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CURRENT PROBLEMS IN RESEARCH

The Chilean Earthquakes of May 1960

Studies of the disaster increase our understanding of earth shocks and of ways to withstand them.

C. Martin Duke

An event of great engineering and scientific interest occurred in south-central Chile last May, when that active portion of the globe was devastated by an earthquake of magnitude 8.5. Besides the major shock, there were several others of destructive effect. A tsunami, or tidal wave, was created, causing widespread loss of life and property on far-flung shores of the Pacific Ocean. A volcano erupted. Tectonic movements occurred. Soft soils were violently shaken and deformed, aggravating structural damage. Shaking of buildings, bridges, and other structures resulted in crippling damage and sometimes complete destruction.

The 500-mile-long disaster region extends from north of Concepción to south of the island of Chiloé (the large island on which Ancud is located, shown at the lower left in Fig. 1); in this area about 4000 people were killed and damage estimated at $400 million was sustained. This area contains 2.5 million people, and the Chilean government reports that 450,000 of their homes were damaged, 10 percent of them beyond repair. The tsunami which was responsible for most of the deaths in Chile caused additional loss of life and property in Hawaii and Japan. The toll in Japan was 180 dead and $50 million property damage.

While workers in the scientific aspects of seismology receive new earthquake data constantly, engineers must rely on experience with and motion records of the relatively infrequent destructive earthquakes. It appeared from preliminary reports that here was perhaps the largest earthquake to afflict a heavily populated area since the earthquakes of San Francisco in 1906 and Tokyo in 1923. Because of the implications for earthquake-resistive design of structures, it was clear that an inspection and gathering of facts should be undertaken by United States engineers. Accordingly, the Earthquake Engineering Research Institute, an organization of engineers and seismologists who donate their time to the institute's program of advancing earthquake safety, established a team to visit the afflicted area. The National Science Foundation made funds available for travel and for preparation of reports. The team members were Karl V. Steinbrugge of the Pacific Fire Rating Bureau, Ray W. Clough of the University of California at Berkeley, and myself. Kiyoshi Kanai of the Earthquake Research Institute, Tokyo University, accompanied the team, which spent two weeks in Chile during June 1960. A very large number of Chilean individuals and institutions graciously made available their knowledge and their assistance. At the time of writing, plans are being made for the preparation of an appropriate report.

The Principal Shock

The first large shock, of magnitude 7.5 on the Richter scale, occurred on 21 May 1960, at 10:03 Greenwich Civil Time. It was centered near the coast line in the vicinity of Concepción. The principal shock, of magnitude approximately 8.5, occurred on 22 May at 19:11 GCT and was centered near the coast line at about the latitude of Puerto Montt. Both of these locations are highly tentative. It has been inferred from observations of damage and from findings on Chilean earthquakes in the past that the disturbances occurred at depths of around 50 kilometers. This and other scientific factors are being currently studied with a view to refinement and correlation. Several earthquakes of magnitude 7.5 to 8 occurred among the hundreds of aftershocks, a shock of about magnitude 7 having been released as recently as 14 August. The magnitude rating is an index of the amount of energy released; magnitude 8 corresponds to an energy release about 60 times that of magnitude 7. For comparison with destructive earthquakes in California it may be noted that at San Francisco in 1906 the magnitude was 8.3; at Long Beach in 1933 it was 6.3; in Kern County in 1952 it was 7.6. However, California earthquakes generally have been at considerably shallower depths (around 18 kilometers) than the 50 kilometers inferred for the recent Chilean earthquakes.

The effects of the May 1960 earthquakes may be outlined with the aid of Fig. 1, a map of south-central Chile. Damage due to the first large shock was limited to the Concepción region, though the shock was felt throughout the area of the map and, fortunately, was taken by the people of Chile as a warning. Most of the geodynamic effects, damage, and loss of life were associated with the principal shock on 22 May. The tsunami thus generated invaded the coastal towns and villages marked on the map with the symbol *T* and swept across the Pacific to

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wreak havoc on the coasts of Hawaii and Japan and, in lesser degree, in California. A tectonic subsidence of 1.6 meters occurred in the Valdivia region. A lava flow erupted from a new vent in the side of Mount Puyehue. Disastrous damage due to shaking occurred at the cities of Valdivia and Puerto Montt, and at a number of smaller communities. Concepción and the surrounding area sustained heavy damage. The consensus among observers is that the heaviest shaking occurred along the coast and along the north-south chain of lakes and volcanoes, with much less shaking in the long central valley between. Most interesting of the hundreds of landslides were the three which dammed the San Pedro River downstream from Lake Riñihue.

