# ARE THE GLORY DAYS ALL BEHIND US?

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ABSTRACT: Breakthroughs in geotechnics in the next century may not be as revolutionary as those in the 1920's and 1930's, but geotechnical engineers will face challenging jobs, particularly in combining soils with other materials and by reducing the adverse impact of construction works on our social fabric.

At the end of this millennium, would it be reasonable to say that the glory days of geotechnics are behind us? Has everything of importance been discovered? The literature of the last two decades contains very little that is really new. The breakthrough ideas of effective stress and its consequences, of consolidation, of shear strength, of soil exploration and identification, of field observations and the observational method, all these seem to be behind us. Rock mechanics, although it started somewhat later than soil mechanics, has made rapid strides. The concepts and techniques of engineering geology are well developed. Could we not reasonably say that all the important principles have been developed and are now in a form for practical use? When we read the papers in any of our learned societies involving geotechnics we see more and more embellishment of principles and practices already well understood. Are there great breakthroughs yet to occur in the next millennium? Do we need more breakthroughs, or can we progress satisfactorily by improving upon and embellishing what we already know?

Surely these questions are not new. Sixty years ago when I first became acquainted with soil mechanics, there were numerous highly regarded practicing engineers who thought we did not need soil mechanics at all, who thought it ridiculous to believe that heterogeneous materials like soils could possibly behave in accordance with such elaborate mathematical theories as that of consolidation, and who dismissed the entire subject as being beyond the realm of theoretical treatment. Furthermore, they said, even if the theories were correct, they were too complicated for practical use. Terzaghi himself emphasized the importance of simple approximate theories that would give results bounding a problem, because no usable theory could take into account all the variables implicit in the behavior of real soils. Certainly that objection to theoretical soil mechanics has diminished in this computer age. In a sense, history is already repeating itself at the end of this millennium in that many practicing engineers, reading the current literature, still question the merits of applying elaborate theoretical solutions to the problems of real soils.

It may well be that most of the great breakthroughs in soil mechanics are behind us, except for cleaning up unfinished business concerning a few areas such as unsaturated soils. Nevertheless we can reasonably look forward to the incorporation of soil mechanics into a number of other problems to which it may be applied.

I would hazard a guess that the application of geotechnics will continue to spread to new and difficult problems using new materials or old materials in new ways. When I was a student, one of the topics we studied was retaining walls. We learned how to design them, but when we said "retaining walls" we specifically meant concrete structures of cantilever, gravity, or counterfort type, and these structures were designed to hold back the earth. We barely noticed that there was an innovation on the horizon, known as crib walls, in which the earth had the ability partly to support the retained soil. Today one only occasionally sees a conventional reinforced-concrete retaining wall. There are reinforced earth walls, tied-back walls, secant pile walls, soil-nailed slopes, a whole host of composite structures in which the soil provides a substantial part of its own support. A whole host of new materials is now incorporated into retaining structures. I suspect that the trend to construct structures of types in which soil and other materials are used in composite fashion will continue. The rate of innovation is rapid today, and it is likely to continue to increase for decades into the next millennium.

Not too long ago the word "foundations" implied spread footings, rafts, piers, or piles. Each type called for suitable combinations of structure and subsurface conditions. Establishing a foundation in deep water required a cofferdam, and if the practical depth of cofferdams would be exceeded by the foundation, the structure was considered infeasible. Then came offshore drilling in the oil industry and the development of a whole series of new techniques for establishing structures in very deep water. Today the techniques for establishing offshore structures for oil are just beginning to be applied to structures having other uses. Progress has been very rapid in this field in the last few decades and shows no signs of diminishing, whereas prospective oil fields are being found under deeper and deeper waters. Almost surely, in the next millennium the boundaries of all types of foundation construction as well as other underground facilities will be pushed deeper and deeper.

