How 100 Years of Old Dusty Records, Observations by Karl Terzaghi and a Walk in the Woods Calmed the Artesian Anxieties

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Where are We?
Glaciated Area of Michigan
Where are We?
Incised Muskegon River Valley
Where are We?
Hardy Dam, Constructed 1929 -1931
Why All the Anxiety?

- Tallest dam in Michigan at 114 feet high
- Largest dam east of Mississippi River when constructed
Why All the Anxiety?

- Constructed of uncompacted sand around a concrete corewall
Why All the Anxiety?

- Artesian pressures of 23 feet above tailrace water elevation, 13 feet above ground
Why All the Anxiety?

- Active springs and boils on land and in river
Why All the Anxiety?

- High permeability confined aquifer, capable of flowing 100s of gpm
Why All the Anxiety?

- Well, who wouldn’t be worried?
LETS DIG INTO THIS
I have checked the report and signed it for Dr. Terzaghi.

Charles Terzaghi

Very truly yours,
Arthur Casagrande

Cambridge, Mass.
June 12, 1928.
1928 Karl Terzhagi Conceptual Model

FIG. 7

- Very permeable layers
- Slightly permeable layers
- Observation wells
- Water level
1907 – 1928 Artesian Conditions

- Heaved
- Flowing Water
- Boil/Spring
Artesian head at 7 ft above river level (El 736.2 ft)
BOIL IN RIVER - 1929
Location of Boils 1931-2015
Let’s Sidetrack for a Minute
Now, Let’s Walk Around and Take a Wider (Geologist’s) View
Muskegon River Downcut into Broad Upland Plain
Boils Downstream of Dam Found in 2015
Boils Downstream of Dam
Dam Section
Dam Profile

1929 Riverbank at Corewall Sta to 24+98 29+26
1929 Riverbank at End of Tailrace Sta 23+65 to 26+30
Base of ~ El 725 ft bluff at Corewall Sta to 23+00 to 29+50
Base of ~ El 725 ft bluff at End of Tailrace Sta to 23+55 to 29+30
2015 CONCEPTUAL MODEL

VIEW LOOKING UPSTREAM

- UPLANDS
- VALLEY SIDES WITH TERRACES
- MUSKEGON RIVER

- SAND AQUIFER
- CLAY LAYER
- "UPPER" CLAY LAYER
- AQUIFER A AND A' (A WHERE CONFINED, A' WHERE UNCONFINED)
- "MIDDLE" CLAY LAYER
- AQUIFER B
- AQUIFER C

- GENERALIZED GROUNDWATER FLOW DIRECTION

- TOP OF DAM

- EL 622 HEADWATER
- EL 722 TAILWATER

- FLOW DOWNSTREAM

- 662 MAX DEPTH OF COREWALL

- 2015 (EL 765)
- 2015 (EL 753)
- 2015 (EL 745)
- 2014 (EL 740)
- 2016 (EL 753)
- 2016 (EL 765)
- 1928 (EL 735)

- RELATIVE RECHARGE VOLUME
Self-filtering Analysis
Self-filtering Analysis - Example

Graph showing the percent passing versus grain size for different sieve sizes. The graph includes data for fraction < 0.84 mm (Sieve #20), fraction > 0.84 mm (Sieve #20), and Gradation Curve 1-C (LS-10) Gravelly Sand.
Strong evidence that artesian pressures are abutment driven, not reservoir driven

Clay aquitards reduce potential for artesian flow at surface

Engineering evaluation shows that sand and gravel aquifers are well graded and will self filter

Historical record of self filtering boils
Calm Does Not Mean Complacent

- Robust, ongoing monitoring program
- Daily and weekly documented visual observations
- Instrumentation program is migrating to vibrating wire piezometers and real time monitoring system
Thanks to the Crews Who Built the Plant
Groundwater Temperature

Figure 1 - Temperatures for Spring, RW-24, Reservoir Water, and Air
Three Things to Remember

- Use What You Own
- Look Around
- Tell the Story
POWERHOUSE AND TAILRACE EXCAVATION, MAY 1930
FINAL PILE DRIVING AT DAM CENTERLINE, JULY 1930
ARTESIAN CONDITIONS

Flowing Artesian Wells

Geologically Controlled

Topographically Controlled

From Freeze and Cherry, 1979
Relief Well Monitoring
Correlation Charts

P-58, Aquifer B

P-57, Aquifer C

RW-24, Aquifer C

P-16A
River Boils
Remediation Options

**OPTION 1**
ALLOW NATURAL FILTER TO DEVELOP

**OPTION 2**
ADD FILTER

**OPTION 3**
ADD FILTER AND SCOUR PROTECTION

Note: Flow is from multiple locations in approx. 7-ft. dia. area for Boil "D"

<table>
<thead>
<tr>
<th>EXPLANATION</th>
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<tbody>
<tr>
<td>Natural undisturbed sand or sand with gravel</td>
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<tr>
<td>Clay</td>
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<tr>
<td>Fine fractions of natural sand</td>
</tr>
<tr>
<td>Coarse fractions of natural sand</td>
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