In due time, as a result of full analysis of damage reports, it will be possible to construct an isoseismal map. Such a map will show, on the Modified Mercalli Scale of 1931, the *intensity*, or severity of shaking, at each place in the afflicted area. A given earthquake has one *magnitude*—for example, 8.5 in the principal Chile earthquake—but it has a whole distribution of intensities. Preliminary estimates of intensity for the Chilean earthquakes are VIII at Concepción, X at Valdivia, XI at Puerto Montt, and VII to VIII at Osorno in the central valley. By comparison, the maximum intensities were X at San Francisco in 1906 and VIII at Bakersfield in 1952. Construction of the isoseismal map for Chile will not be simple, for the several shocks had overlapping effects. Such maps are very useful, when accumulated over a long period of time, both for estimating earthquake risk and for studying intensity and its anomalies as a function of magnitude, hypocentral depth, and geology.

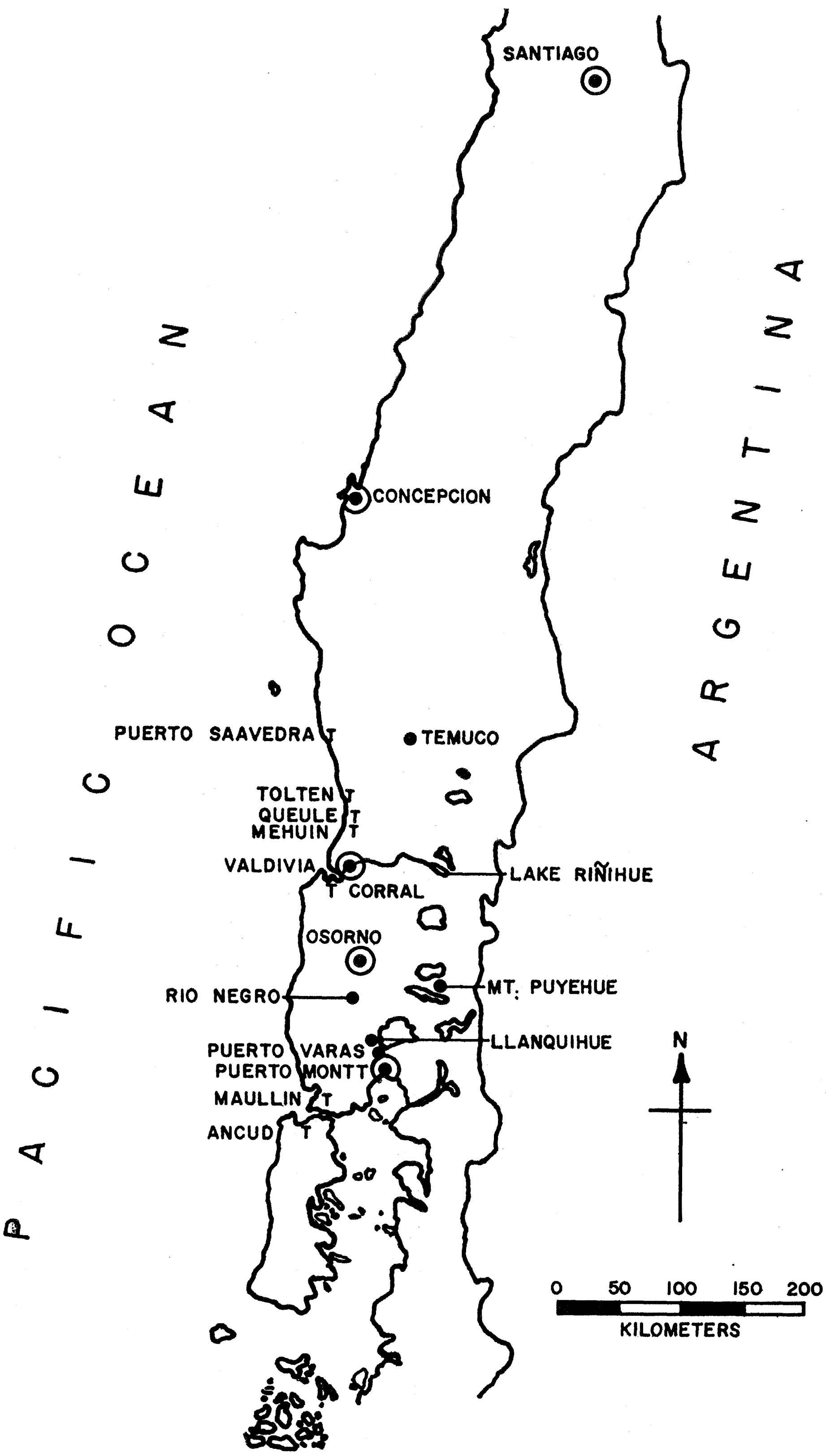


Fig. 1. May 1960 earthquake area. *T*, towns and villages invaded by tsunami.

Seismic Records

Typical of seismograms obtained throughout the world is that of Fig. 2, which is a portion of the record obtained for the principal Chilean shock at the California Institute of Technology campus in Pasadena with a Wood-Anderson seismometer. At this great distance the earth responded in characteristic fashion, the surface waves exhibiting a 20-second period. Figure 3 illustrates another type of record—a type which, unfortunately, could not be obtained in this earthquake. The example shown is a United States Coast and Geodetic Survey strong-motion accelerograph record from the 1952 Kern County earthquake. Data from this special instrument and from the many similar ones in California and Japan are of fundamental value in earthquake engineering, as they show approximately how the ground moves in earthquakes which are strong enough to damage structures and to render the usual sensitive seismographs inoperable. On the basis of many such records obtained in the past 30 years in the United States, important strides are being made in earthquake-resistive structural design. It is of great importance, however, to obtain strong motion records for all seismically active regions in the world.

