Narora Weir – A Historical Perspective of Piping Theory

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Outline

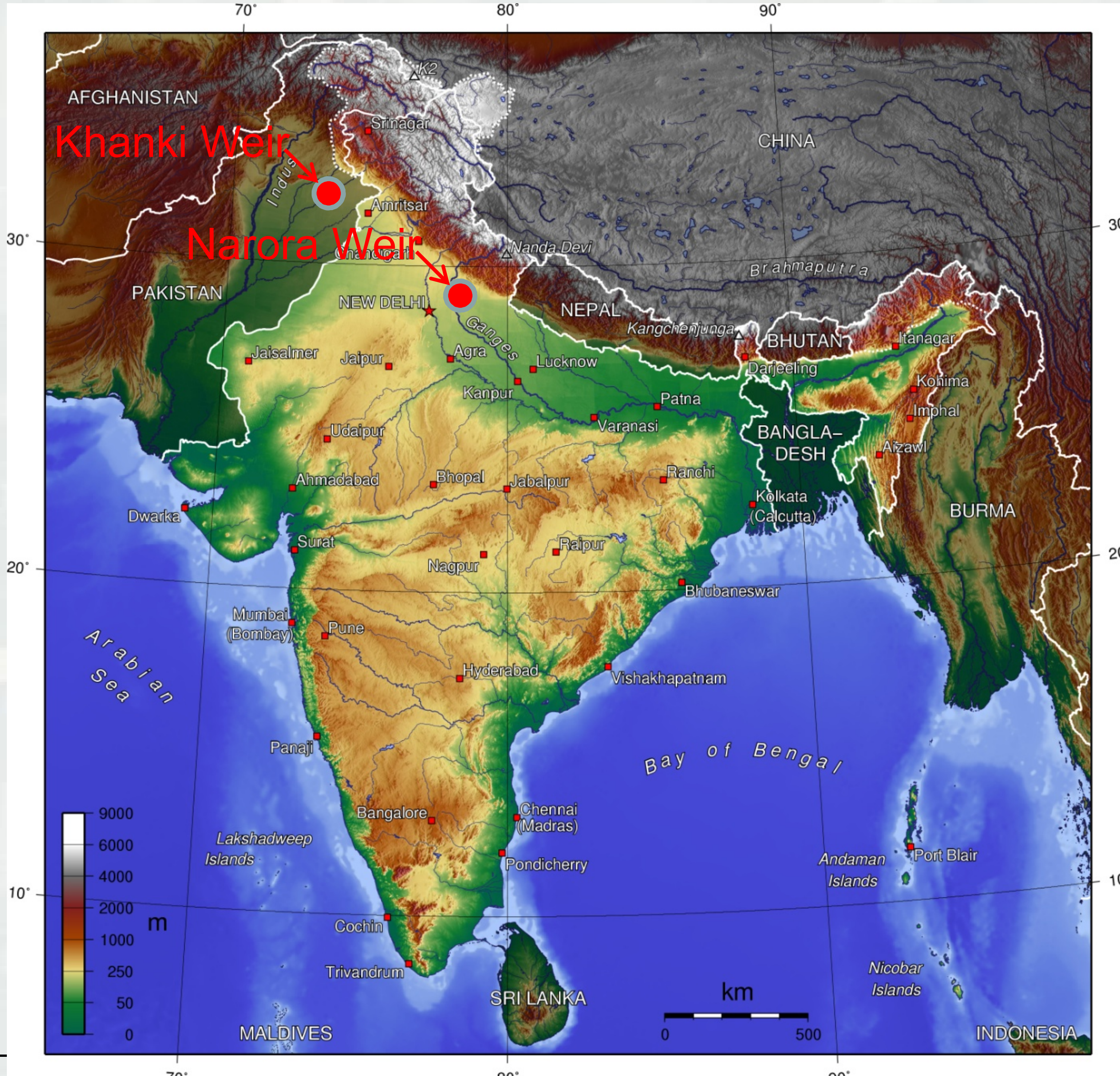
- Background and Historical Perspective
- Khanki Weir Failure - 1895
- Narora Weir Failure - 1897
- Bligh's Empirical Evaluation of Weir Failures - 1910
- Conclusions

