SEISMIC WAVE PROPAGATION IN SOUTH AMERICA

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Abstract

The Comprehensive Test Ban Treaty, at present being negotiated in the Conference on Disarmament, requires an International Seismic Monitoring System and On-Site Inspections. Harjes has recalled three lessons learned from previous Group of Scientific Experts Technical Tests: 1. The International Seismic Monitoring System needs to be calibrated with respect to standard travel-time curves and amplitude-distance relations. 2. Provision of adequate surface wave detection and reporting should be included in the design of the International Seismic Monitoring System. 3. To detect and locate small events, the observation of the seismic wavefield at regional distances is essential. On-Site Inspection requires the location of events, whether earthquakes or explosions, to plus or minus 5 km. In the highly irregular region of northern and western South America, we cannot simply use uncorrected partial derivatives from standard travel-time curves. We have found the response curves of the seismographs that operated at La Paz from the years 1913 to 1962, thus revealing a considerable amount about South American seismicity. We have observed at La Paz that L_g waves of periods of 1.5 and 1.6 s arrive from the Caribbean Sea, north of northwestern Colombia, but not from the Chilean trench to the west of La Paz. We have constructed models of the structure below Iquique, Chile, and of structure below the oceanic trench off the coast from Iquique. For the model of the structure below the oceanic trench off the coast of Iquique, the modes of the shorter periods travel practically entirely in the sediments in the trench (assumed to be of thickness 1 km), while the mode of period 10 s travels predominantly in the low velocity zone at a depth of approxi-mately 110 km. The phase velocities of these modes in the model of the structure below Iquique are between 3.06 and 4.14 km/s; the phase velocities of the Love modes of shorter period (1.9 s to 3.7 s) in the model of the structure below the trench are between 0.51 s and 0.57 s. There is practically no coupling between the Love modes below the oceanic trench and the modes below Iquique. At present we are considering the relation between the Love and Rayleigh modes of short period in our various models and the L_g and the R_g phases. For Colombia, we have constructed models of the regions below Quibdó, below Barranquilla and below the Caribbean Sea northwest of Barranquilla. The Caribe plate motion near Mérida, western Venezuela, suggests, together with right hand strike-slip motion, a substantial portion of thrust. We are at present analyzing by the finite element method the propagation of Love and Rayleigh waves across these regions.

Key Words: Andes Mountains, seismograph response, Love waves, Lg waves, finite element method

SEISMIC WAVE PROPAGATION IN SOUTH AMERICA

Objective

The Comprehensive Test Ban Treaty, at present being negotiated in the Conference on Disarmament (Alewine, 1995; Conferencia de Desarme, 1994a; 1994b), requires an International Seismic Monitoring System and On-Site Inspections. Harjes (1995), discussing the International Seismic Monitoring System, has observed that the use of modern technology does not necessarily improve the seismological results. He has recalled, among other lessons, three principal lessons learned from previous Group of Scientific Experts Technical Tests: 1. The International Seismic Monitoring System needs to be calibrated with respect to standard travel-time curves and amplitude-distance relations. 2. Provision of adequate surface wave detection and reporting should be included in the design of the International Seismic Monitoring System. 3. To detect and locate small events, the observation of the seismic wavefield at regional distances is essential. Kennett (1993) has noted that the seismic source imposes a distinctive pattern on the radiated seismic wavefield, but this pattern is profoundly modified on passing through an irregular region. The crustally guided wave L_g is useful in the discrimination of seismic sources. However, even from a single source, amplitude ratios of short period waves like L_g can vary significantly. On-Site Inspection requires the location of events, whether earthquakes or explosions, to plus or minus 5 km (for an inspection area of 100 km^2). In the highly irregular region of northern and western South America, we cannot simply use uncorrected partial derivatives from standard travel-time curves (to change inconsistencies in arrival times to a change in the position of the event). Eisenberg and his coworkers (1989) located with local seismograph stations aftershocks of the 1985 Chile earthquake and some 1981 earthquakes; they found that almost 10 percent of the National Earthquake Information Service locations of these earthquakes differed by more than 65 km from the locations found from the local stations. We need to understand the structure of the Andean Cordillera and we need to model the ground motion of waves passing across it in order to locate events accurately, to discriminate between them and to estimate correctly their magnitude. The task of the International Monitoring System is considerable. An explosion of 10 kt, fully decoupled in salt, has a magnitude of approximately 3.5 (Sykes, 1995). There are, on average, 57 events of magnitude 3.5 in the world each day; 21,000, each year (Conferencia de Desarme, 1994a). A considerable proportion of these events occur in South America; difficulties of location, discrimination and magnitude estimation need to be reduced.

