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Effects of Earthquakes and Earth Tides on Water Levels in Selected Wells in the Piedmont of Delaware

BY
John H. Talley

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INTRODUCTION

Examination of continuous water-level hydrographs from two artesian observation wells in the Piedmont near Newark, Delaware reveals water-level fluctuations caused by earthquakes and by earth tides. The effects of 14 distant earthquakes with MS (surface wave) magnitudes between 6.7 and 8.0 and MB (body wave) magnitudes between 5.9 and 7.0 (National Earthquake Information Service, 1975-1977) have been recorded over a two-year and ten-month period.

The oscillations recorded appear as sharp marks on the charts lasting from a few minutes to several hours. They result from dilation and compression of the aquifer and vertical motion of the well-aquifer system (Cooper et al., 1965). The largest amplitude oscillations are probably caused by long period Rayleigh waves, which are surface waves that force the rock particles to move in an elliptical orbit in the vertical plane of the path of the waves (Spall, 1978). Amplitudes generated by the 14 recorded events ranged from 0.015 feet (0.46 cm) to 0.215 feet (6.55 cm).

Earth tide-induced fluctuations result from the response of the solid earth to the same forces that produce ocean tides:

(1) the force of gravitation exerted by the moon and sun on the earth;

(2) centrifugal forces produced by the revolution of the earth and moon (and earth and sun) around their common center of gravity.
Earth tides are generally characterized by semidiurnal fluctuations (two minima per day) that correspond to the moon's transit at upper and lower culmination. The larger amplitude and more regular fluctuations coincide with the new and full moon phases while smaller amplitude fluctuations of less regular character occur during first and third.

GEOLOGIC SETTING

Figure 1 shows the location of wells Ca45-39 and Cb41-10 in the Delaware Piedmont. Well Ca45-39 is adjacent to the flood plain of White Clay Creek; well Cb41-10 is 1,350 feet (411 m) to the southeast and close to a small tributary of White Clay Creek. The area is underlain by crystalline rocks of the Wissahickon Formation of the Glenarm Series. Woodruff and Thompson (1974) have divided the Wissahickon Formation into metagraywacke (Wmg) and pelitic facies (Wp) as shown on Figure 1. Both wells are completed in the metagraywacke facies, which consists of interbedded quartz-biotite-oligoclase feldspar gneiss and schist.

WELL CONSTRUCTION AND AQUIFER COEFFICIENTS

Well Ca45-39 is 6 inches (15.24 cm) in diameter and 360 feet (109.7 m) deep. It is cased through a zone of weathered gneiss and schist to 92 feet (28 m) below the land surface and is finished beneath the casing as an open hole in the crystalline rocks. A water-bearing fractured rock zone was identified between 172 feet (52.4 m) and 230 feet (70.1 m) and yielded about 200 gallons per minute (12.6 L/s). The lithologic, caliper, and gamma-ray logs from the well are shown in Figure 2. Analysis of drawdown and recovery data acquired from a 24-hour aquifer pumping test, at a discharge of 100 gallons per minute (6.3 L/s), yielded a transmissivity of 3,700 (gal/d)/ft (gallons per day per foot) (45.8 m²/d) and a specific capacity of 4.9 (gal/min)/ft (gallons per minute per foot) [1.01 (L/s)/m] of drawdown. The water in well Ca45-39 occurs under confined conditions.

Well Cb41-10 is 355 feet deep (108.2 m) and contains 52 feet (15.9 m) of 6-inch (15.24 cm) diameter steel casing. A relatively thick intermittently fractured rock zone that yielded 150 gallons per minute (9.5 L/s) while drilling was penetrated between 130 feet (39.6 m) and 178 feet (54.2 m).
Figure 1. Location and geologic setting of wells Ca45-39 and Cb4l-10.

Wp = pelitic facies, Wissahickon Formation;
Wmg = metagraywacke facies, Wissahickon Formation;
fmg = felsic and mafic gneiss, Wilmington Complex;
--- = geologic contact
The results of a 43-hour aquifer pumping test at 198 gallons per minute (12.5 L/s) show that the transmissivity is 1,700 (gal/d)/ft (21.1 m²/day) and the specific capacity is 2.6 (gal/min)/ft [0.54 (L/s)/m] of drawdown. Water occurs under confined conditions in well Cb41-10.