Background and Historical Perspective

Background and Historical Perspective

- Ganges River Canal System (constructed 1842-1854, expanded 1879)
  - Erie Canal (1817-1825)
  - U.S. Railway Boom 1830s
  - I&M Canal (1848)
  - Thomason College of Civil Engineering, Roorkee, India (Est. 1853)
  - Darcy (1856)
  - Government of India Act (1858) established Queen Victoria as Empress of India
  - Lower Ganges Canal Expansion (new Ganges River diversion into original canal, constructed 1879-1880)
  - Mississippi River Flood Control Works (1879)
- Design Practice in 1870's– Chiefly Empirical
- Khanki Weir Constructed (1891)
- Khanki Weir Failure (1895), Narora Weir Failure (1897)
- "The Practical Design of Irrigation Works", W.G. Bligh (1907)
- Karl Terzaghi, *Erdbaumechanik* (1925)

Ganges & Chenab Rivers



Khanki Weir Failure - 1895

Khanki Weir – Chenab River

Khanki Weir failed in 1895

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Khanki Weir

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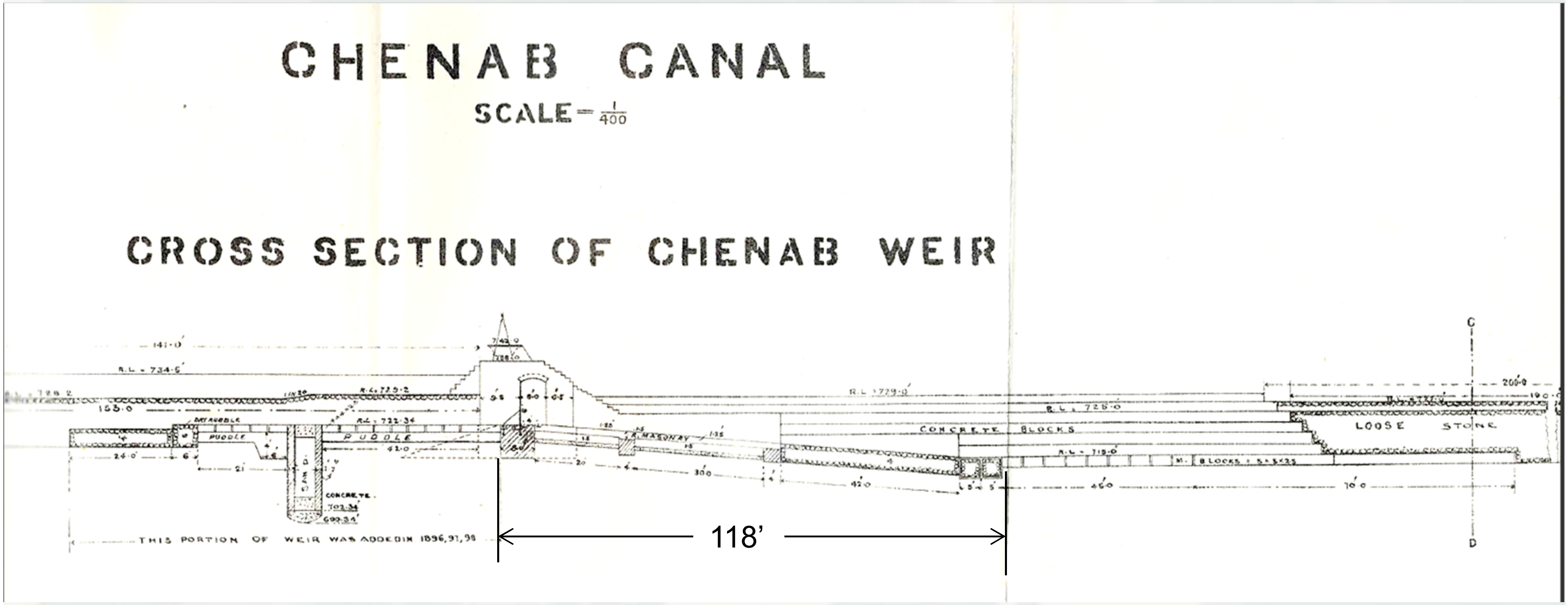
Khanki Weir