The hypothetical mechanism of generation of the May 1960 tsunami is a subsidence of the sea bottom along an off-shore fault trace paralleling the coast. Such a fault is believed to be associated with the principal shock and with the tectonic subsidence around Valdivia. Clear evidence of surface fault movement has not been found to date on land. The heights of tsunami waves were 9 meters at Corral, 8 meters at Puerto Saavedra and Ancud, 5 meters at Hilo, Hawaii, and from 1.2 to 4.2 meters along the Pacific coast of Japan. In both Chile and Japan some of the small coastal villages were literally swept out to sea. There was loss of life at Hilo and in Japan in spite of the successful operation of the tsunami warning instruments in the Pacific. The tsunami is being investigated and reported by others, and I will not consider it further here except to note that much of engineering and scientific value is being learned.

To make the discussion of structural damage more meaningful, I will make some brief comments on the nature of earthquake motions and the manner in which structures resist them. Strong instrumental records such as that shown in Fig. 3, together with observations of damage, reveal that the horizontal components of motion are the most injurious. This is partly because the horizontal motions are more severe than the vertical, and partly because structures usually are moderately well designed for vertical load in order that they may carry their own weight plus the weight of their contents. But since large horizontal forces act on structures only occasionally—forces due to high winds or to earthquakes, for example—they are difficult to comprehend and evaluate and are frequently underestimated or neglected. Elementary practice in earthquake-resistive design of simple structures calls for providing strength to withstand a horizontal force of around 15 percent of the weight of the structure and its contents. All parts and all joints must be able to contribute appropriately to withstanding this force. In addition, the various parts of the structure which must vibrate together are securely tied together and, in turn, tied to the foundation, which must have the capacity safely to transfer the horizontal force into the ground. Careful attention is also given to the quality of the ground itself. In more complex structures, such as bridges, tall buildings, or dams, a much more sophisticated approach is necessary.

