PREDICTING UNDERSEEPAGE OF MASONRY DAMS

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Abstract

This paper reviews the creep ratio concept suggested by Lane (1934) and added new case histories to expand his database. Lane (1934) selected conservative values of safe creep ratios because of the small number of dam failures in his database, which is prudent. The safe creep ratios recommended in this paper for "Gravel and Sand", "Boulders, Gravel, and Sand", and broadly-graded soils are believed to be a conservative interpretation of the available data. As Lane's recommended values appear to be somewhat subjective, considerable engineering judgment is recommended in designing a dam for safety against piping, and Lane's values are a starting point for design, rather than values for a final design.

Introduction

Piping occurs underneath a dam as the seepage force of water becomes great enough to erode soil particles. As this erosion continues, the gradient increases and voids in the soil become larger, forming a pipe from downstream to upstream. As the pipe grows and backwards erosion reaches the reservoir, the increased flow and erosive forces can become large enough that the dam fails and the reservoir empties. This mechanism is distinct from hydraulic heave at the downstream toe. A failure by heave occurs when the porewater pressures in a soil become larger than the soil weight. When this occurs, the soil is arranged in a loose state and flow through the soil increases sharply. Unlike a piping failure, erosion does not occur in a heave failure.

In 1934, E.W. Lane published "Security from Under-Seepage: Masonry Dams on Earth Foundations." He collected and analyzed information concerning 247 masonry dams founded on soil. Twenty-one of these dams failed. Based on his analysis, Lane (1934) recommended a weighted-creep ratio, c_w, for various soil types, as reproduced in Table 1. Lane included the materials "Gravel and Sand" and "Boulders, Gravel, and Sand" in his published table, but did not recommend safe weighted creep ratios for these two soil groups. i.e., creep ratios that would result in satisfactory performance of the dam (see Table 1). Lane defined c_w as:

$$c_w = L_w/H = [\text{Vertical Creep Distance} + 1/3(\text{Horizontal Creep Distance})]/H$$

where L_w is the weighted creep distance and H is the head of water in the reservoir. Refer to Figure 1 for an illustration of the horizontal and vertical creep distance for a dam with a seepage berm and sheet pile cutoffs at its upstream and downstream ends. W.G. Bligh (1916) first introduced the concept of a safe creep ratio in 1910. Lane studied additional case histories and recommended that the horizontal creep distance should be considered 1/3 as effective in preventing piping as the vertical creep distance due to soil anisotropy, i.e., horizontal permeability being greater than the vertical permeability.

Lane (1934) referred to some of Terzaghi's early work on heave as a blowout. However, Lane did not distinguish between failure by heave and failure by piping in his work. According to Peck: "Some of the failures in the statistical studies that [Bligh and Lane] made were failures due to heave. Today we realize that some of those examples should be thrown out of the study, you might say (Peck, 1995)."

The goals of the study described in this paper are to add additional case histories to Lane's (1934) database, determine which failures analyzed by Lane should be attributed to heave and removed from the database, better understanding the relationship between Lane's data and his recommendations, and determine a safe creep ratio for glacial till and a soil consisting of sand, gravel, and boulders.

Table 1. Safe Weighted Creep Ratios as recommended by Lane (1934).

Material	Safe Weighted Creep Ratio (Lane 1934)
Very Fine Silt or Sand	8.5
Fine Sand	7
Medium Sand	6
Coarse Sand	5
Fine Gravel	4
Medium Gravel	3.5
Gravel and Sand	No value
Coarse Gravel, Including Cobbles	3
Boulders with Some Cobbles and Gravel	2.5
Boulders, Gravel, and Sand	No value
Soft Clay	3
Medium Clay	2
Hard Clay	1.8
Very Hard Clay, or Hardpan	1.6

Analysis

For the present study, "Lessons from Dam Incidents, USA (ASCE/USCOLD, 1975)," "Lessons from Dam Incidents II, USA (ASCE/USCOLD, 1988)," and "Critical Appraisal of Piping Phenomena in Earth Dams (Richards and Reddy, 2007)" provide a resource for identifying dams that have failed due to erosion and piping. To simplify the analysis, Lane's data has been entered into an electronic database that includes information such as name, location, head, horizontal creep distance, vertical creep distance, and foundation soil for each dam. Lane's study was limited to dams that meet the following criteria: the dam cannot be an earthfill or rockfill dam, the dam must be founded on soil, cutoffs may not extend into rock, and sufficient data must be available so the horizontal and vertical creep distance along the dam's foundation can be determined. For a dam to be considered in this study, the same criteria had to be met for each case.