- Length 4000 feet
- 6 foot high crest “shutters”
- Impermeable base width 108 ft
- Impounds 13 ft of head
- Crest elevation 722 ft
- Apron elevation 715 ft
- Original weir had 8 spans of 500-ft each, left undersluices (12 of 20-ft each) and canal head regulator (12 of 24.5-ft each)

Khanki Weir



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Causes of Khanki Weir Failure

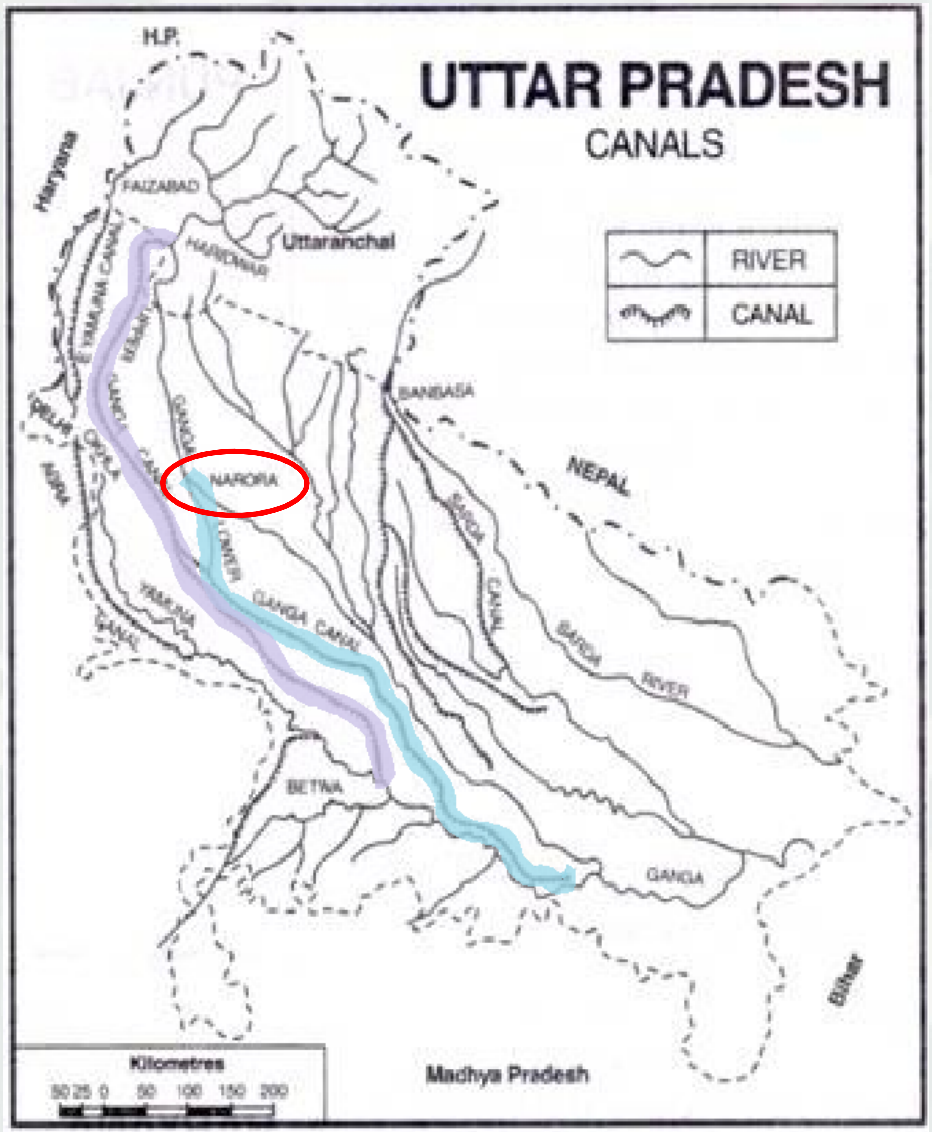
- Edward Wegmann (1918)- In 1895 this weir failed by piping or leakage under the floor, which apparently followed the line of an old side channel of the river, which had been silted up.

