Chapter 2
The Great 1960 Chile Megaquake

Abstract Descriptions of witnesses who experienced the great Chile megaquake may support the idea that prograde ground motion contributes to earthquake damage. Coastal changes in megaquakes may be related to a distinctive tectonic framework.

2.1 A Great Earthquake

On a bright Saturday morning in May, 1960, Chile awakened to a devastating earthquake of magnitude 7.5 that killed more than a hundred people in the city of Concepción, 400 km south of Santiago. Train service and commercial flights to the disaster area were cancelled. It turned out that this earthquake was merely a foreshock to the largest megaquake ever recorded: a main shock of magnitude 9.5, with epicenter about 300 km to the south of Concepción, known as the great 1960 Chile earthquake. The epicenter was near Mocha Island, off the coast of southern Chile.

Sunday, *May 22*, *1960*, *3:15 p.m.* The next day after the Concepción earthquake, some seismologists hitched a ride from Santiago airport on a military aircraft. They landed at Concepción airfield in time to experience the largest of all earthquakes. They were walking along the fence of the airfield when they noticed some parked aircraft rolling slowly back and forth. Then the cars parked outside the airport began to rock and some trees down the avenue tilted. A major earthquake was in progress.

Everything seemed animated by a silent slow motion. The earth was swinging back and forth in a leisurely rhythm of 2 or 3 s period. No earthquake of this size had ever been observed anywhere and no bigger one has occurred since.

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Fig. 2.1 Geological scenario of the 1960 Chile earthquake (bull's eye symbol), after Lavenu et al. (2002). The *arrows* indicate regions of predominantly compressive or extensional deformation

The magnitude was 9.5 on the Richter scale and the offshore Nazca-South America Plate boundary was torn over a 1,000-km fault rupture (Fig. 2.1). Estimated casualties numbered 5,700 dead, many of them reported missing in the tsunami.

There was no possibility of proceeding any further south from Concepción. The Nazca-South American Plate boundary had ruptured and generated a huge tsunami wave which rose to the unprecedented elevation of 30 m at some coastal locations.

In the Bay of Valdivia, wave heights of around 20 m were reported. The water depth in the open ocean is about 4,000 m; water waves propagating on this depth of water can attain about 800 km/h, roughly the speed of an airliner. Thus it is easy to compute how long it will take a tsunami wave to cross the Pacific Ocean from an epicenter in Chile. It can take the better part of a day. Unfortunately the 1960 tsunami caused victims and severe damage in Hilo, Hawaii and in Japan, because of insufficient warning on the arrival times of the tsunami.

In the epicentral region, a major landslide blocked the San Pedro River upstream of the city of Valdivia. Engineers from the Chilean Power Corporation (Endesa) recognized the impending danger and led a concerted effort to excavate a channel across the landslide allowing the water which was backing up at the landslide to be released gradually. But the earth moving operation proceeded slowly and virtually stopped when the equipment bogged down at the onset of the rainy season. The landslide was overtopped on June 23, 1960, less than a month after the earthquake. The flood wave traveled downstream and caused some additional damage to Valdivia but fortunately, no new victims were reported because of timely warning to the population.

The number of casualties in the 1960 megaquake was relatively low as the area was sparsely settled at the time. Many homes were built of wood and resisted the earthquake. Many victims were caused by the tsunami. After the earthquake, a building code was introduced for the whole country, and soft ground was recognized as a major factor of damage. For reinforced-concrete frame construction the code recommended the adoption of shear walls—a new technology at the time. A shear wall is a thin vertical structural element made entirely of reinforced concrete. Experience has shown that the introduction of shear walls in Chile paid off in terms of added seismic safety.

The main lesson of this earthquake was the large number of failures in foundations and embankments. A direct effect of the 1960 earthquake was the creation of the International Tsunami Warning Center (ITWC) in Honolulu, with the participation of most nations around the rim of the Pacific Ocean including all Latin American nations which share a coast on this ocean. The warning center is administered by the US National Oceanic and Atmospheric Administration and the Latin American countries are usually represented by their respective Navies.

2.2 Earthquakes and Coastal Geomorphology

Close to the epicenter of the giant 1960 Chile earthquake was the fishing town of Puerto Saavedra (about 14,000 inhabitants). This village on the estuary of the Imperial River was founded in 1885 as a frontier outpost after the Indian Wars. A campaign conducted by General Cornelio Saavedra had ended with the total defeat of the Mapuche Nation. Because of its exposed location at the mouth of the Imperial River, Puerto Saavedra was totally razed by the tsunami less than an hour after the 1960 earthquake. Most villagers were able to reach high ground but about 50 people drowned or were missing. The second or third wave was the largest. Successive waves continued hitting the town until late in the evening.

Puerto Saavedra is an outlet for agricultural and forestry production in an impoverished area of mostly indigenous population. Prior to 1960 the lower course of the Imperial River was navigable but the river shortened its course during the earthquake so that the estuary shifted its position from point A to point B as a result of coastal subsidence (Fig. 2.2). The fishermen at Puerto Saavedra survive by catering to summer guests and vacationers. Formerly they had access to the ocean but now the strong currents and tall breakers of the new estuary are too dangerous. Also, the port is no longer fronting on the river but on a lateral lagoon.