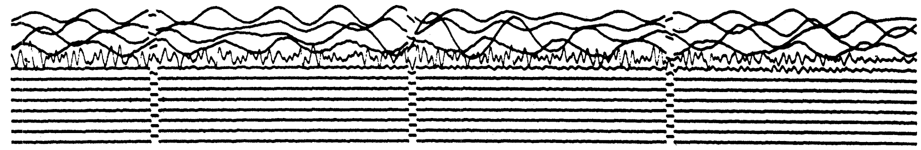


Fig. 2. Portion of a seismogram of horizontal ground displacement during the 22 May 1960 main shock in Chile, recorded at the Pasadena campus of the California Institute of Technology. The instrument was a standard Wood-Anderson seismograph with period 0.8 second and magnification 2800 on the original record. Time marks shown are at 1-minute intervals. [G. W. Housner]

Soil Failure

Deformation and failure of the soil in the Chilean earthquakes were dramatically manifested in many ways—in landslides, slumping and fissuring of soft ground, and failures of foundations and earth structures. The afflicted area is a glaciated region, and the soil types in the heavily damaged zones reflect this geologic history. Three examples follow. The landslides below Lake Riñihue occurred in glaciofluvial deposits that were saturated because of the heavy autumn rains of that region. The soil, of predominantly fine sand, apparently flowed as a liquid under the influence of the vibration. These slides, of which the largest covered about 1 mile along the San Pedro River, raised the level of Lake Riñihue by 15 meters, submerging the town of Riñihue and threatening Valdivia, 50 kilometers downstream, with floods. As a result of earth-moving operations reminiscent of those on the Madison River in Montana after the 1959 earthquake, the danger of sudden erosion of the slides appears at this writing to have been alleviated. Figure 4 shows one of the smaller of the slides. This same situation occurred previously at Riñihue in an earthquake in the year 1575.

Liquefaction of loose, fine, sandy soil seemed again to be the failure mechanism in the cases of the new highway (Fig. 5) between Puerto Varas and Puerto Montt and of the quay wall (Fig. 6) at Puerto Montt harbor. The strength of sandy soil is derived principally from shear resistance due to internal friction, which is proportional to the compressive forces between adjacent soil particles. The compressive forces are due to the weight of the soil. Under intense vibration of a water-saturated loose sand, part of this compressive force is transferred to the water, which has essentially no shear strength, and this results in marked weakening of the soil. The complete

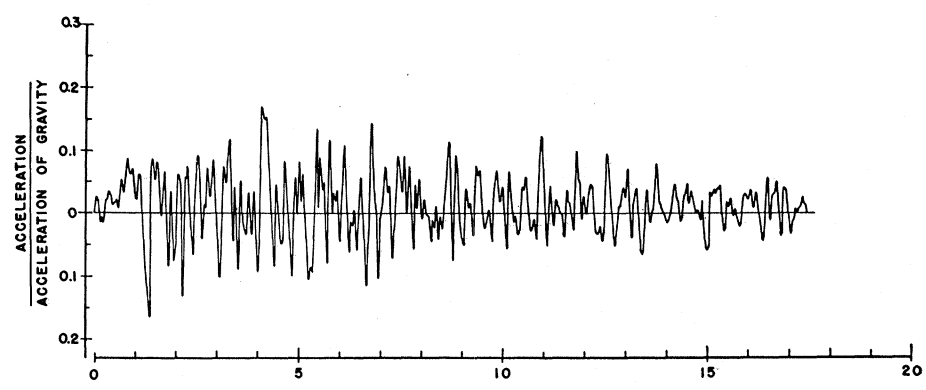


Fig. 3. Typical strong-motion acceleration seismogram of horizontal ground motion at Taft, California, on 21 July 1952. The U.S. Coast and Geodetic Survey accelerographs record one vertical and two horizontal components.

collapse of the highway fill appeared to be due to these characteristics in the fill itself, but the underlying swampy ground doubtless contributed to the difficulty. The catastrophe at the harbor, of which Fig. 6 is merely illustrative, is hard to explain except in terms of this mechanism. Differential settlements and horizontal foundation movements of the order of feet, occurring along the downtown water front of Puerto Montt and at the nearby naval base (Figs. 7 and 8), are associated with the same kind of soil.

