Sensing, Analyzing, and Acting in the First Moments of an Earthquake

by Giuseppe Olivadoti

Earthquakes and seismic activity have always been a hot issue. Attention is focused time and again by disasters such as the earthquakes in Turkey, Taiwan, and India. It has become apparent that the power of an earthquake is not something we are currently prepared to handle. Much of the problem is that the damaging earthquake waves seem to come out of nowhere without warning. However, this may not truly be the case. Earthquakes, if properly analyzed, can actually give warning of their incipient occurrence, even if only moments before the ground starts shaking. A critical objective is to quickly identify the precursors of the destructive waves of the earthquake in time to initiate an alarm and a shutdown of vulnerable facilities.

When feasible, early detection can potentially be very valuable. Consider for instance the devastating damage and loss reported from the earthquake that occurred in Turkey on Tuesday, August 17, 1999. The 45-second earthquake, of Richter magnitude 7.4, had an epicenter approximately 7 miles (11 km) southeast of Izmit, an industrial city roughly 56 miles (90 km) east of Istanbul. The earthquake was felt over a large area—as far east as Ankara, which is about 200 miles (320 km) away. Unofficial estimates place the death toll between 30,000 and 40,000.

Although the collapse of commercial and residential buildings caused most of the deaths and injuries, a widely publicized and spectacular tank explosion—which occurred at the massive Tüpras refinery in Korfez—caused significant deaths and injuries due to the fires that followed in its wake. Fire in one of the tank farms quickly spread to other tank farms through pipelines and distribution systems and burned out of control for several days, prompting an evacuation within a three-mile radius. Some loss of life and property at the Tüpras refinery might have been prevented if valves controlling pipelines and distribution systems carrying highly flammable material had been shut off. A few extra moments to react to the earliest warnings in such a system might have allowed valves to be shut off on pipelines and distribution systems, and an alarm to be sounded.

In many quake-prone locations, safety codes, even for homes, require acceleration-sensitive shut-off valves. While undoubtedly quite useful, they respond only upon arrival of the surface wave, and then only (in many cases) for vibration in a single plane. Also, they may respond with false alarms to vibrations caused by large vehicles and to other non-earthquake shocks, requiring wasteful resetting procedures.

How might earthquakes be analyzed to give advance warning?

When an earthquake occurs, energy radiates outward in all directions. The energy travels through and around the earth as three types of seismic waves called *primary*, *secondary*, and *surface* waves.

The energy of primary waves (or P waves) travels through the earth as a sequence of back-and-forth vibrations in a plane (x- and y-axis) parallel to the direction of propagation of the seismic wave. The wave's passage through the earth causes the pushing (compression) and pulling (dilation) of particles in its path, and it can travel through solids or liquids. P waves are the fastest of the three types of seismic waves. Figure 1 shows the passage of P waves through the earth.

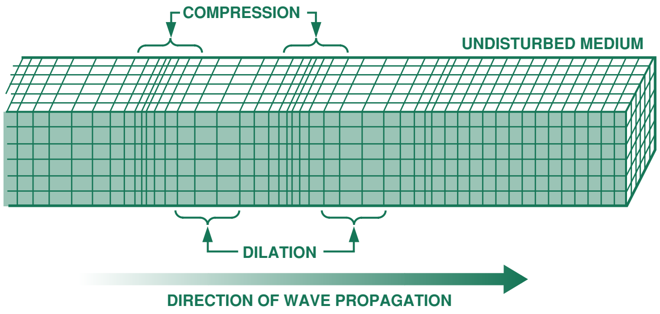

Figure 1. Passage of P waves through the earth's crust*.

Secondary waves (or S waves, see Figure 2), also referred to as *shear* waves, can travel through solids, but unlike *P* waves cannot travel through liquids. The energy of *S* waves travels through the earth as a sequence of up-and-down vibrations perpendicular to the surface of the earth. Its passage causes particles to vibrate in all directions, North-South and East-West. Its velocity is between that of *P* waves and that of surface waves.

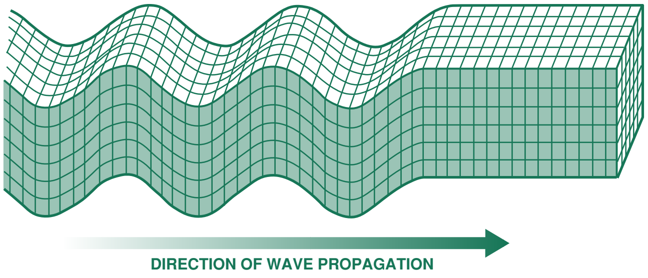

Figure 2. Passage of S waves through the earth's crust*.