<table>
<thead>
<tr>
<th>LITHOLOGIC LOG</th>
<th>CALIPER LOG</th>
<th>GAMMA-RAY LOG</th>
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<tbody>
<tr>
<td>SILT, clayey, brown</td>
<td>(BOREHOLE DIAM)</td>
<td>50 CPS</td>
</tr>
<tr>
<td>Micaceous SCHIST, dark brown and gray, decomposed</td>
<td>(INCHES)</td>
<td></td>
</tr>
<tr>
<td>Micaceous SCHIST, soft, gray, (structured sapphire)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CASING</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micaceous SCHIST, gray and black, dry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micaceous SCHIST, gray and green with thin pegmatite stringers</td>
<td></td>
<td></td>
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<tr>
<td>Quartz-biotite GNEISS and SCHIST, gray and green, taly, some pegmatite. Densely fractured rock with mineralized surfaces.</td>
<td></td>
<td></td>
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<tr>
<td>Chlorite SCHIST with some pegmatite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micaceous GNEISS and SCHIST, gray and very hard</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Lithologic, caliper, and gamma-ray logs of well Ca45-39 (After Talley, 1974).
DISCUSSION

Fluctuations Resulting from Earthquakes

The seismic waves recorded in well Ca45-39 between February 1975 and November 1977 were caused by earthquakes that occurred in various parts of the world: northeastern China, the Philippine Islands, Romania, the eastern Indian Ocean, the southwest Pacific Ocean, the Solomon Islands, and off the coast of northern California. Most of these earthquakes were recorded by seismograph station NED (Newark, Delaware) which is also operated by the DGS. Pertinent data pertaining to each of the 14 events are presented in Table 1.

Several earthquakes have occurred in northern Delaware (Jordan et al., 1972; Woodruff et al., 1973), however, none during the period of this investigation.

Fluctuations with a maximum amplitude of 0.168 feet (5.09 cm) in well Ca45-39 resulting from the August 19, 1977 earthquake of MS (surface wave) magnitude of 7.9 in the eastern Indian Ocean south of Sumbawa Island are shown in Figure 3. These fluctuations persisted for approximately two hours and twenty minutes. During that time the amplitude gradually increased to a maximum and then gradually receded to zero. Superimposed upon earthquake fluctuations was a rise in the "undisturbed" water level of 0.035 feet (1.07 cm) caused by earth tides.

Seven verified seismic events have been recognized in records for well Cb41-10 between August 1976 and August 1977. Several events recorded in well Ca45-39 were not detected in well Cb41-10; well Cb41-10 appears to be less sensitive than well Ca45-39. The amplitudes recorded in well Cb41-10 were in all instances smaller than those recorded for corresponding events in well Ca45-39. For example, the earthquake that occurred August 19, 1977 south of Sumbawa Island was also recorded in Cb41-10 (Figure 4). However, the amplitude in Cb41-10 was smaller than the amplitude in Ca45-39: 0.065 feet (1.98 cm) vs. 0.168 feet (5.09 cm). It is interesting to note that the transmissivity calculated from Ca45-39 test data is larger than the transmissivity calculated from Cb41-10. The larger amplitude fluctuations studied occur in the aquifer with higher transmissivity.
### Table 1: Summary of Earthquakes and Corresponding Water-Level Fluctuations in Wells Ca45-39 and Cb41-10

<table>
<thead>
<tr>
<th>Origin Time</th>
<th>Date UTC</th>
<th>Origin Coordinates</th>
<th>Magnitudes</th>
<th>Depth</th>
<th>GS No.</th>
<th>Response</th>
<th>Amplitude</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>MB</td>
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<td>NO. STA.</td>
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<td>UGC No.</td>
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</tbody>
</table>

**Date and Time:**
- Feb 2, 1975: 08 43 39.1 51.18 171.3E
- July 27, 1976: 19 42 34.6 39.75N 177.85E
- July 28, 1976: 10 11 05.9 118.12N 118.42E
- Aug 16, 1976: 16 1 12.7 124.14E
- Aug 27, 1976: 11 19 23.1 41.35N 135.77W
- Sept. 11, 1976: 15 20 2.6 129.58W
- Oct. 20, 1976: 20 30 57.4 20.46S
- Nov. 26, 1976: 11 19 23.1 41.35N 135.77W
- Nov. 30, 1976: 00 00 57.4 20.46S
- Dec. 20, 1976: 20 30 57.4 20.46S
- Mar. 4, 1977: 07 21 11.2 90.97S
- April 3, 1977: 07 21 11.2 90.97S
- April 7, 1977: 04 24 09.6 90.97S
- April 21, 1977: 22 09 33.4 158.38S
- June 27, 1977: 11 53 53.6 25.86S
- Aug. 22, 1977: 06 08 55.2 11.08S
- Oct. 10, 1977: 11 53 53.6 25.86S
- Nov. 23, 1977: 09 26 35.7 71.75S

**Depth:**
- 10 km for earthquakes whose character on seismograms indicates a shallow focus but whose depth is not satisfactorily determined by the data.
- 33 km for earthquakes whose character on seismograms indicates a shallow focus and whose depth is satisfactorily determined by the data.