Lake Budi, south of the mouth of the Imperial River, is a brackish allogenic lagoon. It connects with the ocean through a narrow tidal channel known as the Budi River, with a length of about 15 km. The 1960 tsunami invaded Lake Budi and the water level in the lagoon rose about 2 m above the pre-1960 level. This represents the amount of coastal subsidence. The lagoon itself was recognized as a

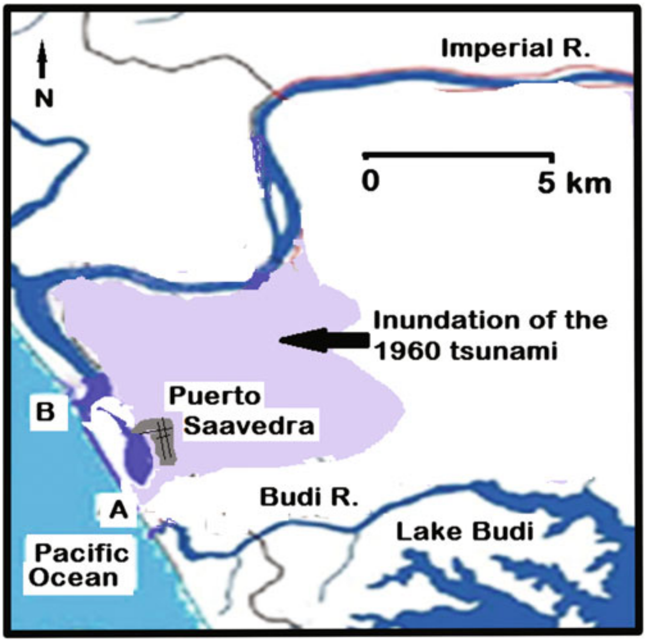

Fig. 2.2 Allogenic lagoon formation in the estuary of the Imperial River, southern Chile. *Shaded*, area of 1960 tsunami inundation; *A*, location of pre-earthquake estuary; *B*, present estuary. The Budi River, now a tidal channel, was once the lower course of the Imperial River

meander of the Imperial River that was cut off from it by some prehistoric earthquake (Lomnitz 1970, Wallner 2007).

The coastal configuration of southern Chile cannot be understood without investigating the geologic history of the area. The back-arc tectonics changes at the 38th Parallel (Fig. 2.1). To the north we find the strongly folded Sierras Pampeanas; active volcanism is absent. But south of 38° latitude the basement shows little deformation, active volcanism reappears and transpressional tectonics dominate in the magmatic arc. Wallner's drilling campaign in Lake Budi produced sedimentary cores that indicated a sudden change of regime from freshwater to brackish, about 2000 years before present. This finding confirmed that the lake had formerly been part of the lower course of the Imperial River: it was cut off by the receding coastline. Lake Budi was created by a large seismic event dated at about 2000 years ago. This "Year-Zero Earthquake" was a megaquake, of similar or larger magnitude than the 1960 earthquake.

No other information is available about this event. But it suggests that a systematic coastal subsidence of at least 2 m has occurred repeatedly on this stretch of coast at a possible time interval on the order of twenty centuries. The process of lagoon formation in the Year-Zero Earthquake was repeated in 1960 at Puerto Saavedra, where the river shortened its course once again and created a brackish lagoon. Another example of coastal recession in megaquakes is the 2011 Tôhoko earthquake, when the coast of NE Japan subsided by up to 1.2 m.

2.3 An Observation of Long-Period Surface Waves on Soft Ground

In 1968, 8 years after the great Chile megaquake, a visit to the epicentral region provided a new observation of the amount of coastal subsidence. Using some pre-1960 aerial photographs and taking the water level in Lake Budi as a proxy of mean sea level it was found that a permanent subsidence on the order of two meters had occurred. Boroa Mission, inland from Lake Budi and a two-hour drive from the provincial capital of Temuco, was used as a base of operations.

Boroa Mission was founded by Capuchin monks in 1883, after the Indian Wars. An earlier mission at Puerto Saavedra had been overrun and burned by the Mapuche warriors. The late Rev. Juan Bautista Wevering, missionary priest at Boroa, was interviewed about his personal observations of the 1960 earthquake. Father Wevering, then in his Forties, was born near the Dutch-German border. He joined the Capuchin Order after the Second World War.

He claimed to have actually *seen* the seismic waves. His testimony was intriguing, especially because he was not aware that elastic waves are invisible to the human eye. This may have enhanced his credibility: he was not prejudiced by any prior information he might have received. On the day of the earthquake, Father Wevering said, he took his lonely Sunday walk to a favorite spot at the top of a NNW trending fault scarp which overlooks the coastal plain. At a quarter past 3 p.m., in clear sunny weather, he strongly felt the earthquake. But he was not afraid. He intently watched a collective phenomenon he described as "seismic waves" rolling inland from the general direction of the epicenter (north-northwest). "The waves kept coming, row upon row, toward where I was standing," he explained. "The earthquake was still in progress: it lasted a long time. Clumps of trees standing on some low hills in the plain would bend over as the waves passed by. It was a beautiful sight. The waves looked and behaved like water waves except that they swept over solid ground."

If we may accept the observation of Rev. J.B. Wevering as a sighting of hybrid elastic-gravity surface waves by a nonscientist, there are some peculiar features of his description which deserve comment. He watched surface waves propagating on soft ground over the sedimentary coastal plain, coming from the direction of the epicenter. The phenomenon struck him as orderly, not chaotic. An essential point in his description was the detail that the trees in the coastal plain tilted in the direction of propagation, "like water waves". These hybrid waves, which we may call *transelastic waves* for short, were intermediate phenomena between elastic waves and gravity waves. As the ground tilted into the direction of propagation the ground motion must have been prograde, as in water waves.

Prograde ground motion helps explain why the overturning moment generated by these waves can be so significant. Much of the damage to tall, rigid reinforced-concrete structures in the period range of 1.5–2.5 s must be attributed to trans-elastic waves.

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