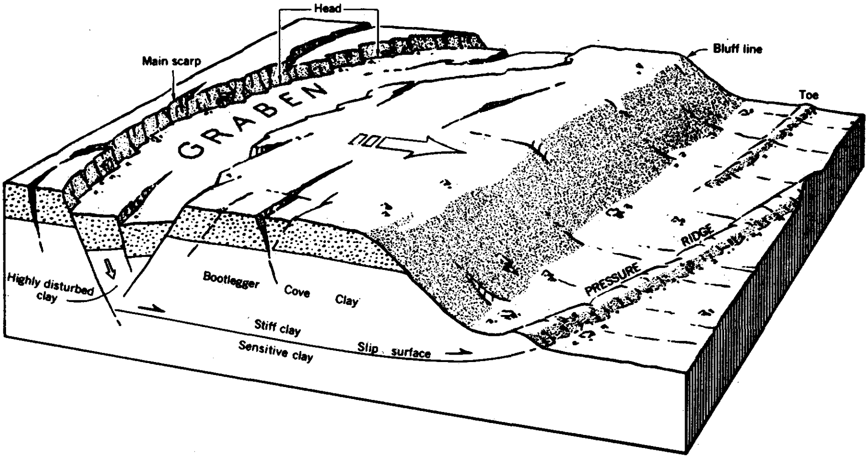


FIG. 11. — *Block diagram of a translatory landslide, as exemplified by the "L" Street slide.*

The graben rule. — The graben rule affords a rapid, yet reliable, estimate of the depth of failure of a translatory landslide. The graben rule should apply to any translatory slide in which flowage of material from the zone of failure has not been excessive. Because the cross-sectional area of the graben trough approximates the cross-sectional area of the space voided behind the block as the block moves outward, the depth of failure can be estimated from the simple relationship $D = A/l$ where D is the depth of failure, A is the cross-sectional area of the graben, and l is the lateral displacement of the block. For example, the Fourth Avenue graben, on the average was about 3.3 m deep, 30.5 m across, and had an area (A) of about 101 m^2. Its maximal lateral displacement (l) was about 5.3 m as determined by postquake resurveys. The calculated depth of failure (D) was about 19 m, or about 13 m above mean sea level. Subsurface exploration was somewhat indecisive but yielded a nearly identical figure.

Geometric development. — Geometric development of the translatory slide is reconstructed in the following postulated sequence: prolonged strong earthquake shaking drastically reduced the shear strength of saturated sensitive zones in the Bootleger Cove Clay. Some of this clay was saturated beyond its liquid limit and was only marginally stable before the earthquake. At Turnagain Heights, the bluff line had been actively slumped over a period of years and was a continuing maintenance problem for property owners before the quake (Miller and Dobrovolny, 1959, p. 103). The strength of the clay, therefore, fell below the level of shear stress caused by the weight of material in the bluff and the accelerations of the quake. A postulated rapid build-up of pore-water pressures in interbedded sand layers perhaps led to liquifaction of the sand and to further loss of strength in the enclosing clay mass (Seed and Wilson, 1973, p. 120). Under the influence of gravity, a prismatic block of earth began to move laterally on a nearly horizontal slide surface toward the free face of the bluff. In effect, the block was afloat on a zone of disturbed clay whose strength properties were those of a confined viscous liquid. As the block started to move, tension fractures formed at the head of the slide and widened as movement progressed. These tension fractures dipped toward the slide block at angles of about 60 to 70°. As the fractures widened, their hanging wall (on the moving block) lost support and collapsed along one or more antithetical fractures to form a graben.

The downward pistonlike movement of the graben was synchronous with the lateral slippage of the slide block. Continued slippage placed more ground under tension behind the slide, and additional fractures formed as the slide retrogressed headward. In the more complex slides such as the Government Hill slide and, especially, the Turnagain Heights slide, this process occurred repeatedly, and a series of alternate horsts and grabens developed retrogressively, parallel to the direction of slippage.

As the block moved outward, tension at the head of the slide was partly countered by compression at the toe, and pressure ridges formed in the flats below. This step may have been transient, because continued compression led to rupture and overthrusting. Both steps occurred in each of the translatory slides and caused extensive local damage. The Turnagain Heights slide not only sheared off at the toe, but it slid freely under gravity down the mudflat into Knik Arm (fig. 12)—at one point it slid more than 0.8 km. But where resistance in the toe built up to a level equal to the thrust of the moving block plus the shear resistance of the clay at the slip surface, motion was stopped.

Sliding was precipitated by gravity as soon as the accelerations of the quake had reduced the shear resistance of the soil to the point of failure. The earthquake

FIG. 12. — *Slip surface of the Turnagain Heights landslide exposed near tidewater at west end of slide. Landslide blocks slid freely down this surface into tide water. Dark area to lower right is inundated at high tide. Dark material at upper left is peat and muskeg, which was lowered onto slip surface when clay slid and flowed out from beneath it.*

was the "trigger"; gravity was the "propellant." Seemingly, sliding began about 2 minutes after the onset of shaking and continued as long as the gravitational component on the sliding surface exceeded the shear resistance of the soil. Shear resistance would tend to rise as soon as earthshaking stopped; most sliding seems to have stopped when strong earthquake ground motion ceased, although this assertion cannot be verified. Certainly, an observer on a moving landslide would not know whether or not earthquake motion was still in progress. At Turnagain Heights, however, evidence suggests that sliding continued a full minute or more after earth shaking had stopped.

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