Surface waves are the slowest and by far the most destructive of the three types of seismic waves. Surface waves travel along the surface of the earth as two types of waves: Rayleigh waves have a horizontal shearing motion similar to S waves, while Love waves have a rolling motion in the vertical plane much like water waves. Figure 3 shows the passage of both the Rayleigh and Love waves through the earth.

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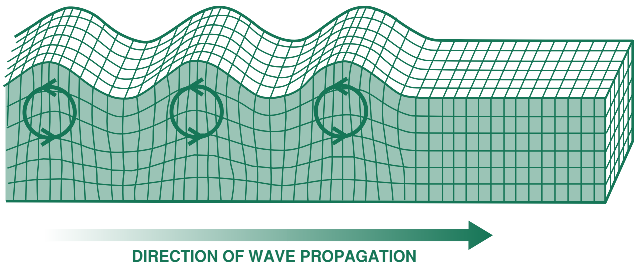
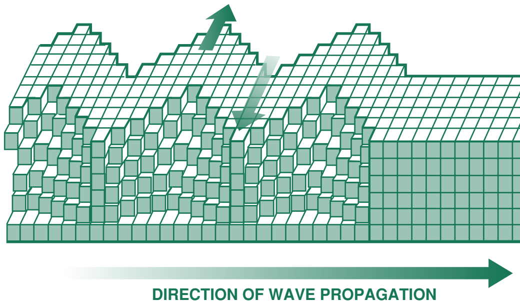


a. Passage of Rayleigh waves through earth's crust.



b. Passage of Love waves through earth's crust.

Figure 3. Surface Waves*

P waves typically travel 1.68 times faster than S waves and 2 to 3 times faster than surface waves, which typically travel at about 3.7 km/s. Thus there is typically a one-second separation between the *P* and *S* waves for every 8 km traveled. S waves travel about 4 km/s faster than surface waves, so every 4 km away from the epicenter typically adds one extra second of delay between the P-S complex and the arrival of the surface waves.

The various types of earthquake waves follow this pattern. At a given distance from the epicenter, the P wave arrives first, then the S wave, both of which have such small energies that they are not threatening. Finally, the surface waves arrive with all of their damaging energies (Figure 4). It is predominantly the surface waves that we would notice as the earthquake. This knowledge, that preceding any surface or destructive earthquake waves there are tell-tale body waves, can be used to help predict the arrival time of the damaging surface waves.

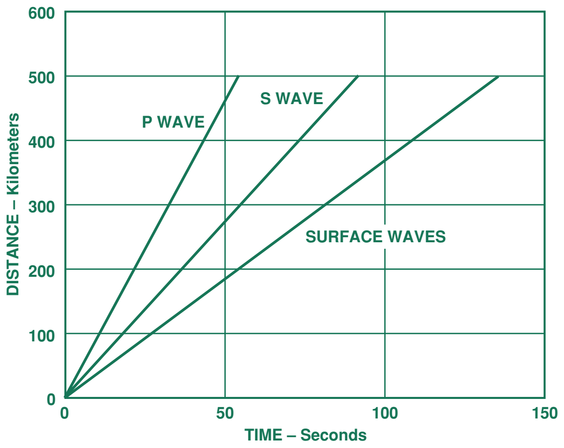


Figure 4. Comparison of arrival times at a given distance from the epicenter. Calculations are based on short distance approximations of Surface and Body wave velocities.

For example, at a distance of 7 miles (11 km), nearly 3 seconds would elapse during which the P-S complex could be sensed and identified, and alarms and valve closures initiated. Rapidly responding low-cost sensors and digital signal processors could render a rapid decision and allow nearly 100% of this time for mechanical operations.

The elements of a detection system, shown in Figure 5, would include 3-dimensional sensing of earth motion, filtering, analysis, and actuation of alarms, valve closures, etc.

