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An experimental study on embankment failure induced by prolonged immersion in floodwater

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Abstract

Prolonged immersion in floodwater is one of the main causes of embankment failure or dam breaks, although failure mechanisms have not been extensively studied. In this study, an embankment model was constructed to investigate the influence of prolonged immersion in floodwater on the failure of an embankment. The results indicate that: (1) the phreatic surface gradually rises and negative pore pressures gradually dissipate with the time of prolonged immersion in floodwater, and, finally, a stable and fully saturated state is reached; (2) observable cracks and a heave phenomenon are found near the downstream toe and in the top stratum of the foundation, which are attributed to the large uplift pressure on the interface between the top stratum and the pervious substratum, the tremendous impact effect induced by the rapid rise in water level, and the reduction of shear strength of heavy silt loam. The present study enhances our in-depth knowledge of the mechanisms of embankment failure induced by floodwater, and provides experimental data for validation of mathematical models of the embankment seepage failure.

Keywords: Embankment; Floodwater; Seepage failure; Prolonged immersion; Heave phenomenon

1. Introduction

Prolonged immersion in floodwater is one of the main causes of embankment failure or dam breaks in the flood season. For example, the 1998 great flood in the Yangtze River Basin, lasting from late June to early July (Zong and Chen, 2000), caused damage to about 9396 main embankments of the Yangtze River, and economic losses were estimated at over US$ 36 billion (Ye and Glantz, 2005). The flood in New Orleans during Hurricane Katrina on August 29, 2005 caused levees and floodwalls to fail at more than 50 locations. Of the 284 miles of federal levees and floodwalls—there are approximately 350 miles in total—169 miles were damaged (Andersen et al., 2007). As a result, the problem of embankment failure induced by floodwater is a very important and urgent problem that should be studied in depth.

Generally, studies on seepage failure of the embankment have been mainly focused on two aspects: steady flow conditions and transient flow conditions. In examples of the former, Sellmeijer (1988) and Sellmeijer and Koenders (1991) developed an expression for the critical hydraulic head which should not be exceeded to avoid failure due to piping. Asaoka and Kodaka (1992) found that the critical hydraulic head difference in the medium-dense sand was more than three times as large as that in the loose sand. Ojha et al. (2003) presented a critical head model that provided a theoretical basis for Bligh's empirical model. Benmebarek et al. (2005) identified the conditions for seepage failure caused by boiling or heaving of the soil behind sheet piles. Fontana (2008) investigated critical hydraulic heads for the failure of hydraulic structures and assessed the coefficient of safety against heaving. Gregoretti et al. (2010) determined the minimum level of the upstream reservoir leading to the failure of landslide dams. Maknoon

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and Mahdi (2010) found that the upstream water head did not have an important influence on the suffusion on the interface between the core and filter layers.

In examples of the latter, Ozkan (2003) and Ozkan et al. (2008) defined a sinusoidally varying boundary condition to simulate the changing water level, and studied the effects of transient flow and repetitive flood events. El Shamy and Aydin (2008) developed a three-dimensional fully coupled fluid-particle model, which can simulate the process of seepage failure of hydraulic structures due to a rapid rise in upstream water level. Awal et al. (2011) pointed out that the failure modes of landslide dams depend on the rate of water level rise in the upstream reservoir and the strength of the dam body. The experiment carried out by Luo et al. (2013) indicated that suffusion failure in transient flow conditions with the long-term large hydraulic head in the flood season was more likely to happen and much more serious than it is in steady conditions.

At present, seepage failure under transient flow conditions due to changes in the water level has not been analyzed in detail. Studies on steady flow are not consistent with actual conditions, because the typical flood conditions only act for a period of days to weeks, which may not be sufficient time to reach steady-state conditions. In studies on transient flow, the adverse influence of a rapid rise in water level has been considered, but the influence of prolonged immersion in floodwater on the seepage failure has not been extensively studied. Therefore, it is necessary to emphasize research on the mechanisms of the embankment failure induced by prolonged immersion in floodwater.