As a part of this study, the dam failures reported by Lane (1934) were analyzed to determine which failed by heave. "Security of Masonry Dams on Earth Foundations (Lane, 1932)" and the National Performance of Dams Program (NPDP) supplied data on the failures reported by Lane. The available data was inadequate to determine the exact failure mode for all dams. For this study, if the mode of failure was uncertain, it was assumed to be by piping.

To determine how Lane's data relates to his safe creep ratio recommendations in Table 1, for each soil category the reservoir head for each dam has been plotted vs. the weighted creep distance in Figures 2 through 7. A line representing the safe weighted creep ratio has also been plotted based on Lane's recommendations. Points above this line are "unsafe" while points below the trend line are deemed "safe." Lane did not make a safe creep ratio recommendation for soils that consist of both fine and coarse –grained soil. Thirty-eight of the dams reported by Lane appear to belong in this category. Twenty-eight of these dams are located in the northern U.S. and Canada and are likely founded on glacial till. These 38 dams have been grouped into a soil category named "Broadly-Graded Soils." Fifteen different soil categories were plotted for this study, the fourteen materials in Table 1, plus the broadly-graded category.

The distribution of data points above and below the safe creep ratio line does not appear consistent. According to Lane, his safe creep ratio values are those, "…which the analysis of all available data indicates as necessary for safety against failure from piping along the contact of the structure and its foundation (Lane, 1934)." No further explanation of the values was given. A statistical analysis has been conducted in an attempt to quantify the relationship between the safe creep ratios and Lane's data. Each soil category with 10 or more data points has been considered separately; categories with fewer points were considered too small to yield a useful trend. Several potential relationships were explored, including: the relationship between the smallest creep ratio of an unfailed dam and the safe creep ratio (the larger the creep ratio, the safer the dam should be), the relationship between the range in creep ratios for unfailed dams and the safe creep ratio, and the relationship between the largest creep ratio of a failed dam and the safe creep ratio. This study found that the strongest relationship relates the safe creep ratio to the largest creep ratio for a failed dam in a given soil category. Generally, the safe creep ratio is about 1.6 times greater than the largest creep ratio of a failed dam in the analyzed soil categories. The exception is for fine sand, for which it appears Lane (1934) gave a particularly conservative value, which is justified based on his fine sand data (Figure 2). The relationship is not useful if no dam failures are recorded for a given soil category.

Several methods have been utilized to determine a safe creep ratio for sand and gravel, a soil consisting of boulders, sand, and gravel, and broadly-graded soils. These methods include: determining a lower-bound creep ratio, which is equal to the maximum reported safe creep ratio, examining Lane's recommendations for other similar soil categories, and subjectively drawing a line that gives a similar fit to the data as that observed in the data for which Lane made recommendations.

Results

Three dams were added to Lane's (1934) database and information on these cases is presented in Tables 2 and 3. The safe creep ratios for these dams are plotted in Figures 2-4. Ashley Brook and Hauser Dams failed, while Box Canyon Dam has not. There is not sufficient additional data to justify any modifications to Lane's recommended safe creep ratios. Based on Figures 2 – 4, the new data is in agreement with Lane's recommendations.

Table 2. General Information About Dams Added to Lane's (1934) Database.

Name	Location	Fail?	Foundation Material	Foundation Material Based on Lane's Categories
Ashley Brook	Pittsfield, MA	Y	Clay, interspersed w/ Shale	Medium Clay
Hauser	Missouri River, MT	Y	Gravel	Medium Gravel
Box Canyon	Pend Oreille River, WA	N	Fine Sand	Fine Sand

Table 3. Creep Ratio Information About Dams Added to Lane's (1934) Database.