Through their joint efforts, the Chilean Institute of Geologic Investigation and the U.S. Geological Survey are demonstrating a direct relationship in Valdivia and Puerto Montt between local soil conditions and damage to the indigenous wood-frame houses. As has been found elsewhere in many previous earthquakes, such houses on soft, marshy, or loose soil, especially if these soils are deep, are much more generally and severely damaged than those on the firmer, usually higher, ground.

Structural Damage

Damage to railway and highway bridges was widespread. This, coupled with many failures of highway and railroad embankments, landsliding, and land submergence due to subsidence around Valdivia, effectively cut off land transportation in southern Chile. A rough survey suggests that most of the bridge damage was due to abutment failures. For example, at the Isla Tejas bridge in Valdivia both end spans were badly damaged, and the piers on both ends tipped toward the banks, because the river banks at both abutments slid toward the river. The same phenomena occurred at a second bridge in Valdivia of the same design. The railroad bridge at Llanquihue had a 4-foot longitudinal displacement relative to its abutment. Many bridges seen by the team exhibited this kind of damage resulting from abutment failure. In other cases deck spans dropped because of the movement of piers. At the Bio Bio River bridge in Concepción, four piers tipped over completely, breaking off from their pile foundations and falling in the plane of the bridge axis. At a bridge 20 kilometers north of Valdivia, deck spans fell because of the rotation of piers which resulted from an abutment's sliding toward the river.

Houses in the northern part of the damage area were predominantly of crude masonry and adobe. The disintegration so familiar to students of earthquakes was the usual failure mechanism. To the south, most houses were built of wood, and the failure of the walls to resist the lateral forces resulted in many collapses and in many instances where the walls tipped from 5 to 20 degrees, leaving floor and roof relatively horizontal. Very common in the case of the frame houses was the tipping over of the foundation walls or piers or the horizontal sliding of the house off its foundation. Fortunately, very few fires broke out in connection with the earthquakes, and those few were confined to single buildings. Figure 9 shows the collapse of a composite

