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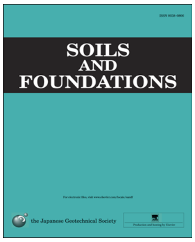

Simulation of pipe progression in a levee foundation with coupled seepage and pipe flow domains

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Abstract

A very large percentage of piping cases have been brought about by internal erosion, which is the primary cause of dam failures. This study developed a numerical model to simulate the pipe progression in a levee foundation by analyzing the inception and transportation of erodible particles from the soil fabric. An approach that considers the turbulent flow in an erodible pipe and the seepage flow in the remaining area of a levee foundation is employed to capture the main hydraulic characteristics of piping. The mechanical analysis of individual erodible particles is considered to quantify the critical condition for particle inception in an erodible pipe. In addition, physical piping model tests are numerically simulated to examine the proposed approach. The simulation demonstrates that the flow in a pipe can progress backward from downstream to upstream when the upstream water head reaches a critical value. Furthermore, the function mechanism of a cut-off wall can be explained by this model. The results have revealed that this model can reproduce the experimental data, such as the critical water head and the progression time, which are obtained from the physical model. The relationship between the depth of a suspended cut-off wall and the critical water head is obtained; this relationship facilitates the practical design of the critical depth of a cut-off wall for a given water head.

Keywords: Piping; Pipe flow; Seepage; Element free Galerkin method; Levee

1. Introduction

Most of the levees in China have a two-layer foundation composed of a nearly impervious surface layer and a pervious underlying layer. Generally, the soil in the upper layer is clay, silty clay, or silt with mucky intercalations scattered in local areas; the underlying layer is primarily composed of pervious soil such as sandy gravel, sandy cobble, or decomposed bedrock. In flood seasons with high water levels, many levees suffer from severe piping. Some statistic research indicates that piping is a primary cause of the serious failure of embankment dams which brings about the risk of flooding in downstream areas (Foster et al., 2000). As a consequence, it has become of great interest to improve the understanding of the piping flow in such two-layer structures for effective seepage control.

There has been much research work on piping within levees and a general understanding of piping phenomena has been achieved. Some researchers have proposed the internal stability of soil, which is based on the grain size and the distribution of the soil, to identify the susceptibility of soil to piping failure (Istomina, 1957; Kezdi, 1969; Kenney and Lau, 1985). Chang and Zhang (2013) extended the criteria of internal stability to soils containing a significant amount of fine particles. From the viewpoint of engineering applications, the critical water head or hydraulic gradient has been established; it provides an overall description of piping behavior that may result in the failure of a

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levee (Bligh, 1910; Sellmeijer, 1988; Weijers and Sellmeijer, 1993; Ojha et al., 2003; Richards and Reddy, 2007). The process of pipe progression has been widely explored in laboratory model tests (Wit et al., 1981; Kohno et al., 1987; Yao et al., 2007; Zhou et al., 2007b), followed by studies on the transport behavior and the mechanism of fine particles through the soil pores (Vardoulakis et al., 1996; Sterpi, 2003; Cividini and Gioda, 2004). A few efforts to numerically simulate pipe progression have recently been reported (Sellmeijer and Koenders, 1991; Yin, 1998; Hagerty and Curini, 2004; Fujisawa et al., 2010; Zhou et al., 2012).