Preliminary Research Results

We have found the response curves of the seismographs that operated at La Paz from the years 1913 to 1962, thus revealing a considerable amount about world, and especially South American, seismicity. "Data for the southern hemisphere were much improved by the establishment of the station at Riverview (near Sydney), Australia, beginning March 18, 1909.... A further improvement followed the installation at La Paz (Bolivia), with reports beginning May 1, 1913. La Paz at once became, and still remains, the most important single seismological station of the world. This is a consequence of its isolated location, the sensitive instruments, and the great care with which records were interpreted and reports issued under the direction of Father Descotes" (Gutenberg and Richter, 1954, p.6; in 1962, the World-Wide Standard Seismograph Network became operational). For the three seismographs recording on smoked paper, dynamic magnification equals $V/D^{1/2}$, where V is static magnification and

$$D = \left[1 - \left(\frac{T}{T_o}\right)^2\right]^2 + \frac{4\ln^2\epsilon}{\pi^2 + \ln^2\epsilon}\left(\frac{T}{T_o}\right)^2$$

T being the ground period, T_o the period of the seismometer, ϵ the damping ratio and ln the logarithm to the base e. V, T_o and ϵ are given in the La Paz Boletín Sísmico; r/T_o^2, the solid (or pen) friction, is also given, but its effect, except for very large pen movement, is included in the damping ratio ϵ (Sohon, 1932, p. 63 ; Byerly, 1933; 1942, p. 110). At a period of 12 s, the dynamic magnification of the two horizontal seismographs recording on smoked paper was approximately 500 (Fig. 1). For the Galitzin-Wilip seismographs, dynamic magnification equals $T/C'UD^{1/2}$, where C' is $\pi L/AK$, L is the distance from the hinge to the center of oscillation of the pendulum, A is the optical lever arm of the galvanometer, K is Galitzin's 'transfer factor', U is $1+(T/T_g)^2$, T_g is the period of the galvanometer, μ^2 is $1-\zeta^2$, ζ is the fraction of critical damping of the seismometer and

$$D = (1 + (T/T_o)^2)^2 - 16\mu^2(T/T_o)^2$$

(Galitzin, 1911, p.266). T_o, T_g, μ^2 and log C' are given in the La Paz Boletín Sísmico. At a period of 8 s, the dynamic magnification of the Galitzin-Wilip seismographs at La Paz was approximately 2000 (Fig. 2).

In northern Bolivia, the Andean Cordillera forms the Cordillera Occidental, at the border with Chile, and, 250 km northeast, the Cordillera Real. These two branches of the Cordillera are separated by Lago Titicaca and the Altiplano. In central Bolivia, on account of the Arica 'elbow' of the western South American coastline, the Nazca plate is forced to spread and change its strike from approximately NW-SE to approximately N-S (Omarini et al., 1991; Dorbath et al., 1993; Baby et al., 1993; Lamb et al., 1993). We have observed at La Paz that L_g waves of periods of 1.5 and 1.6 s arrive from the Caribbean Sea, north of northwestern Colombia,