Col. Clibborn's Findings

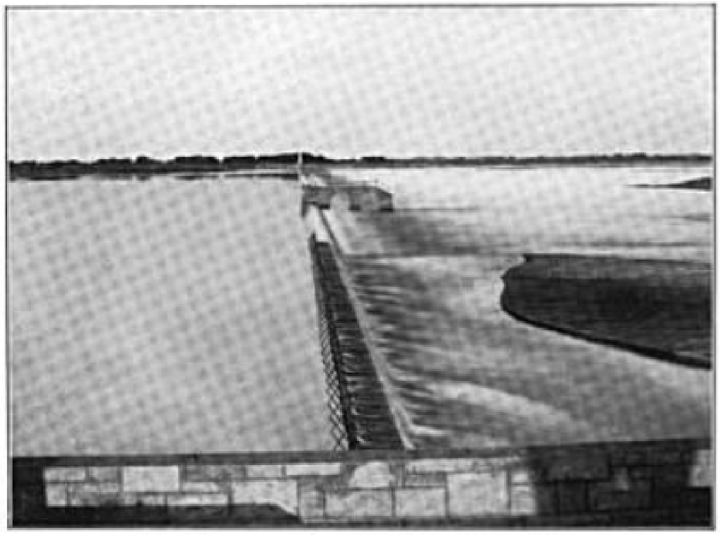
- The resistance of the floor to upward pressure depends entirely upon its effective weight, which is its own weight less that of the volume of water it displaces…it is easy to find cases where effective weight at a particular point is little more or even less than the pressure at that point
- Weight of floor should be sufficient to prevent any lifting of it…whereby subsoil leakage passages would be formed. Intermediate spring near the centre of a floor will reduce its resistance to piping by half.
- Lengthening the structure actually increases the pressures at intermediate points.
- An increase in depth of the tail curtain wall will increase the upward pressure on the floor of the weir.
- When designing a weir, it is advisable to ascertain what length of sand is required practically to stop the flow of water through it as this will determine the length of the apron and floor required.
- One foot in depth of curtain wall is equivalent to three feet in width of floor.
- Useful effect of a curtain wall is the checking subsoil currents from following the under-surface of the floor. The benefit of downstream curtain wall is that it forces water to percolate upwards at the exit, which is a more stable condition than a horizontal exit.
- Where hard material exists in contact with sand, the line of least resistance lies along the hard material (This is due to hard material deflecting the forces of current to directions in which they can erode the sand).
- Piping can start in fine sand at horizontal gradients as low as 0.1.

Narora Weir Failure - 1897

Lower Ganga Canal



Narora Weir



NARORA WEIR AT THE HEAD OF THE LOWER GANGES CANAL.

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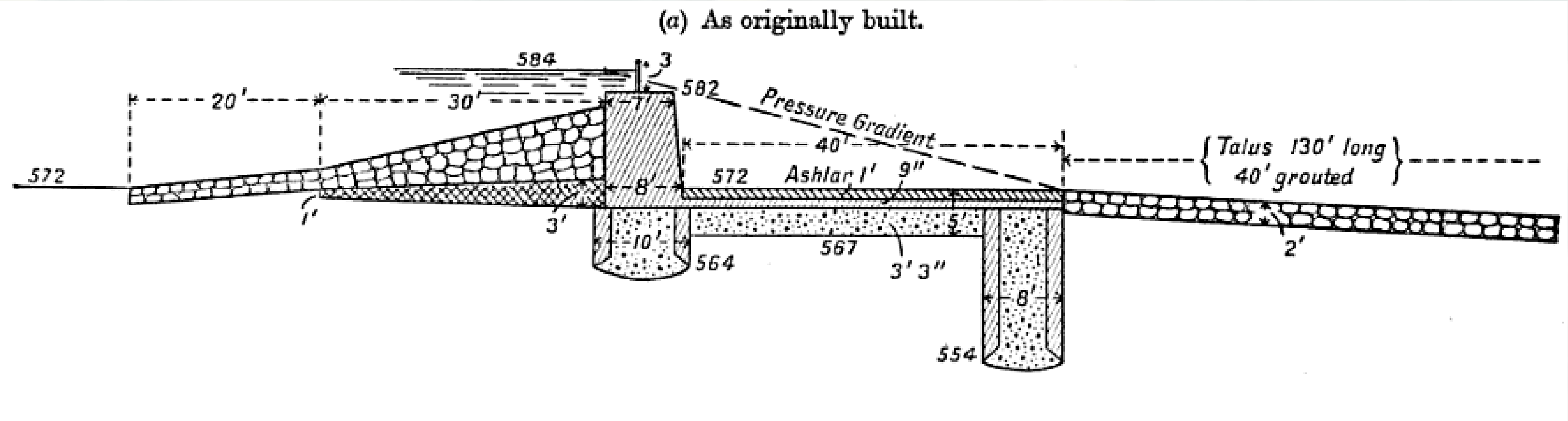
Narora Weir