Moreover, geotechnics is becoming an inherent part of progress toward achieving commercially and environmentally acceptable construction works. Not too many years ago, when an extension to the Chicago Subway system was being planned, a Board of Consultants was appointed that included not only technical people, but sociologists, city planners, and environmentalists. The idea of locating a line to serve neighborhoods that might not generate much traffic but needed to be renewed, or neighborhoods that perhaps did not even yet exist, was novel. Today this approach is taken for granted. It often requires construction not in locations where the soil conditions are favorable for tunneling, but locations that are favorable to the sociological development of a community. The ease, or even the cost, of underground construction has become less and less significant. This means greater challenges for the subsurface engineer. Almost surely this trend will continue in the next millennium, and the physical challenges to the geotechnical engineer will become greater and greater. There will be no end of problems to solve, and there will be no end to the need for cooperation among engineers, nearby residents, sociologists interested in developing or preserving neighborhoods, and construction carrying out the work in such a way as to disrupt normal living as little as possible.

There will, in other words, be much more attention to the side effects of our activities. Society may be more and more willing to pay for preserving or improving the quality of life. So it is probably safe to say that geotechnical people working cooperatively with planners, designers, politicians, and citizens in the neighborhoods will face new and challenging problems.

Geotechnicians will play a major role in developing new and more friendly solutions for the growing population of the world and the desire of that population for better conditions under which to live.

The Glory Days of great breakthroughs in geotechnical engineering may be behind us, but geotechnical engineers will surely be busy in the next millennium. They will be doing things that we do not envision today, and they will continue to unlock Nature's secrets for the benefit of their fellow human beings.

## "THE NO-FILTER FACTOR OF SAFETY AGAINST PIPING THROUGH SANDS"

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### ABSTRACT

Progressive internal erosion by piping still presents a major failure threat to dams built with and/or over cohesionless soils. Many engineers do not understand the mechanics of piping and design using an empirical method more than 60 years old. We now know enough to improve this situation. A review of 115 horizontal piping tests indicates the predominant importance of a sand's coefficient of uniformity in determining the hydraulic gradient needed to develop piping, with layer depth, pipe length, density, anisotropy, layering and inclination also having important effects.

This paper adds to our physical knowledge about piping, connects piping with liquefaction and presents a new test-based design method for determining the factor of safety and reliability vs. piping at any point in a trial piping path in cohesionless soils. When using filters for safety vs. piping, the new method provides redundancy. It uses the simplifying concept that very low effective stresses and the vertical seepage gradients at the advancing end of a pipe determine its advance, and that the pre-pipe gradients at any point in the pipepath have an important effect on the degree of safety at that point.

Section 6. presents a design method for the safety factor vs. piping, with an example. Sections 2. thru 5. give the theoretical and practical details leading to the new method. Section 7 discusses some of the possible criticisms of the method.

# 1. INTRODUCTION

## 1.1 Review of Piping, Use of this Paper

"Piping" describes the erosion of soil, due to concentrated internal seepage, within a mass of soil. "Scouring" describes the erosion along a soil surface due to water flowing along that surface, without the need for seepage through the soil to that surface. Piping forms a below-surface open channel, or "pipe", within which water can flow and carry soil particles. Such a pipe begins at a downstream boundary where the soil particles can leave and clear the pipe. With the proper seepage gradient and roof support conditions this pipe can gradually lengthen by progressing upstream and may eventually extend all the way through the dam to the upstream head source. Then the waterflow velocity in the pipe increases greatly, the pipe can enlarge rapidly by scouring, and the dam can fail. The Section 10. GLOSSARY includes the definitions of "dam" and "piping" as used herein.

This paper should prove useful to engineers who design dams and embankments and must consider the possibility of failure by piping, and to engineers evaluating an existing dam or embankment for its safety vs. piping. They can, if they wish, go directly to Section 6. herein for a step-by-step description of a proposed new design method, with an example. Those readers interested in some or all of the theoretical and practical details involved can read about them in Sections 2. through 5. Section 7. attempts to anticipate and answer 21 potential reader questions and criticisms.

