ARTICLE IN PRESS
ENGEO-04343; No of Pages 10
Engineering Geology xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Engineering Geology
journal homepage: www.elsevier.com/locate/enggeo

Experimental and numerical investigations of dyke failures involving soft materials

Elliot James Fern [a,*], Dirk Arie de Lange [b], Cor Zwanenburg [b], Johannes Antonius Maria Teunissen [b], Alexander Rohe [b], Kenichi Soga [a]

[a] University of Cambridge, Department of Engineering, Trumpington Street, Cambridge CB2 1PZ, United Kingdom
[b] Deltares, Geo-Engineering, Boussinesqweg 1, 2611 HD Delft, The Netherlands

ARTICLE INFO

Article history:
Received 20 February 2016
Received in revised form 11 July 2016
Accepted 16 July 2016
Available online xxxx

Keywords:
Dyke
Levee
Soft soils
Slope failure
Centrifuge testing
Material point method

ABSTRACT

This paper presents the results of an experimental and numerical investigation on the collapse of dykes involving soft soils. Nine centrifuge tests were carried out to investigate the dyke-subsoil interaction. The tests consisted in placing a dyke made out of Speswhite clay or Baskarp sand on a subsoil. The dykes and the subsoils were alternatively changed to explore the different contrast in stiffness ranging from stiff dykes on soft subsoil to soft dykes on stiff subsoils. The small scale models were placed in the centrifuge and were progressively accelerated up to a maximum of 100 G. The recordings, which were then processed by Particle Image Velocimetry (PIV), offered an insight onto the deformation and failure mechanisms. The results showed that dykes placed on a stiff subsoil underwent brittle failures with the development of slip surfaces whereas the same dyke placed on a soft subsoil underwent large deformation which presented a serviceability issue. These tests were then modelled with the Material Point Method (MPM), which is a continuum-based method for numerical simulation dedicated for large deformation problems. Simple constitutive models were used for which the parameters could be estimated using state indices.

1. Introduction

The rapid expansion of urban areas and the rise of sea levels associated with the subsidence of land are putting ever increasing economical and social pressures on the flood defence systems of urban deltas (Seed, 2007). The lowlands of the Netherlands is home to more than 50% of its population and economical activity which includes the regions of Amsterdam, the Hague and Rotterdam. These areas are protected against flooding by an extensive network of dykes for which the design requirements are extremely high; the design return period is 10,000 years. However, a number failures have taken place in the past two decades. The Bleiswijk dyke, located near Rotterdam, failed in August 1990 (Vink, 1994). In 2003, the Wilnis dyke, located near Amsterdam, collapsed causing no casualties but extensive damage to property (*i.e.* Van Baars, 2005). These failures are not specific to the Netherlands. The United States has also experienced failures of dykes and levees. In 2005, Hurricane Katrina caused many dykes, levees and flood barriers to fail in the vicinity of New Orleans, Louisiana. The failures were attributed to a lack of assessment of the mechanical properties of the subsoil outside the footprint of the levee and unforeseen failure mechanisms, among other reasons (Andersen et al., 2007; Sills et al., 2008). Following this event, the US Army Corps of Engineers assessed the stability of their dykes and found nearly 150 which posed unacceptable risk of failure during major flood episodes (Abdoun et al., 2010). The Dutch authorities carried out a similar investigation and identified some dykes as being critical (*i.e.* Markermeer). However, the long history of these dykes and the reduction in loads, due to the construction of a closure dams and flood barriers, raise the question of how the stability of these dykes should be addressed and this requires a thorough understanding of the failure mechanisms. However, the failure of a dyke is complex and can involve several mechanisms, which are not always fully understood; Koelewijn et al. (2004), Zwanenburg et al. (2012), and Van Baars (2005) give a description of three different failure mechanism, respectively.

Following the Wilnis dyke failure, a number of experimental programmes were carried out in the Netherlands (*i.e.* Koelewijn and Van, 2002). Among them was the IJkdijk project (*i.e.* Zwanenburg et al., 2012) and consisted of a full-scale dyke subjected to an increase in pore pressure which caused the failure. The results showed that the soft layers of soil influenced the failure mechanism. Large scale tests mobilise a lot of human, technical and financial resources and could only be carried out in small numbers. Centrifuge testing offered an alternative with which it was possible to carry out more tests within a short period of time and at a smaller cost. Preliminary studies were carried out to investigate the feasibility of testing dyke failures in the centrifuge (Van et al., 2009) and were used as a basis for the tests presented in this paper. The loading paths of a dyke leading to failure are experimentally difficult to reproduce and control (*i.e.* groundwater seepage, piping,

* Corresponding author.
E-mail addresses: jf497@cam.ac.uk (E.J. Fern), dirk.delange@deltares.nl (D.A. de Lange).

http://dx.doi.org/10.1016/j.enggeo.2016.07.006
0013-7952/

Please cite this article as: Fern, E.J., et al., Experimental and numerical investigations of dyke failures involving soft materials, Eng. Geol. (2016), http://dx.doi.org/10.1016/j.enggeo.2016.07.006

etc.). Thus, a simpler loading path was favoured, though not realistic, but could be fully controlled during the experiment - gravity loading.

In this study, nine centrifuge tests were carried out and consisted of dykes made out of Speswhite clay or Baskarp sand and placed on a subsoil. The dyke and the subsoil were alternatively changed to explore different contrast in stiffness ranging from stiff dykes on soft subsoil to soft dykes on stiff subsoils. The small scale models were placed in the centrifuge and were progressively accelerated up to a maximum of 100 G depending on when the failure occurred. This loading path differed from those observed in the field. However, it offered simplicity in execution and understanding for a first testing programme. Numerical modelling and analysis were then carried out using the Material Point Method (MPM) (Sulsky et al., 1994, 1995) in order to investigate the feasibility of MPM to capture the observed failures and gain additional insight on the failure mechanisms.