- Constructed on micaceous sand “almost as fine as flour”
- Length 3800 feet
- Impermeable base width 78 ft
- 3 meter high crest “shutters”
- Crest elevation 582 ft
- Apron elevation 572 ft
- Impounds 13.5 ft of head
- Observed to have high uplift pressures and significant voids under apron 2 days before failure

Narora Weir



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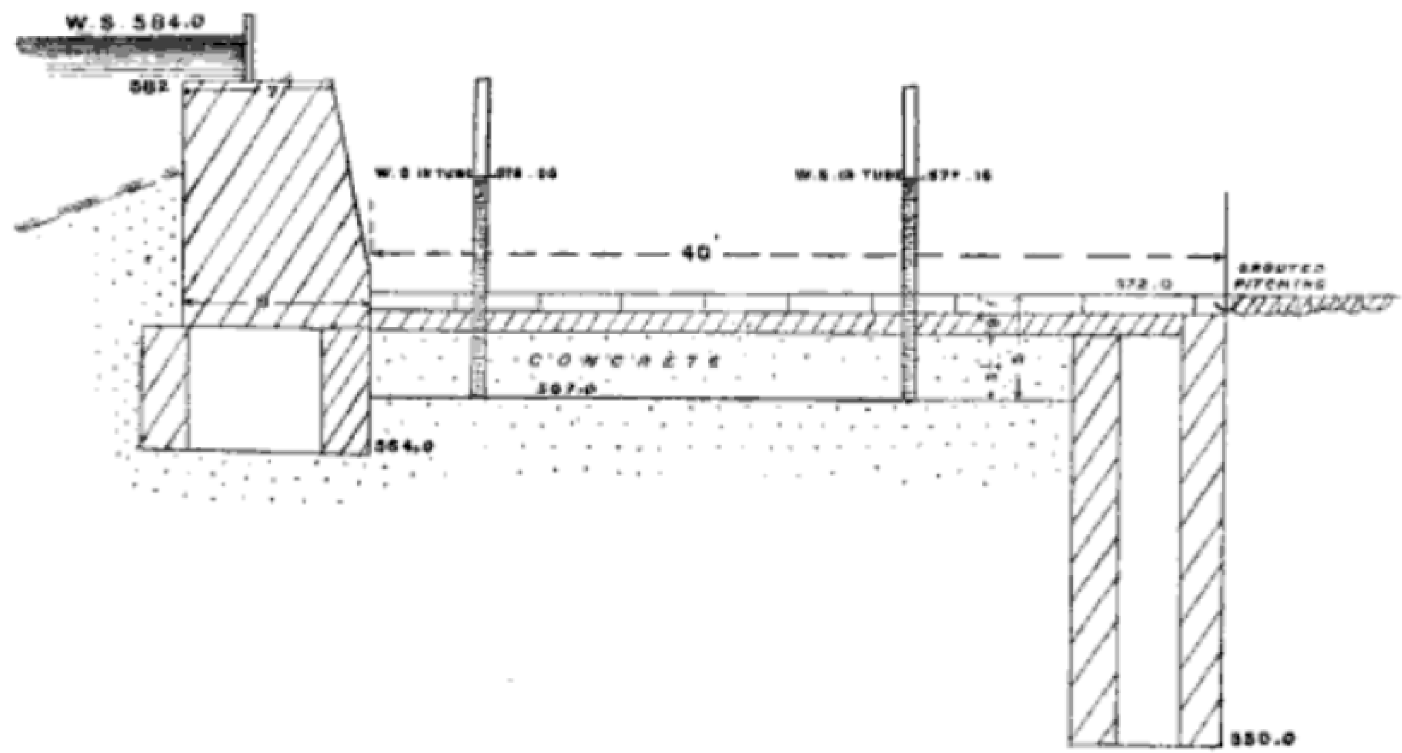
“Percolation Pressure Tests”