Name	Head (ft)	Creep Distance (ft)		Weighted Creep Distance	Weighted Creep Ratio
		Vertical	Horizontal		
Ashley Brook	40	50	29	60	1.5
Hauser	69	97	95	129	1.9
Box Canyon	60	260	512	431	7.2

Lane did not recommend a safe creep ratio for sand and gravel. Using the methods discussed previously, an attempt has been made to determine a safe creep ratio. The results are summarized in Table 4 and Figure 5. Relating the safe creep ratio to the maximum creep ratio of a failed dam using the previously mentioned relationship (the safe creep ratio is about 1.6 times the largest creep ratio of the failed dams) gives a safe creep ratio of 2.0. This value is felt to be an upper bound on the value of the safe creep ratio. The lower bound safe creep ratio is felt to be excessively conservative. Rather, the subjective best fit safe creep ratio and the safe creep ratio that have been determined by examining Lane's other recommendations seem to be reasonable safe creep ratios. The average of these two values gives the recommended safe creep ratio of 4.5 (Table 4). Lane also did not present a safe creep ratio recommendation for boulders, sand, and gravel. This category is felt to be similar to the sand and gravel category (see Figure 6). However, for this study this data was analyzed as well, and a smaller safe creep ratio of 4.0 is recommended if boulders are present near the dam foundation, this reflects the fairly non-erodable nature of the boulders.

The broadly-graded soil category contains two failures by heave. These failures were not considered when developing a safe creep ratio recommendation. The same methods discussed previously were used to determine a safe creep ratio and the results are summarized in Table 4 and Figure 7. A subjective best-fit line recommends a safe creep ratio of about 4.0. Lane does not make any recommendations for a combination of coarse- and fine-grained soils for comparison. However, assuming the clay-size fraction controls the permeability of the soil, a safe creep ratio of 3.0 (corresponding to soft clay) has been considered. Based on the limited failure data and the lack of any other recommendations for soils containing both coarse- and fine-grained soils, a conservative value of 4.0 is recommended (Table 4).

Table 4. Determination of Recommended Creep Ratio.

Soil Type	1.6 * Max. Failed Creep Ratio	Lower Bound	Best-Fit	Based on other Lane (1934) Recommendations	Recommended
Sand and Gravel	2.0	12.0	4.0	5.0	4.5
Boulders, Sand and Gravel	1.5	11.4	4.4	3.5	4.0
Broadly-Graded Soil	2.2	13.3	4.0	3.0	4.0

Conclusions

Lane (1934) selected conservative values of safe creep ratios because of the small number of dam failures in his database, which is prudent. The safe creep ratios recommended in this paper for “Gravel and Sand”, “Boulders, Gravel, and Sand”, and broadly-graded soils are also believed to be a conservative interpretation of the available data. As Lane’s recommended values appear to be somewhat subjective, considerable engineering judgment is recommended in designing a dam for safety against piping, and Lane’s values are a starting point for design, rather than values for a final design.