2. Description of centrifuge tests

The centrifuge tests were carried out at Deltares (formerly GeoDelft), the Netherlands, with their geotechnical centrifuge (Fig. 1). It is a 300 G-force beam centrifuge with an arm length of 5.5 m.

The tests consisted in modelling the failure of dykes resting on different subsoils. Six tests consisted of clayey dykes made out of Speswhite clay and resting on a silicon subsoils which were used to replicate the large deformation capacity of soft soils such as peat, which are difficult to model in the centrifuge due to their fibrous nature. However, the silicon can only reproduce the stiffness of the soft material and not the elasto-plastic behaviour of real soil. The stiffness of silicon can be controlled during preparation and three silicon blocks were built with, respectively, three different stiffnesses which mimicked different soft soils. Three additional tests were carried out and consisted of dykes made out of Baskarp sand. One consisted of a sandy dyke resting on a soft silicon subsoil and two tests consisted of a sandy dyke resting on a remoulded, natural and soft clay called Oostvaardersplassen (OVP) clay (Hjortneas-Pedersen and Broers, 1993). These two tests were identical but showed different failure patterns due to the natural imperfection in the OVP clay. Table 1 summarizes the test programme, where SW stands for Speswhite, B for Baskarp and OVP for Oostvaardersplassen.

All models were built in a plane strain configuration inside a rectangular strong box with a glass face. The dimensions of the dyke and the thickness of the subsoil changed between tests with a silicon subsoil (Model 1) and those with the OVP clay subsoil (Model 2). The latter was smaller in order to reduce the consolidation time due to the time constraints of the project. The dyke and the subsoil were made out of, respectively, one material. In other words, the dyke was made entirely out Speswhite clay or Baskarp sand and the subsoil entirely out of silicon or OVP clay. The dyke had an asymmetric geometry with one steep slope (1:1.5) and shallower slope (1:2). The dyke was truncated in order to force the failure in one direction. Fig. 2 shows a photograph of the centrifuge model and Fig. 3 gives the dimensions.

Table 1
Centrifuge test programme.

Test	Dyke	Subsoil	Model
A	Med.-Stiff SW clay	Stiff silicon	1
B	Med.-Stiff SW clay	Med.-stiff silicon	1
C	Med.-Stiff SW clay	Soft silicon	1
D	Soft SW clay	Stiff silicon	1
E	Stiff SW clay	Stiff silicon	1
F	Stiff SW clay	Soft silicon	1
G	Dense B sand	Soft OVP clay	2
H	Dense B sand	Soft OVP clay	2
I	Dense B sand	Soft silicon	1

The models were subjected to an increase in gravity from 1 to 100 G with a rate of 1 G/min. For operational reasons, a vacuum was created in the centrifuge chamber in order to reduce the drag force. This was carried out at 20 G for the clayey dykes and at 40 or 50 G for the sandy dykes. During this phase, the G-level was maintained constant but displacements of the crown were still observed and will be discussed in a later section (Fig. 7). No other loads were applied to the model.

2.1. Model preparation and instrumentation

The clayey dykes were made out of Speswhite clay which is a fined grained kaolin with a low permeability ($K_{sat} = 10^{-9}$ m/s), a liquid limit of 69% and a plastic limit of 38%. It was prepared in a stiff tub and consolidated with a vertical pressure $\sigma'_{v,c}$ of 50, 100 or 150 kPa. It was then extracted from the tub, cut into a block and placed in the strong box on the silicon block. The faces of the strong box were smeared with Vaseline in order to reduce the friction between the model and the strong box. The contact between the dyke and the subsoil was carefully prepared in order to obtain a intimate contact between them. Once the block was in place, the Speswhite clay was trimmed into a dyke. Speckles were then blown on the face of the dyke in order to allow the Particle Image Velocimetry (PIV) analysis (White et al., 2003). The front and the rear panels of the strong box were mounted and the container was sealed until the test was carried out the next day.

The sandy dykes were made out of Baskarp sand which is a uniformly graded silica sand with a dominant grain size of 0.1 mm. It has a critical state friction angle φ'_{cs} of 32°, a minimum void ratio $e_{\min}$ of 0.65, a maximum void ratio $e_{\max}$ of 0.96 and a specific gravity G_s of 2.65. The silicon block was first placed in the strong box and the sides of the strong box mounted. Then, the sand was placed and tamped under water to achieve a relative density of 90%. Different layers of sand were coloured in order to facilitate the visualisation of the deformation. The sand was then drained and trimmed to the shape of the desired dyke. The strong box was then covered and the test took place the next day.

The silicon subsoil was prepared in the form of blocks and to achieve a specific stiffness. A specific block was chosen according to its stiffness

Fig. 1. The beam centrifuge at Deltares, the Netherlands.

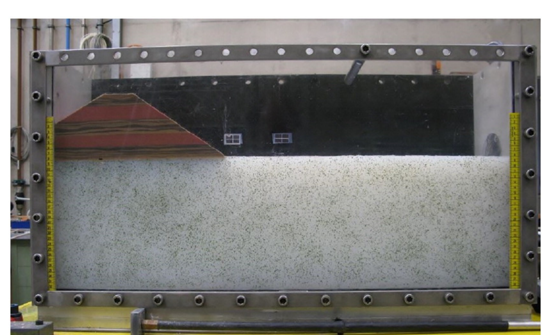

Fig. 2. Model 1 with a stiff sandy dyke and a soft silicon subsoil (Test I).