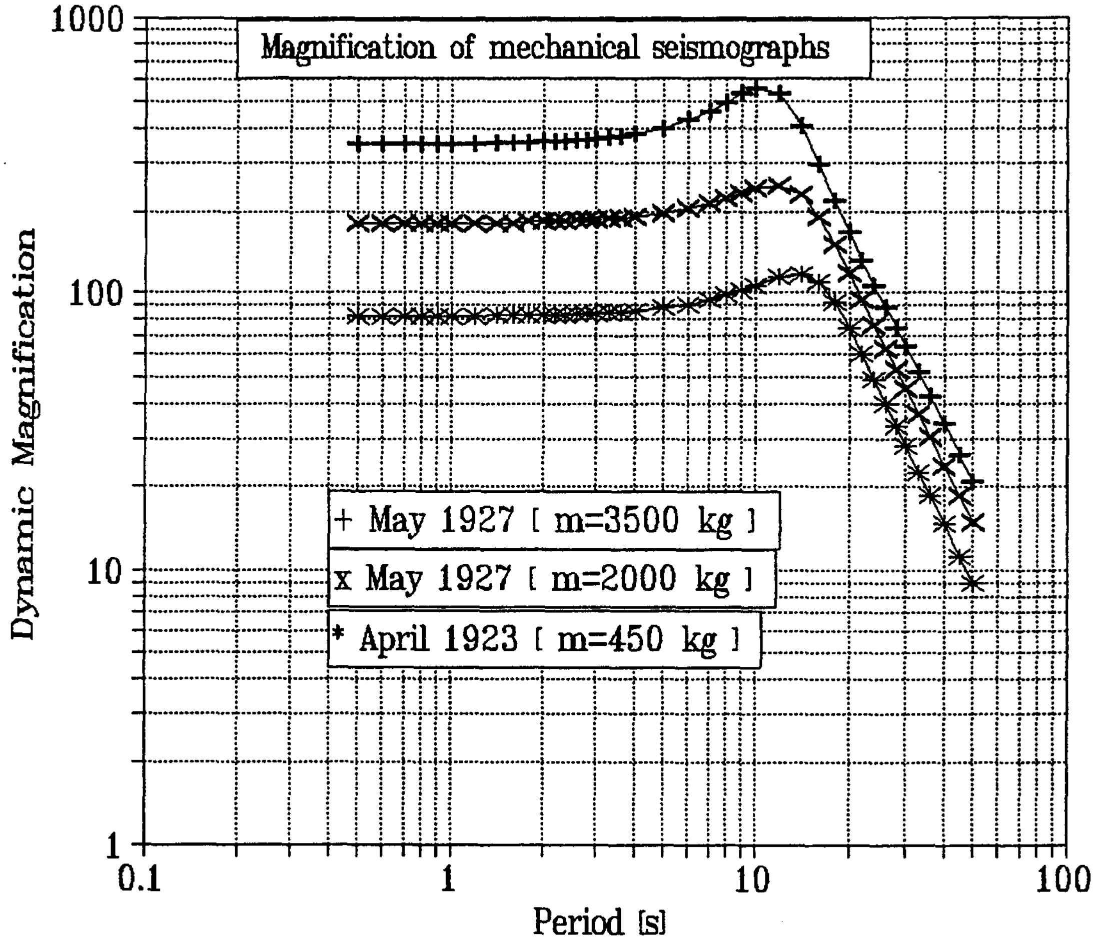

Fig. 1. Examples of the dynamic magnification of the mechanical seismographs recording on smoked paper at La Paz: E-W (3500 kg), May, 1927; N-S (2000 kg), May, 1927; E-W (450 kg), April, 1923.

but not from the Chilean trench to the west of La Paz. We have constructed models of the structure below Iquique, Chile (20°13'S, 70°10'W), and of structure below the oceanic trench off the coast from Iquique (Tables 1 and 2; Wigger et al., 1994; Dziewonski et al., 1975; Dziewonski and Anderson, 1981; Drake, 1989). The variation of displacement with depth of the fundamental Love modes of periods 0.7 s, 1.5 s, 5.0 s and 10.0 s for the model of the structure below Iquique are shown in Fig. 3; the modes are normalized so that the energy they transmit is proportional to the product of their angular frequency and wavenumber (Lysmer and Drake, 1972). The variation of displacement with depth of the fundamental Love modes of these periods for the model of the structure below the oceanic trench off the coast of Iquique cannot be conveniently shown, because the modes of the shorter periods travel practically entirely in the sediments in the trench (assumed to be of thickness 1 km), while the mode of period 10 s travels predominantly in the low velocity zone at a depth of approximately 110 km (Drake and Bolt, 1980). The phase velocities of these modes in the model of the structure below Iquique are between 3.06 and