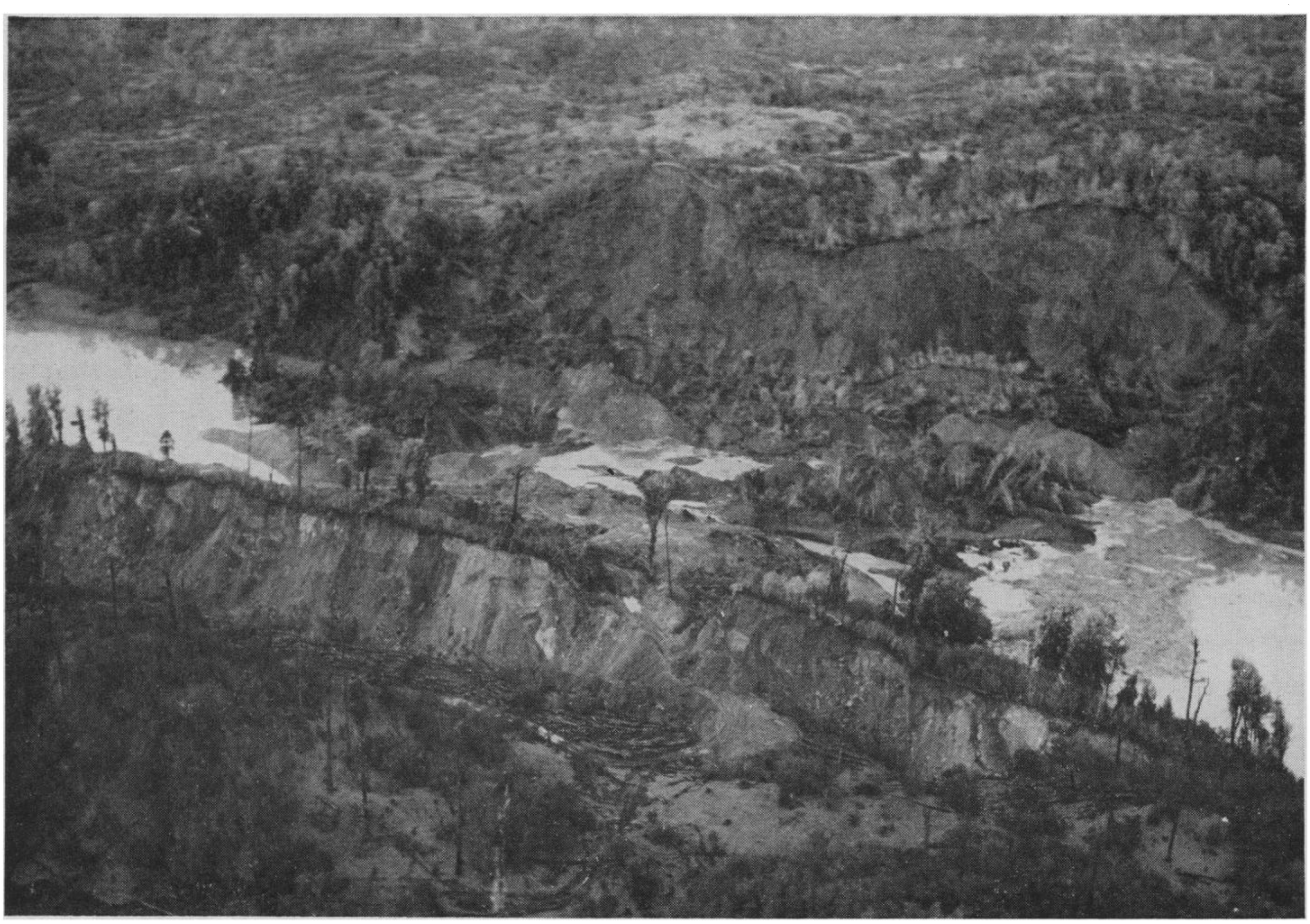
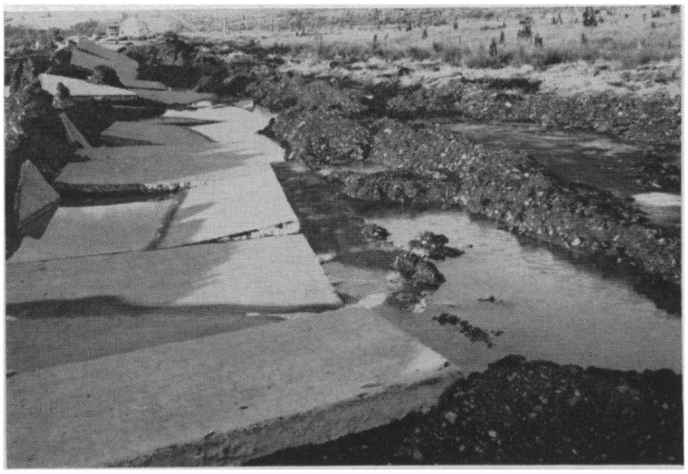


Fig. 4. One of the smaller landslides on the San Pedro River below Lake Riñihue.



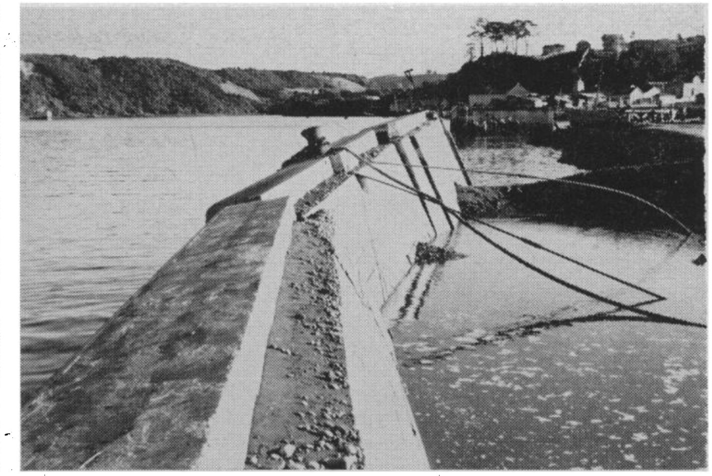


Fig. 5 (left). Failed highway fill between Puerto Varas and Puerto Montt. Fig. 6 (right). Failed gravity quay wall at Puerto Montt harbor.