The numerical approach to piping simulations can be roughly grouped into three categories in terms of the representation of the piping phenomena. The first approach, a traditional approach, is simply to increase the permeability coefficient of the piping zone, while conducting a routine seepage analysis based on continuum formulations and Darcy's law (Yin, 1998; Hagerty and Curini, 2004; Li et al., 2005). It can be used to analyze the effect of the piping zone on the remaining seepage field, but fails to reproduce the process of the pipe progression. The second approach is the discrete element method (DEM) (Zhou et al., 2007a; El Shamy and Aydin, 2008a, 2008b). As an alternative approach, the porous soil medium is modeled as a mixture of water and solid particulates. The water flow is described using an averaged form of the Navier–Stokes equations, while soil particles are modeled at the microscale using DEM. The total number of tracked particles is too large to make it applicable to engineering practice. The third approach is the multi-phase soil model (Stavropoulou et al., 1998; Bonelli et al., 2006; Luo et al., 2010; Fujisawa et al., 2010). The soils are divided into several phases according to different erosion models. The water and fine soils in pores are distinguished from the soil fabric, and the erosion of the fine soils from the fabric is accounted for. Such an approach enables the capturing of the main characteristics of piping, and its applicability to engineering problems has been shown. For example, Fujisawa et al. (2010) successfully simulated the temporal alteration and the spatial distribution of porosity and predicted the typical development of piping within an embankment. Zhou et al. (2012) conceptualized the computation domain as the coupling of two zones: an erodible piping zone and a zone without erosion. They reproduced the process of the backward pipe progression shown in their laboratory model tests. In such models, however, there is no universally accepted mechanism of internal erosion which can depict just how fine particles are eroded from the soil fabric and transported out of the soil mass.

It is possible that the water flow in the piping zone and the water flow in the seepage zone follow different governing laws. It is beneficial, therefore, to consider the computation domain as coupled zones (Sellmeijer and Koenders, 1991; Koenders and Sellmeijer, 1992; Schmertmann, 2000; Zhou et al., 2012). The aim of this paper is to provide a practical method for engineering applications by following Zhou et al. (2012). A new mechanism for soil inception and transportation in porous media has been proposed. The time for the piping progression has been estimated, which benefits the safety control of levees.

The method is firstly examined against laboratory model tests and then applied to a real levee foundation. The behavior of a suspended cut-off wall in controlling the pipe progression is explored; this helps demonstrate the potential value of the present method in practical applications.

2. Model development

For a two-layer levee foundation, piping generally begins with a soil flow at an unfiltered exit on the back side of the levee, after which an erodible pipe is gradually developed. The erodible pipe progresses backward along the interface between the nearly impervious surface layer and the underlying pervious layer, which may harm the safety of the levee. Artificial barriers, such as cut-off walls, may impede the progression of the pipe, as shown in Fig. 1. They are usually adopted as practical seepage control measures.

2.1. Governing equations for flows

The flow in the piping zone may be either laminar or turbulent, depending on the flow velocity as well as the pores formulated by the soil skeleton. Soil particles are eroded from both the tip and the wall of the pipe and are carried away by

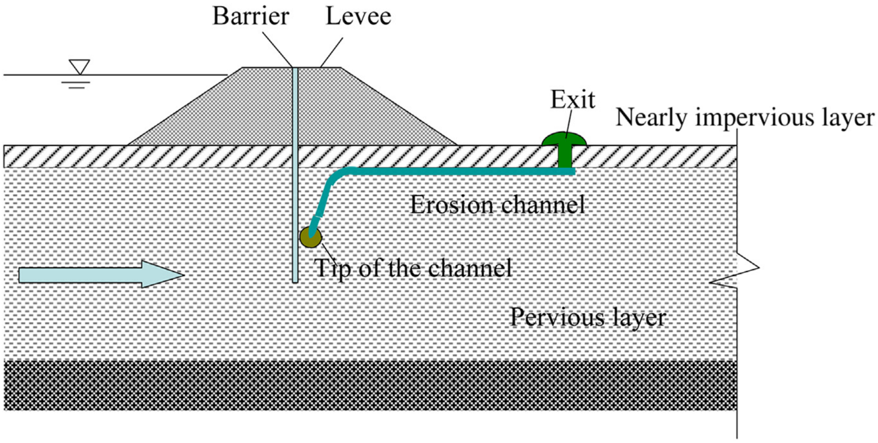

Fig. 1. Sketch of piping in two-layer levee foundation with hypothetical barrier.