Pressure Experiments at Narora Weir.

Causes of Narora Failure

- Burton Buckley, Superintending Engineer of the Indian Public Works Department: “At the time of the accident a **strong spring burst through the floor** at the toe of the crest wall, and passing under the stone flooring, lifted it bodily over a length of 340 feet to a maximum height of 2.23 feet. The weir wall settled in a length of 120 feet about 3 inches and the flooring showed vertical cracks. The grouted pitching below the floor was blown up. Upstream of the part of the weir which was damaged, the apron had disappeared and the wall was exposed to a depth of 8 or 9 feet. **Borings through the floor revealed cavities extending to about 50 feet on each side** of the point of fracture.”
- N.F. MacKenzie, M. Inst. C.E.: “The author’s opinion… is that the **floor was first undermined by piping**; the concrete, or perhaps the concrete and masonry, settled away from the ashlar, leaving a horizontal joint into which water found its way, and this probably occurred when the water up-stream and down-stream of the weir was at about the same level...When the floor first settled it would probably crack at the toes of the crest wall, thus accounting for the strong spring at that point. The sand blowing in the talus is also accounted for by piping, as the **removal of most of the foundation sand under the floor means that there was little friction to reduce the velocity due to the head**…It will be seen that the theory of piping and settlement is quite as consistent with the facts as the blowing up theory, and for this reason the local engineers are by no means positive as to the actual cause of the accident.”

J.S. Bresford

- Bresford read Clibborn’s findings in December 1896 and suggested “experiments” by drilling a few holes in the floor of Narora Weir to test percolation pressure.
- The experiment was not conducted until March 1897. It “…showed clearly that the upward pressure…had reached an intensity which rendered the stability of the weir very precarious and orders were given…to consider the question of strengthening the work, or, rather reducing the percolation pressure…” The weir failed two days later. <u>This example may be the first time an engineering analysis and site investigation predicted failure at a dam before it happened.</u>
- Bresford concluded “Had the experiment suggested in January 1897 been made at the time, it is probable measures would at once have been taken which would have prevented any such failure of the work as occurred more than a year later.”
- Beresford made experiments in 1898 that showed for the first time the positive effect of an inverted filter in providing additional safeguard against piping.

