Earthquake Hazards Program

Groundwater Effects from Earthquakes

Note: Some of the explanations below are speculative and should not be relied upon for decision-making. Please see the reference articles (below) for published results.

Seismic waves have **two main types of effects** on groundwater levels: **oscillations**, and **"permanent" offsets**. Muddy or turbid water at long distances from the epicenter are most likely an aftereffect of oscillations.

Oscillations

Oscillations have been known for decades (see papers by Rexin below). The oscillations are rarely recorded with a short enough sampling period to see details of the wave train. On chart recorders they show up as vertical lines and on digital data sampled every few minutes they show up as a few errant data points. When they are recorded with a sampling interval of about 1 sec, they generally look like low-pass-filtered seismograms. Dominant periods are about 20 sec, consistent with the idea that the water level changes are predominantly caused by long-period surface waves.

A **theory** for the oscillations was developed by *Cooper et al.* and refined by *Liu et al.* This theory is based on the idea that seismic waves cause expansion and contraction of the aquifer tapped by the well, in turn causing oscillatory pore pressure changes. If the aquifer has high enough transmissivity, then these pressure changes cause flow into and out of the well. The flow in turn sets up resonant motion of the water column. For most well-aquifer systems, the theoretical dominant frequency is around 10-30 sec based on the height of the water column. Following this theory, the head changes in the aquifer induced by the seismic waves are actually only a fraction of the water-level changes in the well.

The theory is only now being rigourously tested by quantitatively comparing seismograms with the "hydroseismograms", and so far the conclusion is that the resonance effect is not actually that important. This implies that the pore pressure changes in the aquifer are about the same size as the water level fluctuations in the well. If this holds true for additional sites, it means that seismic waves induce bigger pore pressure changes in subsurface formations than previously thought.

Offsets

The "offsets" are harder to explain. They have also been known for decades (eg., the 1964 Alaska quake papers). We do expect offsets in the "near field" of an earthquake because the fault offset produces permanent expansion and contraction of the surrounding rocks. At distances of 100's or 1000's of km, however, the permanent ground deformation is negligible.

Some observations about the steps:

- Certain wells exhibit the offsets; most do not.
- At wells that respond this way, the offsets are always in the same direction; that can be either up or down.
- In hot-water wells, the offsets are frequently rises.
- The largest offset recorded digitally is a 1-m rise caused by the 1989 Loma Prieta earthquake in the BV well at Parkfield (see *Roeloffs, 1998*).
- The offsets can be "instantaneous" (to the resolution of the water level sampling interval), or they can begin abruptly and take days to weeks to reach their maximun (or minimum) values. The slower responses generally follow curves that are well-matched by a 1-D groundwater diffusion model, ie., the shapes of these curves suggest that seismic waves change water level "instantaneously" at a location near, but not at, the well.
- The offsets are not limited to shallow depth. The deepest recorded one was probably the response of the Long Valley Exploratory well to the Oct 16, 1999 Hector Mine earthquake (about 400 km away). Fluid in the this well is in communication with a transmissive fracture at a depth of 2.6 km.
- For each well exhibiting offsets there is usually a magnitude-distance threshold that will predict whether or not an offset will be observed. For example, a M5 event 20 km away might produce a step; if the event is 400 km distant it would need to be a M7.

Some possible mechanisms for the steps

- For upward steps in shallow wells, compaction of overlying alluvium such as occurs during liquefaction is a possibility (*Roeloffs, 1998*)
- Escape of small amounts of exolved gas from pore space could cause fluid pressure drops (*Matsumoto and Roeloffs*)
- A change of permeability due to unclogging of a fracture by flow induced by seismic waves (*Brodsky et al.*)
- At Long Valley, incremental amounts of dome inflation triggered by seismic waves (*Roeloffs et al.*)

- In hot water wells at Long Valley, thermal pressurization due to upward movement of hot fluid triggered by seismic waves (Roeloffs et al., submitted). Scientific importance of all this: From my viewpoint, the most important scientific implications have to do with the remote triggering of seismicity (and possibly volcanic eruptions) by large earthquakes. Seismic waves at distant locations are transient, yet they can trigger seismicity that persists for days (or longer) or larger events that are delayed. It is known that increasing fluid pressure can trigger earthquakes (lab and induced seismicity studies), and the seismic-wave-induced fluid pressure offsets are effects that last much longer than the duration of the seismic wave train. It also appears that triggered seismicity preferentially occurs in hydrothermal areas, and that in these areas fluid pressure rises are more likely to be increases. The exact mechanism linking the fluid pressure changes and triggered earthquakes isn't yet pinned down, but the circumstantial evidence for a connection is rather compelling.

Further Details

Confined vs. unconfined aquifers: In the "near field" of an earthquake (say 10-20 km), confined aquifers are more likely to show a response to permanent deformation caused by the fault offset. However, seismic waves seem to be able to cause groundwater level changes in other ways, and these changes can show up in either confined or unconfined aquifers.

Changes caused by permanent deformation (strain) only last until the pressure equilibrates with the water table. This can happen in minutes or may take months. The time scale is approximately given by the square of the aquifer depth divided by the vertical hydraulic diffusivity of the overlying material. This is only relevant in the near field of the earthquake. Other step-like changes tend to recover on the order of weeks or months. The mechanisms of most of these changes are unknown, so the mechanism of their recovery is unknown. The recovery may take place by flow to the boundaries of the hydrologic system, so the time scale is governed by the distance to the boundaries and the hydraulic diffusivity.

Could water levels be affected several times per year? If a well exhibits seismic oscillations, then it could potentially have oscillations for many earthquakes of M7 occurring within a distance of 3000-4000 km. However, the water level usually comes back to the pre-earthquake value within minutes or tens of minutes after the earthquake, so this should not pose a problem in a remediation scheme. Wells that exhibit "long-term" offsets tend to do so for larger, nearer earthquakes. So such a well could be affected several times a year if it's in a seismically active area.

When an earthquake in Alaska changes water levels in the midwest US, for example, producing a "step-like" change, we don't really know the reason. So, we also don't know how the aquifer pressures are affected away from the wells, and we don't know the types of flow that would be set up by these effects.

References

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