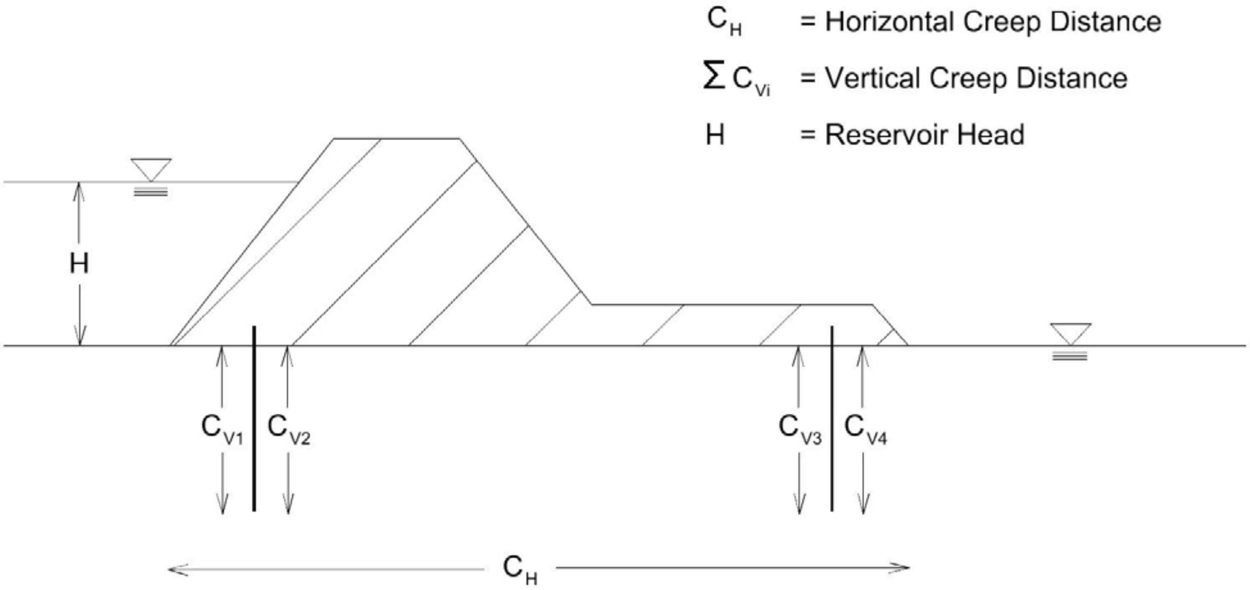

Figure 1. Definition of Horizontal and Vertical Creep Distance.

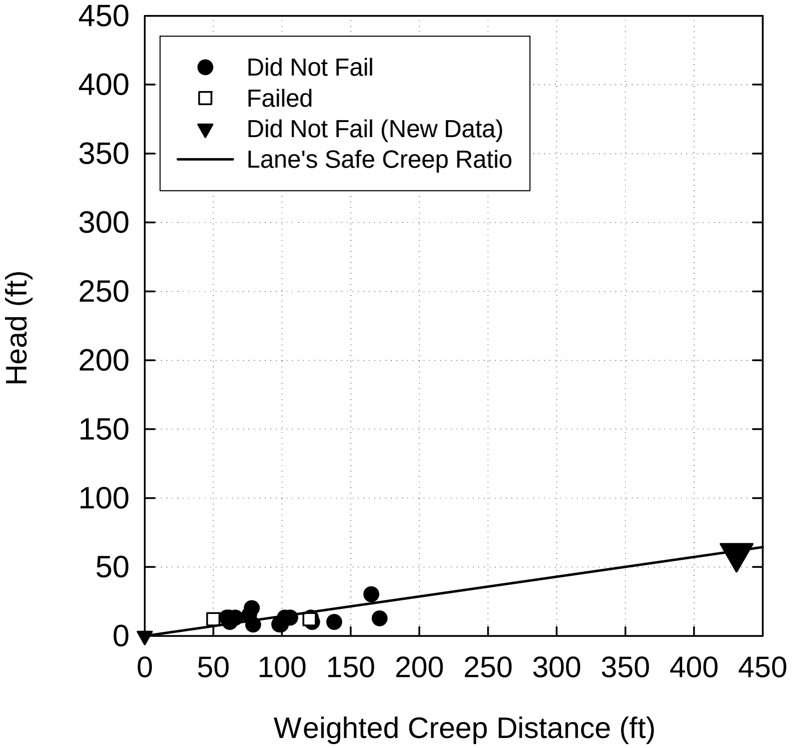

Figure 2. Data for Fine Sand, n = 21.