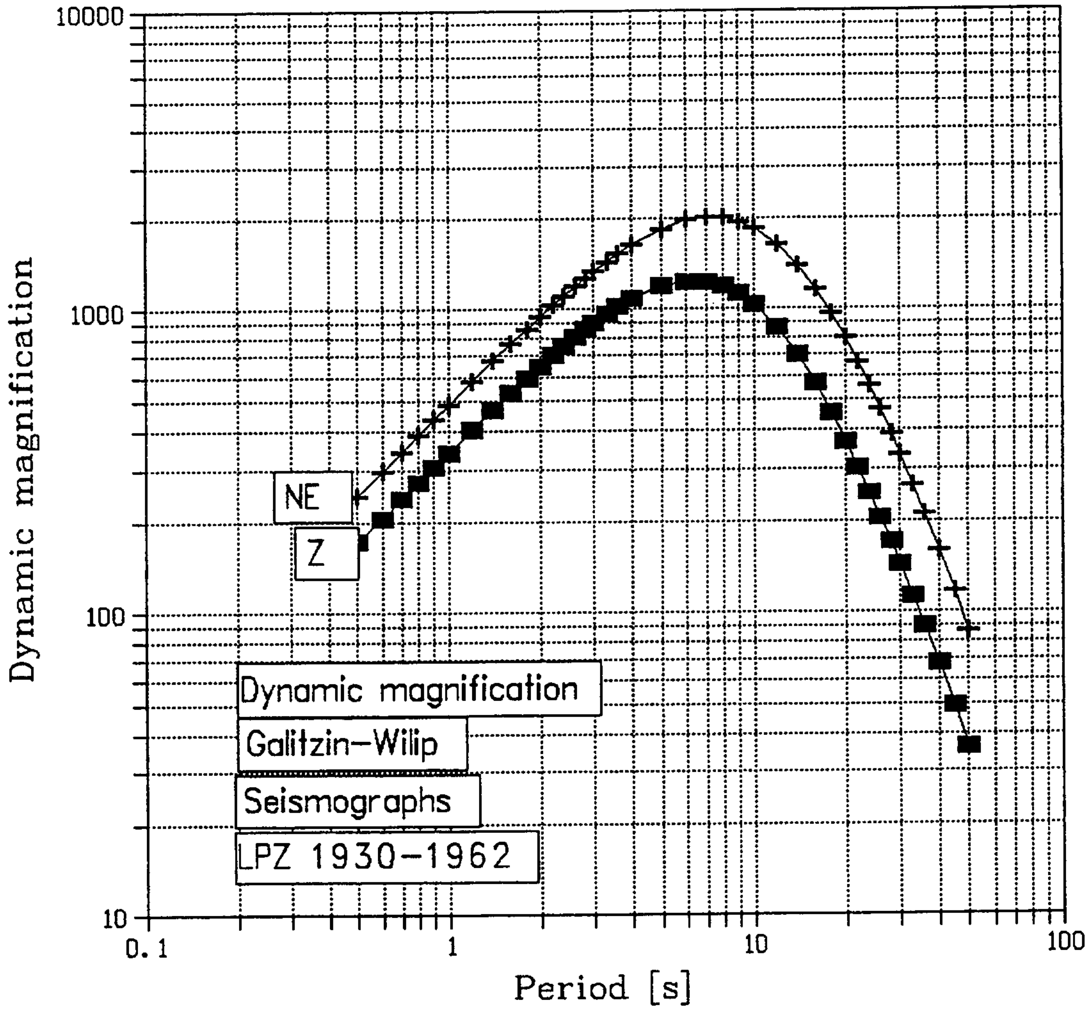

Fig. 2. Examples of the dynamic magnification of the Galitzin-Wilip seismographs operating at La Paz: N-S and Z for 1960; E-W is very similar to N-S.