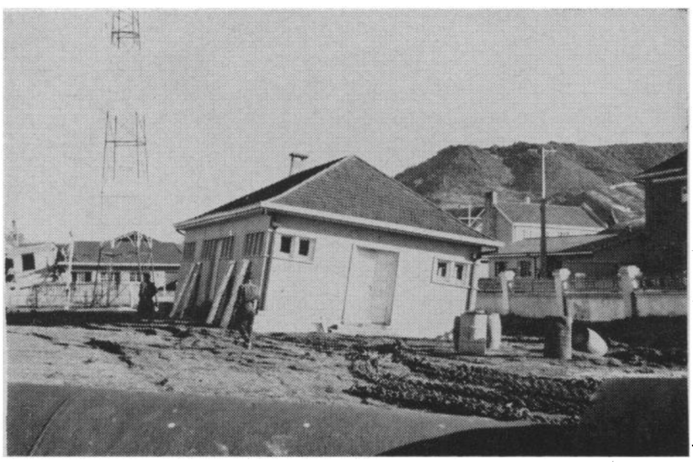
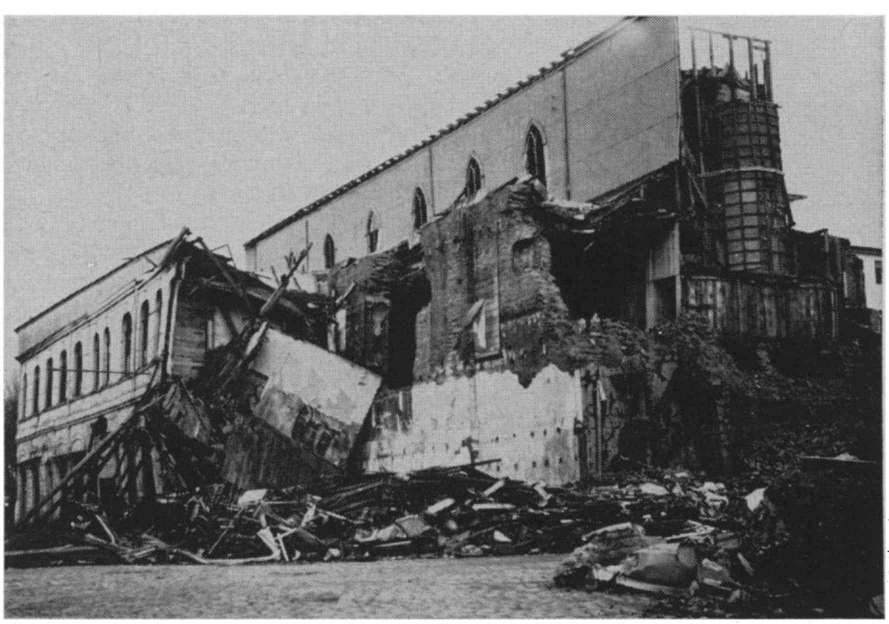


Fig. 7 (left). Settlement at the naval base, Puerto Montt. Fig. 8 (right). Relative horizontal movement of two parts of a building near the naval base, Puerto Montt.



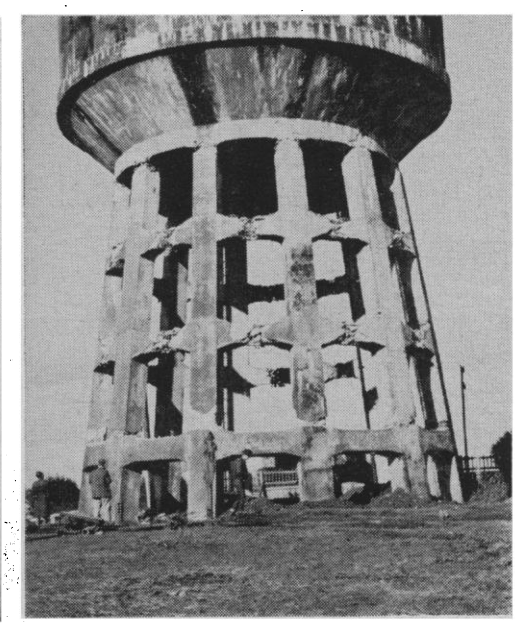


Fig. 9 (left). Collapse of a composite wood-frame and adobe building in Valdivia. Fig. 10 (right). Failure of the supporting members of an elevated water tank in Rio Negro.

adobe and wood-frame building in Valdivia.