## 1.2 Further Review of the Piping Mechanism

The reader might find it useful to imagine, within a dam, a horizontal open channel (the pipe) with a sloping face (the pipehead) and a small and roughly half-circular cross-section. It starts at a downstream particle discharge point and progresses upstream, generally along seepage flowlines. The overhead soil has sufficient cohesion to prevent collapse into the pipe. Locally near the pipe, the 2D seepage through the dam (see flownet examples in Figs. 8A and 14) has its flowlines converge to the pipe and pipehead in a 3D pattern (see Fig. 1) examples). This causes a large increase in gradients and a consequent large decrease in effective stresses around the pipehead vs. the pre-pipe conditions. The increased horizontal and new vertical gradients loosen the soil at the pipehead sufficiently that the particles at the pipehead move downstream. They move by some combination of rolling and sliding, driven by the viscous drag of the water flowing in the pipe and helped by the suspending action of the vertical gradients. The loss of particles at the pipehead causes the pipe to advance upstream, producing a new flow and gradient concentration at the pipehead, etc., in an approximately continuous process. Eventually either the dam breaches due to the consequences of rapid scour when the pipe reaches the upstream head source, or the pipe advance stops within the dam or its foundation due to too-low local 2D gradients to continue the process.

### 1.3 Why the Need for Test Corrections and How Done

How easily a pipe can advance through a particular dam section depends on how easily the flow can concentrate to develop the 3D gradient conditions needed for piping. These gradients depend on such geometric and permeability factors as the total pipe length, the depth of the piping layer, and the relative permeability of underlying layers. Therefore, when predicting field behavior from a laboratory test with different geometry or boundary conditions and therefore different gradients, or a different sand, one needs to make corrections to account for the differences.

Such corrections involve identifying a parameter of importance to piping, quantifying it and formulating a correction factor for that parameter to apply to the laboratory results to predict field behavior. The writer does this. He then develops an overall correction factor that equals the product from those from each parameter. Section 5. will discuss the corrections in detail. Section 6. provides examples of their determination and use in an example dam piping safety factor analysis.

### 1.4 The Present State-of-Design

Many dams have failed by the phenomenon we refer to as "piping". Yet, piping remains poorly understood by most engineers. Even the most recent books (Terzaghi et. al., 1996) haltingly recommend a design procedure dating back to 1935 (Lane) known as the "Weighted Creep Ratio Method" - an entirely empirical and sometimes non-conservative method, based on a prior study of failures and non-failures mostly under small masonry dams in India. However, piping failures continue to occur. The writer had an involvement with two low dams in Florida that appear to have failed by piping, with resulting investigation, repair and other costs estimated at over $ 200M. The profession still needs a rational design method versus piping.

A Building Research Establishment publication (BR 171, 1990) succinctly stated the situation in 1990 as quoted below:

"3.5.2 Internal erosion

> Internal erosion can be a major threat to the safety of embankment dams, yet the mechanisms involved are not well understood and no analytical techniques are available which are comparable to those used to calculate a factor of safety against shear failure. The problem sometimes receives relatively little attention, yet it may be the greatest hazard to the safety of many embankment dams."

This situation does not appear to have changed much since 1990, with the possibly important exception of the Sellmeijer theory, noted below:

1.4.1 <u>Sellmeijer Theory</u>: Until recently the piping phenomenon has defied rational analysis. It involves a complex, three-dimensional seepage into the advancing end of the pipe, or "pipehead", to begin the erosion and then the movement of the sand through to a downstream discharge point. Since about 1980 Sellmeijer and his various colleagues have made a significant improvement in their understanding of the piping process in a horizontal, 2D piping channel in a homogeneous sand. Their work developed within the framework of the Delft test results, discussed later in Section 2.3. The writer will make frequent reference herein to this work, which he first became aware of in 1996. The work described herein and that by Sellmeijer <u>et</u>. <u>al</u>. generally complement each other. Their work has a primarily theoretical, and for the writer dauntingly mathematical basis, but with test underpinning. The present work has a test basis with a simplified theoretical underpinning.