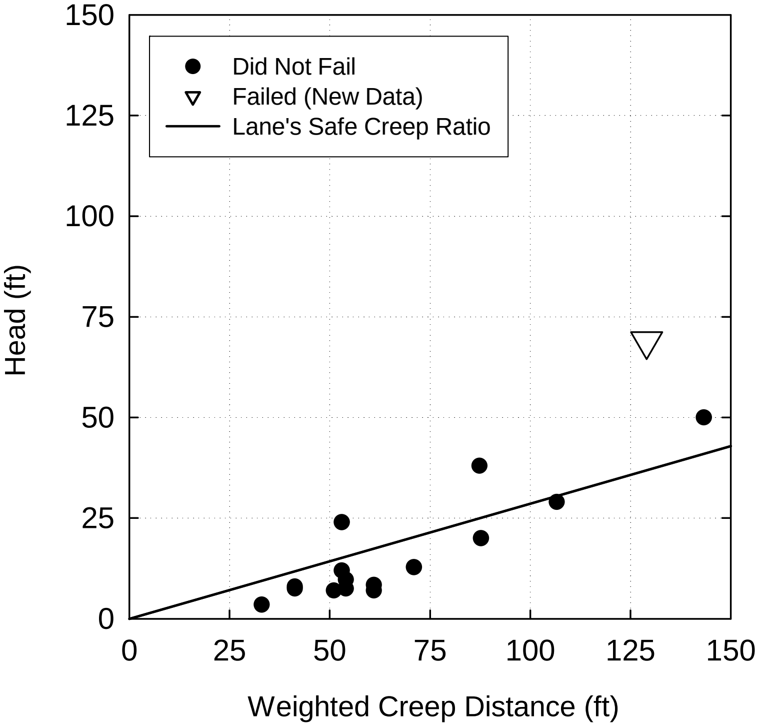

Figure 3. Data for Medium Gravel, n = 16.

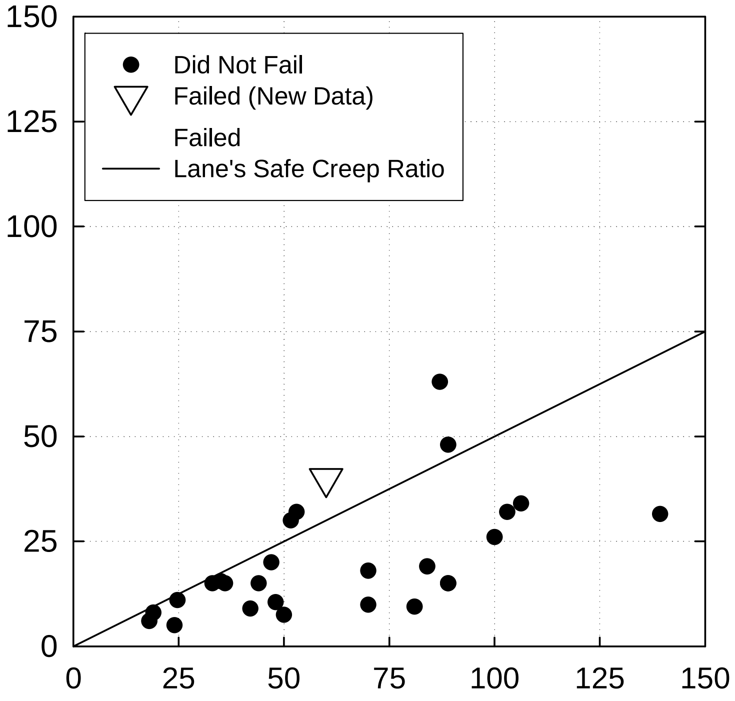

Figure 4. Data for Medium Clay, n = 30.

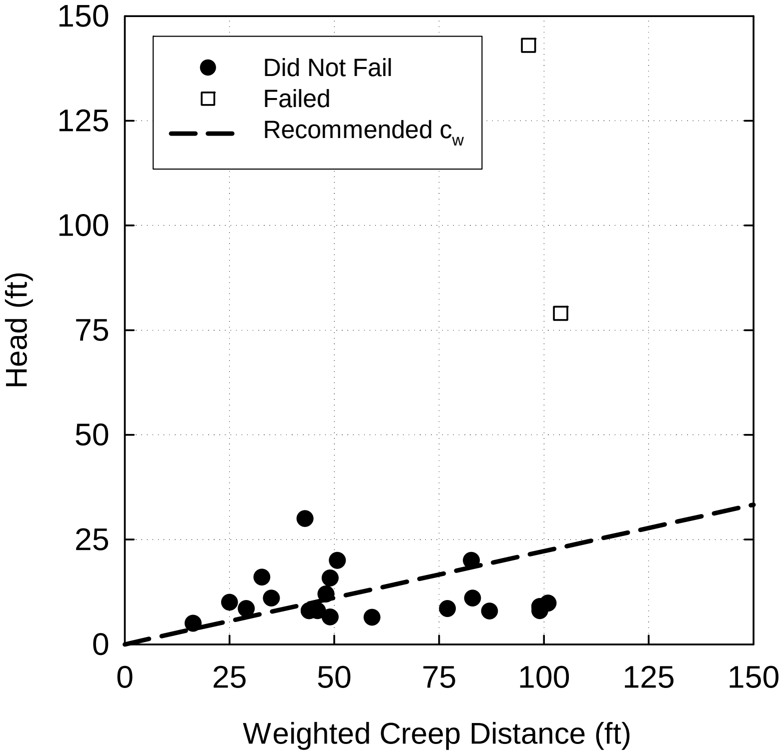

Figure 5. Data for Sand and Gravel, n = 26.