4.14 km/s; the phase velocities of the Love modes of shorter period (1.9 s to 3.7 s) in the model of the structure below the trench are between 0.51 s and 0.57 s. There is no need to analyze a two-dimensional finite element model to see that there is practically no coupling between the Love modes below the oceanic trench and the modes below Iquique. In 1957, Ewing, Jardetzky and Press (p. 219) noted that as little as 2° of intervening ocean is enough to eliminate the L_g phase entirely. At present we are considering the relation between the Love and Rayleigh modes of short period in our various models and the L_g and the R_g phases (Press and Ewing, 1952; Nuttli, 1986). For Colombia, we have constructed models of the regions below Quibdó (05°42'N, 76°40'W; Flüh et al., 1981), below Barranquilla (10°59'N, 74°48'W) and below the Caribbean Sea northwest of Barranquilla. We have also constructed models of the regions below the Coastal Cordillera, east of Iquique, below the Cordillera Occidental, below the Altiplano, below La Paz and below the Cordillera Oriental. We are at present analyzing by the finite element method the propagation of Love and Rayleigh waves across these regions.

TABLE 1. MODEL OF IQUIQUE TO A DEPTH OF 220 KM

Layer thickness km	Compressional velocity km/s	Shear velocity km/s	Density g/cm^3	Poisson's ratio	Quality factor Q
0.3	3.80	2.28	2.35	0.219	20
1.5	5.50	3.30	2.63	0.219	20
1.8	5.90	3.51	2.68	0.227	20
10.4	6.30	3.74	2.75	0.227	30
6.0	6.80	3.98	2.83	0.240	40
8.8	7.00	4.09	2.86	0.240	60
13.6	7.40	4.27	3.14	0.250	80
9.0	8.20	4.80	3.30	0.240	400
22.6	8.02	4.69	3.35	0.240	400
23.0	8.02	4.69	3.36	0.240	400
23.0	8.02	4.69	3.37	0.240	400
20.0	7.85	4.46	3.38	0.262	80
20.0	7.85	4.46	3.39	0.262	80
20.0	7.85	4.46	3.40	0.262	80
20.0	7.85	4.46	3.41	0.262	80
20.0	7.85	4.46	3.43	0.262	80

TABLE 2. MODEL OF IQUIQUE TRENCH TO A DEPTH OF 220 KM

Layer thickness km	Compressional velocity km/s	Shear velocity km/s	Density g/cm^3	Poisson's ratio	Quality factor Q
6.0	1.52	0.001	1.03	0.500	500
1.0	2.15	0.50	1.80	0.471	20
1.0	4.70	2.50	2.50	0.303	40
5.0	6.80	3.80	2.90	0.273	60
20.0	8.20	4.70	3.31	0.255	400
27.0	8.20	4.70	3.33	0.255	400
20.0	7.90	4.34	3.34	0.284	80
20.0	7.90	4.34	3.36	0.284	80
20.0	7.90	4.34	3.37	0.284	80
20.0	7.90	4.34	3.38	0.284	80
20.0	7.90	4.34	3.39	0.284	80
20.0	7.90	4.34	3.40	0.284	80
20.0	7.90	4.34	3.41	0.284	80
20.0	7.90	4.34	3.43	0.284	80

Recommendations and Future Plans

We have recently obtained the Mapa Neotectónico de Venezuela (Beltran, 1993), which includes the faults of much of eastern Columbia and their directions of movement. Also, we have obtained a recent estimation of plate motions and boundaries (Gordon, 1995). The general motion near Cumaná, in eastern Venezuela