**Magnitude:**
- Body wave magnitudes
- Surface wave magnitudes

**No. Sta.:** number of stations reporting P or Pn phases used in computation

**POE No.:** refers to the issue of the "Preliminary Determination of Epicenters" and "Earthquake Data Report" in which the computation was originally published.
EARTHQUAKE - South of Sumbawa Island, 931 miles SE of Jakarta
Date and Time: August 19, 1977 06 08 55.2 UTC
Coordinates: 11.08S 118.46E
Magnitude: 7.9

Figure 3. Short-period fluctuations of ground-water levels in well Ca45-39 caused by an earthquake and earth tides. Maximum amplitude of the earthquake is 0.168 feet while the maximum amplitude of earth tides is 0.070 feet. Upper culminations of the moon are shown by short vertical lines.
Figure 4. Short-period fluctuations of ground-water levels in well Cb41-10 caused by an earthquake and earth tides. Maximum amplitude of the earthquake is 0.065 feet while the maximum amplitude of earth tides is 0.077 feet.
The recorded duration of this event was probably similar in both wells. However, the duration in well Cb41-10 was difficult to determine because of the small time scale: 0.3 inches (0.762 cm) per day.

**Fluctuations Resulting from Earth Tides**

Fluctuations caused by earth tides are evident in Figures 3 and 4. Two minima (troughs) occur each day and coincide with the upper and lower culmination of the moon. Both troughs occur during high earth tides, at which time this portion of the earth is expanded, aquifer pressure is reduced, and water levels decline in the well. As can be seen in Figure 3, during any semidiurnal fluctuation there are two troughs, one of which is deeper than the other. The deepest troughs, which are marked by short vertical lines in Figure 3, indicate times of upper culmination of the moon when the tide-generating influence is at a maximum. These times occur approximately 50 minutes later each day in response to lunar retardation as the tidal day has an average period of 24 hours and 50 minutes.

The peaks occur at low tide when the tide-generating forces are at a minimum. During this period of time this portion of the earth is compressed, the water is under increased pressure, and the water level rises in the well.

Maximum and regular fluctuations take place during the new and full moon while smaller and irregular fluctuations mark the first and third quarter phases. For example, in Figure 4, regular fluctuations of maximum amplitude coincide with the full moon (July 30, 1977) and the new moon (August 14, 1977). Like ocean tides, at new and full moon (syzygy), the sun and moon line up so that gravitational forces reinforce each other thereby producing maximum solar and lunar tides.

During the third quarter phase of the moon (August 6, 1977) the tide-producing force was at a minimum because the gravitational attraction of the sun and moon on the earth is exerted at right angles to one another with each force tending to counteract the other. As a result, fluctuations during this quarter are smaller and more irregular than at new and full moon.
CONCLUSIONS

Water-level fluctuations that occur as sharp vertical traces with amplitudes of fluctuation both above and below the "undisturbed" water level are attributable to earthquakes. A minimum MS (surface wave) magnitude of 6.7 and MB (body wave) magnitude of 5.9 for a specific event were required to cause detectable water-level fluctuations in well Ca45-39.

For a particular seismic event, the amplitudes generated in well Ca45-39 were in all instances larger (1.9 to 3.9 times as large) than those recorded in well Cb41-10. Thus, a relationship between aquifer transmissivity and amplitude is suggested as the transmissivity in Ca45-39 is 2.2 times as large as the transmissivity in Cb41-10.

The conclusion that semidiurnal water-level fluctuations are a result of earth tides is supported by the following:

1) each day is marked by two cycles of fluctuations;

2) large regular fluctuations occur during periods of new and full moon while smaller and irregular fluctuations coincide with first and third quarter phases;

3) minimum water levels (troughs) coincide with high tides during the upper and lower culminations of the moon.
PERTINENT REFERENCES


Robinson, R. W., 1939, Earth tides shown by fluctuations of water levels in wells in New Mexico and Iowa: Transactions American Geophysical Union, v. 20, p. 656-666.


Woodruff, K. D., and Thompson, A. M., 1974, Geology of the Newark area, Delaware: Delaware Geol. Survey Geologic Map Series No. 3.