A large number of reinforced-concrete elevated water tanks were damaged. Figure 10, a tank in Rio Negro, shows the characteristic pattern of shear failure of horizontal members and bending failure of columns. These tanks were constructed after a design, originating in Germany, which apparently did not provide for the transmission by the supporting members of the horizontal seismic forces between the heavy tank and the ground.

Chile had had a catastrophic earthquake in 1939, in the Concepción region, in which 30,000 people were killed. As a result of that experience, a new building code was put into effect, and major buildings erected since that time have been subject to a design requirement that takes earthquake loading into account. Thus, it was not surprising that the post-1939 construction behaved markedly better on the average than the older buildings. This was particularly noticeable in Concepción, where, though some of the newer large buildings were damaged, the damage to the older structures was much more pronounced. Errors in design or construction, or lack of knowledge about the behavior of soils and foundations in earthquakes, were the causes of most damage to the newer large buildings throughout the afflicted area.

Two examples of damage to modern buildings, from among the cases where soil conditions were not the dominant feature, are illustrative. The first of these buildings is of reinforced concrete, and the second of steel-frame construction, though in fact there were relatively very few steel-frame buildings in the afflicted area. The reinforced-concrete building is a seminary consisting of a three-story and a four-story wing resting on firm high ground in Puerto Montt. The columns proved unable to transfer the horizontal force down to the ground, and many of the columns, especially in the second stories of both wings, were completely shattered, as were many of the masonry partition walls. It appeared that the concrete was of substandard quality. The steel-frame building is a three-story chemistry laboratory at the University of Concepción, on a rigid concrete raft footing resting on deep, soft alluvium. The open first floor contained a number of steel diagonal members with welded joints connecting bottoms of columns with second-floor girders in both longitudinal and transverse directions. The welded joints failed early in the first large shock, but the building was able to ride out the violence of this and the subsequent earthquakes without collapse. There are important lessons to be learned from these and many of the other damaged as well as undamaged modern buildings. The learning of these lessons will require detailed analyses based on the original structural designs.

Conclusion

Both the scientific and the engineering aspects of our knowledge of earthquakes will be significantly augmented as a result of the reports now being prepared by investigators from Chile, Mexico, Japan, and the United States. The wisdom of making full reports and analyses was demonstrated from the comprehensive treatments published after the great earthquakes in San Francisco (1906) and Tokyo (1923); on the basis of those reports and analyses, technical papers are still being written today. Engineers stand to gain valuable information on the suitability of modern antiseismic design methods and criteria, on the currently emerging concepts of dynamic design and limit design, on soil behavior and the action of foundations and earth structures, on characteristics of tsunamis, and on tsunami warning systems. Scientific study of volcanoes, tsunamis, tectonic movements, faulting, earthquake mechanisms, and the character of the earth will be aided. The people of Chile, who are moving with energy and purpose toward reconstruction, may find some comfort in knowing that the world is learning from their tragedy.

Scientific Progress and the Federal Government

The Panel on Basic Research and Graduate Education of the President's Science Advisory Committee reports.

This paper is a brief statement on a large set of problems: the problems which center on the advancement of science by basic research and the making of scientists by graduate education. This is only one part of the complex world of modern American science, but it is a critically important one. We have tried to state clearly the fundamental character of the environment which is required for scientific progress and for the making of good young scientists. We then consider the way in which these requirements should affect the policies of both the federal government and the universities, which are today the two forces in our society whose actions most affect the health and strength of basic research and the training of scientists.

We find much, both in the government and in the academic community, which needs improvement, but we have made no attempt to prescribe detailed policies for either party. The last 20 years have seen a remarkable growth of support of many kinds for basic research and graduate education, and the role of the federal government has, on balance, been highly constructive. On the whole, our universities are much stronger today in science than they were a generation ago. We have great confidence that energetic leadership and constant effort can find good answers to the practical problems of the future. A short statement like this may hope to contribute, not specific solutions, but rather some general ideas about the nature of the task and the principles that should guide us in working on it.