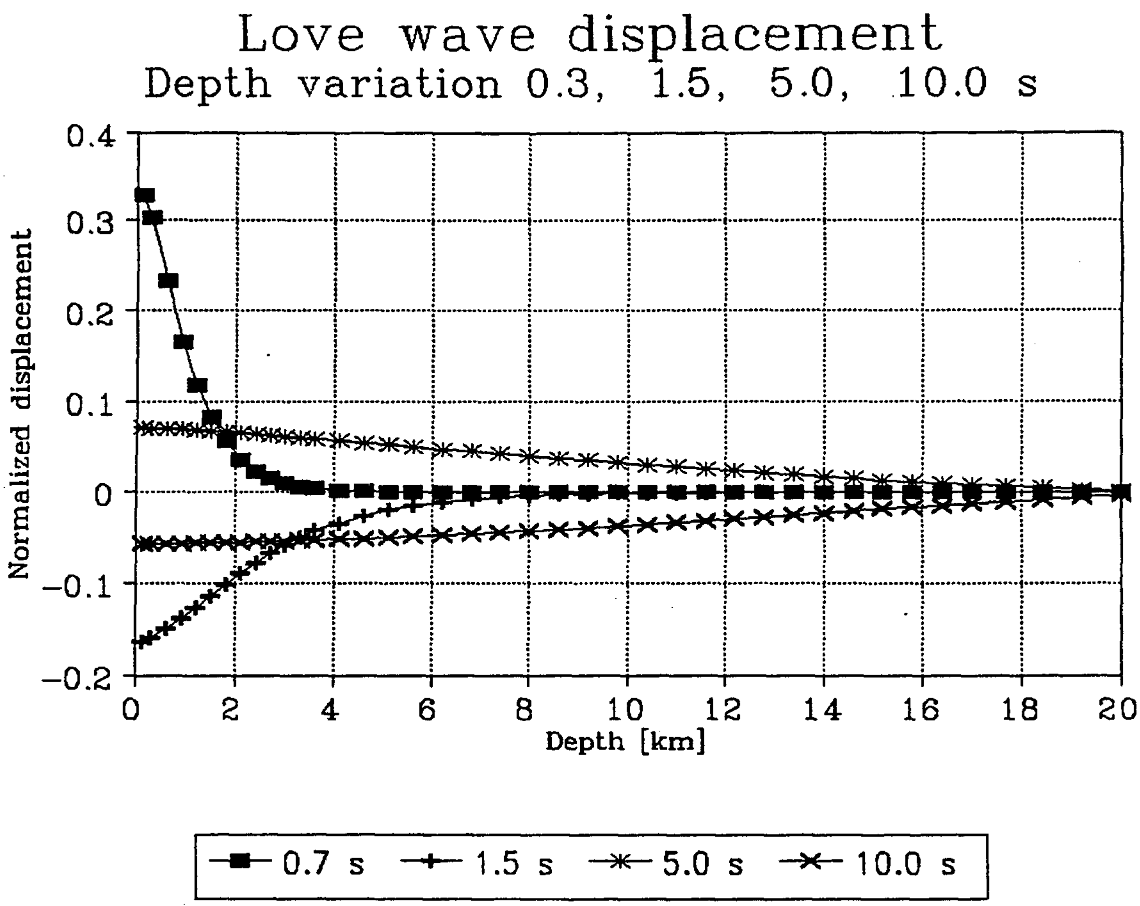

Fig. 3. The normalized variation of displacement with depth of the fundamental Love modes of periods 0.7 s, 1.5 s, 5.0 s and 10.0 s for the model of the structure below Iquique.

(10°28'N, 64°10'W) is clearly right-hand strike-slip, but the right-hand strike-slip motion near Mérida, in western Venezuela (08°36'N, 71°08'W), if we assume approximately rigid Caribe and South American plates, must include a substantial portion of thrust. Bueno and his coworkers (1993) consider the Lake Maracaibo region in western Venezuela to be part of the South American plate. However, it appears that much of Colombia is part of neither the South American plate nor the Caribe plate, but is part of the bloque Andino (Ramírez, 1977; Pennington, 1981). We plan to continue to model by the two-dimensional finite element method the propagation of Love and Rayleigh waves, considering also L_g and R_g phases, across Bolivia, Chile and Colombia. Also, with improved models of these regions, we can consider the more accurate location of events.

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