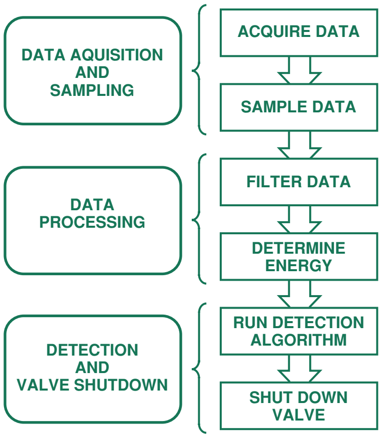


Figure 5. Functional diagram of detection system.

The simplest of approaches is shown in the flow diagram (Figure 6). While continuously monitoring the X, Y, and Z accelerometer outputs, an unusually large acceleration disturbance is identified, and labeled as a possible P (compression) wave. The system stands by, waiting to identify a following transverse disturbance as an S wave. If none occurs within a time corresponding to (say) 500 km of P-wave travel, the system shrugs it off as a false alarm (or a distant phenomenon). If, on the other hand, a transverse disturbance does show up, the detection system actuates an alert, which includes a surface-wave ETA (estimated time of arrival), and possibly seeks confirmation from similar systems in the locality before issuing the alarm. If they are in constant contact, this could all occur within less than a few milliseconds after the presence of an S wave is verified.

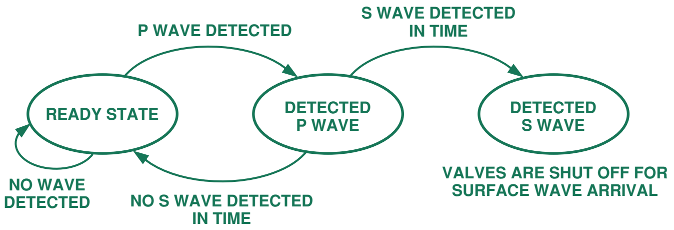


Figure 6. Detection and verification process flow chart.

Applying signal processing to solve this problem

In addressing this problem the motion in all three axes—X, Y, and Z—must be measured promptly and accurately. An accelerometer would be a perfect example of a device that is capable of sensing this sort of seismic movement. An example could be the fast-responding Analog Devices ADXL202 high-sensitivity and very-low-cost, two-axis accelerometer family. The data produced by the array of accelerometers would then need to be processed

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continuously. The data would need to be filtered so that random noise would be removed and any received signal compared with earthquake signatures using energy-detection algorithms to identify and predict the arrival time of an earthquake at the sensing point (and elsewhere)—and the likely energy level of the surface waves. An example of a device for this sort of processing is a DSP, such as the low-cost, high-performance floating-point ADSP-21161N. It offers 32-bit precision, on-chip memory, and a host of other advanced architectural features that make it suitable for filtering and analysis, as well as decision-making.

The key advantages of doing this type of detection:

This type of detection could be very useful in high-risk earthquake areas. Exploiting the differences in arrival time of an earthquake could offer a few seconds advance notice that a destructive wave will be present shortly. This time could be used for a number of things, such as stopping the flow of hazardous or flammable waste from flowing through pipes, and halting production lines of hazardous or flammable materials. This type of detection can also offer fairly reliable earthquake identification by exploiting its characteristic multiple wave system. It is because of the knowledge that seismic waves travel in groups of three that the detection system can filter out extraneous noise such as might be produced by large trucks, rock blasting, etc.

The disadvantages of relying on this type of detection:

This approach (and most others) will be ineffective if the epicenter of the earthquake is too close to the sensing device. There will generally not be enough time for mechanical devices to react, even if the entire analysis process requires only a few milliseconds or less. Since the time difference between seismic waves is due to their propagation velocity relative to each other, there needs to be some minimum distance away from the epicenter (see Figure 4) to establish an identification with reasonable confidence. That minimum distance will depend on the application. For instance, in protecting a gas or oil line, one must take into account the speed with which a valve can seal the pipe.

CONCLUSION

It is reasonable to consider that a low-cost seismic detection system can be designed using tried-and-true high-performance digital signal processing plus the kinds of motion sensors that are now used in collision detection for airbags in millions of automobiles. An example of an experimental system embodying these principles, using an Analog Devices DSP and accelerometer, can be seen in the *SHARC 2000 International DSP Conference* proceedings. A seismic detection system offers the possibility of having a few critical moments of advance notice before the arrival of a destructive surface earthquake wave. Perhaps if these ideas plant the seed of designs for useful devices that can undergo extensive testing and be produced in high volume, some aspects of seismic disasters could be contained, saving human works and lives.

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