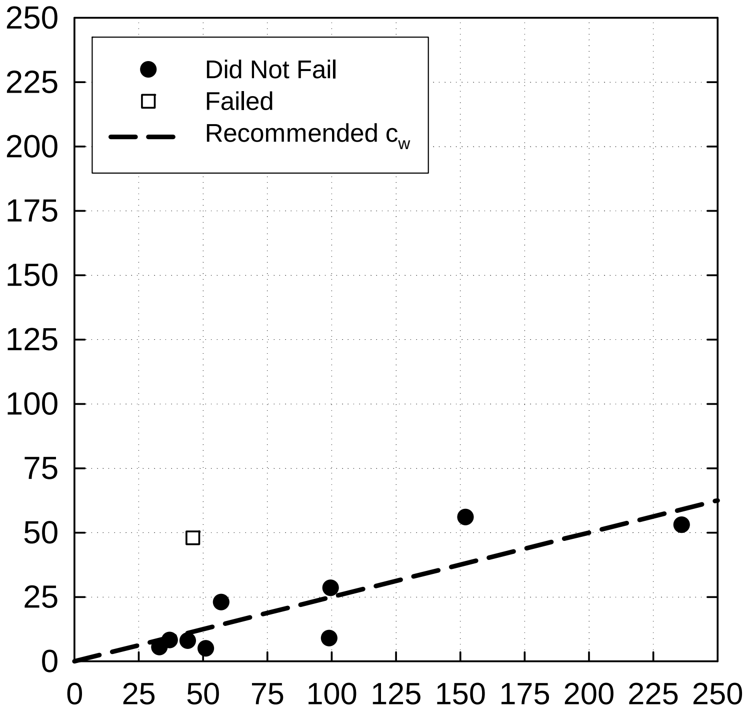

Figure 6. Data for Boulders, Sand, and Gravel, n = 10.

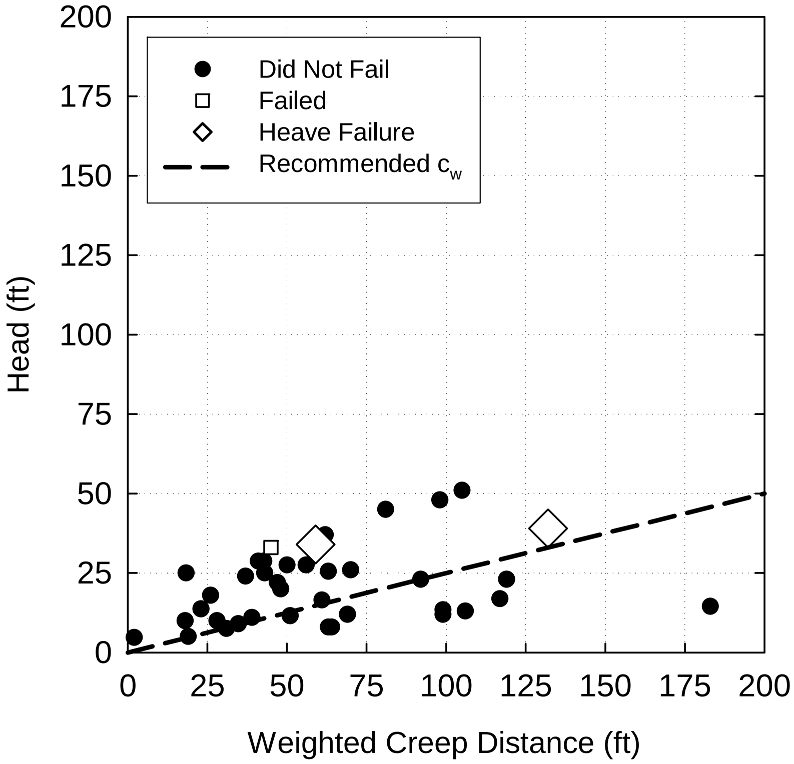

Figure 7. Data for Broadly-Graded Soil, n = 39.

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