In this study, an embankment model was designed to investigate the influence of prolonged immersion in floodwater on seepage failure of the embankment. The variation of pore pressure, the evolution of the phreatic surface, and the seepage failure mode were analyzed.

2. Embankment failure experiment

2.1. Embankment model

The experiment was carried out in a glass-sided flume with a length of 3.75 m, a width of 0.5 m, and a height of 0.8 m. Water was fed into the flume through an attached upstream water tank and a glass plate with holes, used to prevent turbulence and produce a uniform flow. A schematic diagram of the embankment model is shown in Fig. 1. The embankment model was composed of 13 compaction layers with a height of each layer of 0.05 m (CLN1 to CLN13), of which CLN1 was constructed with sand, and CLN2 to CLN13 were constructed with heavy silt loam. The two types of soil are widely used for levee construction in China. The initial upstream and downstream slopes of the embankment were 1:1.3 and 1:1.2, respectively. Twenty pore pressure transducers were embedded at the preset positions to monitor the pore pressure over the whole process of the experiment. Table 1 shows the coordinates of all pore pressure transducers.

Fig. 2 depicts the grain size distributions of heavy silt loam and sand. The optimal water content, maximum dry density, and permeability of the heavy silt loam were 30%, 1.43 g/cm^3, and 1.04×10^{-6} cm/s, respectively, according to the normal laboratory experiments. The optimal water content, maximum dry density, and permeability of the sand were 12.36%, 1.5 g/cm^3, and 1.35×10^{-4} cm/s, respectively. Table 2 shows the soil-water characteristic relationships of the heavy silt loam and sand.

2.2. Experimental process

The experiment mainly contained the following six stages:

(1) Material preparation and compaction: A certain amount of material was mixed with sufficient water, and then, with the optimal water content, the mixture was compacted layer by layer. Heavy silt loam mud was smeared on the side wall of the flume before compaction to avoid seepage on the interface between the model and the side wall.

(2) Embedment of pore pressure transducers, as shown in Fig. 3: The transducers were embedded in the holes, and heavy silt loam mud was poured to ensure close contact between the transducers and the surrounding soil. Then, a certain amount of soil was added into the holes and compacted again. Because the scale of the transducers was very small in the context of the entire embankment model, the influence of transducers on the failure process was ignored.

(3) Discharge of air from the catheters of pore pressure transducers: Air entrapped in the catheters will influence the sensitivity of pore pressure transducers, so air discharge is

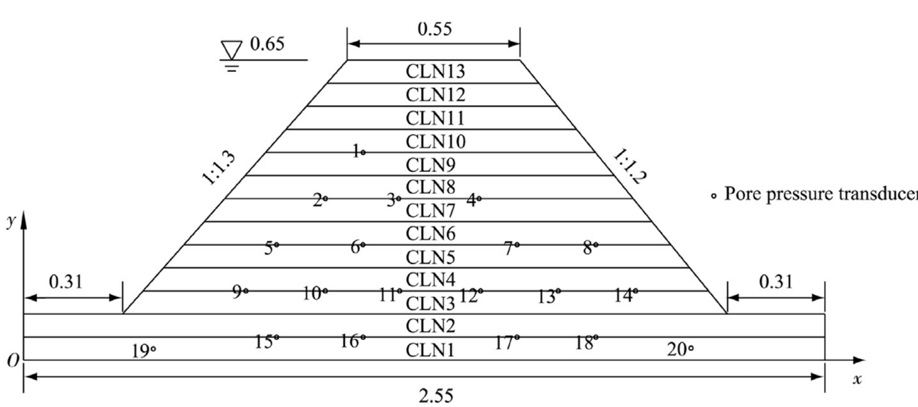

Fig. 1. Schematic diagram of embankment model (units: m).