Bligh’s Empirical Evaluation of Weir Failures - 1910

Bligh's 1910 Assessment of Narora Weir

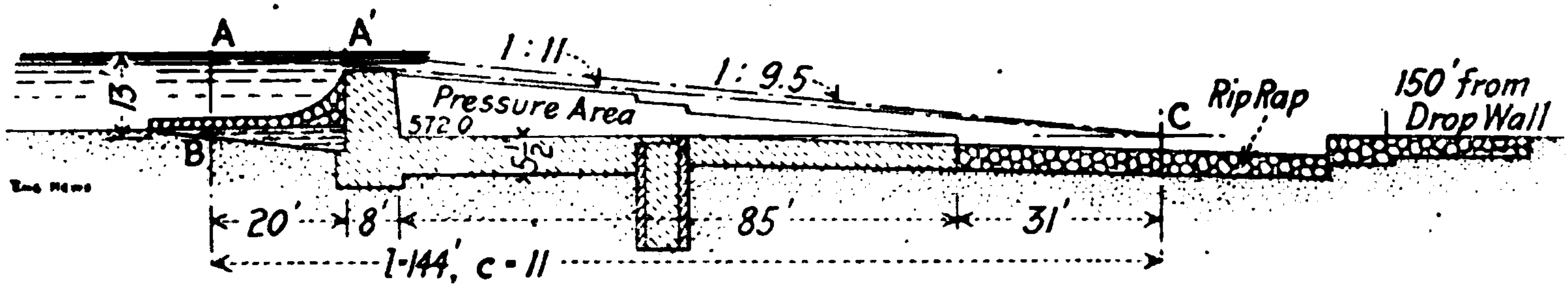


FIG. 9. NARRORA WEIR AS ORIGINALLY BUILT.

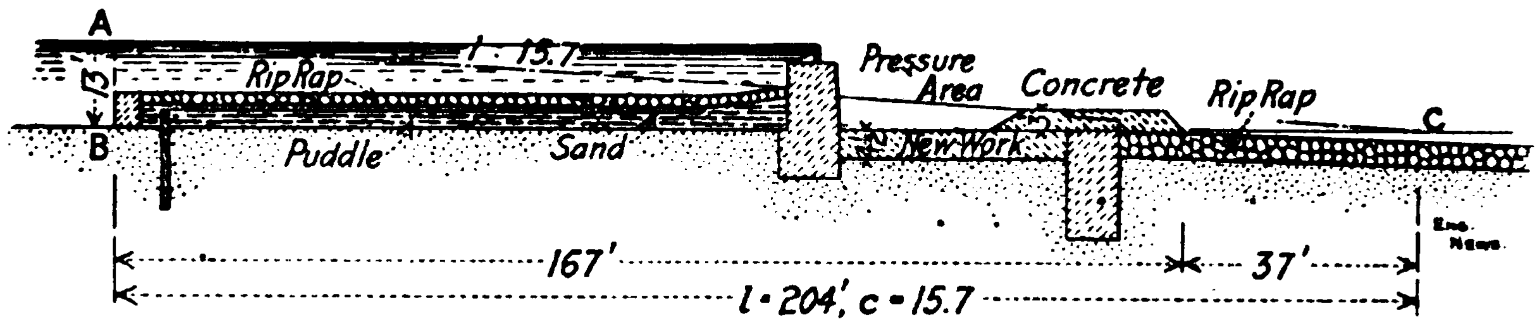


FIG. 10. NARRORA WEIR AS RECONSTRUCTED.

Bligh’s Findings

- Both Khanki Weir and Narora Weir were founded on fine sand.
- Failure at both sites occurred with a percolation factor of ~9.
- Increasing the percolation factor to 16 and adding upstream sheet pile cutoff and impervious blanket is sufficient to stabilize the structure from seepage.
- “…piping is a gradual process, and as, is proved in both this [Khanki Weir] and the previous case [Narora Weir] may last for some years before failure actually takes place.”
- Caused Bligh to abandon his “frictional stability of substratum” theorem

Conclusions

- Design for uplift pressures using Hydraulic Gradient Theory and use of Percolation Factors based on seepage length versus hydraulic head developed as a result of these seminal dam failures.
- Earlier dam designs were based on precedent and foundation soil characteristics. A new, empirically-based engineering approach began with Col. Clibborn, Beresford, and Bligh's work at the end of the 19^{th} century.
- Bligh's use of the empirical method to define safe Percolation Factors triggered much controversy, research, and later recognition that internal erosion is a complex process.
- Bligh's original method and later improvements by Lane (1935) and Khosla (1936) were used into the 2010's but are currently being replaced with newer methods.
- Failure and reconstruction of Khanki and Narora Weirs triggered early research in dam designs and helped to introduce the modern era of dam engineering.
- Lengthening of seepage path to reduce piping potential with use of upstream sheet pile cutoff walls and extended upstream impervious blankets begin as a result of the Narora Weir failure and Col. Clibborn's research.
- Ultimately, the failure of Narora Weir was instrumental in the development of early piping theory (Bligh 1910), which eventually led to the understanding that piping and heave are influenced by both the hydraulic head and foundation conditions at a dam.