<u>1.4.2 Filters and Redundancy</u>: In today's practice engineers commonly use soil or geosynthetic filters to prevent piping by preventing the soil discharge needed for piping to occur. They place the filter(s) to intercept likely or possible pipepath(s). However, it may prove impractical or uneconomical to intercept all such paths or even to include filters - especially in small dams. Furthermore, filters may not provide for redundancy in protection vs. piping unless more than one filter intercepts each path. Filters can also fail by not functioning as intended or by incorrect installation.

The writer assumes that an engineer using the design method described herein desires redundancy vs. piping even though a dam may include filters. However, the added safety from redundancy may come with an added cost.

### 1.5 Concept of Progressive Safety & Need for Use of Flownets

This paper provides a method for calculating an average or global factor of safety, such as noted in 1.4 for a potential shear failure surface, as well as the point-by-point variation of the factor of safety vs. piping along a potential pipepath. Compared to piping, shear failure usually occurs relatively suddenly, and using an average resisting shear strength and factor of safety seems appropriate for shear stability problems. On the other hand, piping by its nature happens progressively and the engineer needs to try to understand the point-by-point progression of the safety factor.

To determine the progression of safety the engineer must first know the details of the before-pipe seepage gradients across the dam section. This requires constructing flownets or their mathematical equivalent. All the other design methods known to the writer use the overall or global gradient to evaluate safety vs. piping. These methods do not require flownets but they also tell the engineer little or nothing about the possibly important details of safety vs. piping.

Casagrande (1935), in his discussion of Lane's paper, argued against empiricism and for the use of more rigorous analysis methods, such as the use of flownets, and his discussion includes six example flownets.

The writer used approximately 120 flownets to assist him with understanding the piping phenomenon. Figure 1 shows examples of some of the flownets used. Piping involves a 3D concentration of seepage and this work also used the computer studies of 3D seepage by Wong (1981) which followed a preliminary 2D computer study of pipehead gradients by Logan (1980). However, combining longitudinal, transverse and horizontal section 2D flownet information also permits at least estimating the 3D conditions around an advancing pipehead. The writer relied heavily on the use of flownets when developing Section 5. herein.

## 2. LABORATORY PIPING TESTS

The writer has some experience with piping tests. Others have also done valuable piping tests. The paper will now document 115 such tests from primarily two sources, namely the University of Florida and the Delft Hydraulics Laboratories. All these tests can now provide some valuable insights into the piping process.

## 2.1 Test Procedures

For the reader not familiar with piping tests, such tests followed the procedure briefly noted below:

- Place the test sand in the test flume, under water for near-saturation and in as uniform condition as practical.
- Place a transparent cover over that part of the horizontal sand surface where the pipe will propagate along the interface.
- Apply a surcharge to assure good cover/sand contact.
- Provide an upstream water supply with adjustable head and a constant head downstream water reservoir.
- Slowly increase the constant head difference, and therefore the global gradient, in small increments until pipes form at the downstream discharge provided in the model (Delft), or a short starter pipe (UF) begins to progress upstream.
- Increase the test global gradient as needed to keep the pipe progressing upstream until reaching the test maximum gradient that will cause the pipe to progress all the way to the upstream head source. The writer herein uses "$\bar{\imath}_{pmt}$" to denote this maximum test global gradient needed for complete piping. $\bar{\imath}_{pmt}$ then also represents the minimum needed for complete piping as determined from the test.

## 2.2 Tests by University of Florida

To help investigate the piping phenomenon, and after the failure of a dam, apparently by piping, the Florida Power and Light Corporation sponsored the construction and initial testing with a horizontal seepage flume designed by the writer for the specific purpose of investigating and quantifying piping behavior. Figure 2 shows plan and elevation drawings of this flume. The photos in Figure 3 show the flume in operation. Altogether, over the period 1981 to 1995, the writer and the University of Florida used the flume to conduct 37 piping tests on 10 different sands, plus scour tests on two of these sands (as discussed subsequently in Section 2.5.3).