Computers and Geotechnics 63 (2015) 83–98

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Influence of river level fluctuations and climate on riverbank stability

C. Liang [a,*], M.B. Jaksa [a], B. Ostendorf [b], Y.L. Kuo [a]

[a] School of Civil, Environmental and Mining Engineering, University of Adelaide, SA 5005, Australia
[b] School of Earth and Environmental Sciences, University of Adelaide, SA 5005, Australia

ARTICLE INFO

Article history:
Received 19 May 2014
Received in revised form 26 August 2014
Accepted 27 August 2014
Available online 21 September 2014

Keywords:
GIS
Riverbank stability
Limit equilibrium method
Drawdown
River level fluctuation
Evaporation
Rainfall
Soil suction
River Murray

ABSTRACT

Riverbank collapse is a natural part of the evolution of rivers. An unprecedented period of dry conditions and low flows between 2005 and 2010 led to more than 162 reported riverbank collapse-related incidents along the Lower River Murray, in South Australia (downstream of Lock 1 at Blanchetown to Wellington). On 4 February, 2009 a 60 × 20 m (70,000 m^3) section of riverbank, near Long Island Marina, Murray Bridge, collapsed into the river, taking with it three unoccupied vehicles and several trees. This paper aims to: (i) model the Long Island Marina riverbank collapse incident in both 2D and 3D; (ii) examine the influence and sensitivity of river level fluctuations and climatic factors on riverbank stability; and (iii) determine the dominant triggers affecting collapse. The analysis has been undertaken using an integration of the limit equilibrium method, transient unsaturated flow modeling and digital elevation model and high resolution aerial images from a Geographic Information System. The paper demonstrates the efficacy of this framework and the accuracy of the predictions. It also reveals that river fluctuation, rather than climatic influences, dominates riverbank collapse in the Lower River Murray.

1. Introduction

Bank collapse is a natural and expected phenomenon associated with the evolution of rivers worldwide. Over the last 5 years or so, climatic factors such as rainfall, evaporation and river level fluctuations have combined with geographical and geotechnical factors, such as topography, stratigraphy and soil characteristics, to induce more than 162 reported riverbank collapse-related incidents along the lower River Murray, in South Australia (downstream of Lock 1 at Blanchetown to Wellington). Among these, 114 occurred during a period of extremely low river levels (lower than −0.5 m AHD[1]) due to an unprecedented period of dry conditions and low flows between 2005 and 2010. The most significant collapse occurred at Long Island Marina on 4 February 2009, where a 60 × 20 m section of bank collapsed into the river [2–6]. Based on site inspections, a large number of deep-seated circular failures in the soft and very soft clays of Holocene age were recognized as the dominant bank collapse mechanism along the lower River Murray [7].

The effects of climate and river level fluctuation on the stability of riverbanks have been extensively explored and discussed by several researchers [8–20]. Compared with the assessment of landslides in mountainous regions, changes in pore water pressure, in particular soil suction (negative pore water pressure), plays a more fundamental role in the stability of riverbanks [8,10,15,17,21]. The pore water pressure significantly affects riverbank stability by changing the soil shear strength [6]. As stated by Fredlund [22], soil suction can vary from zero to approximately 1000 MPa in the unsaturated (or vadose) zone [23] and is highly dependent on the properties of the soil, hydrological conditions and soil–atmospheric interactions [12].

Rainfall has long been recognized as one of the most significant factors responsible for initiating slope failures in many tropical or subtropical regions [24]. Generally, rainfall-induced slope failures are observed as shallow failures, however deep-seated rotational failures are also reported [24]. According to Rahardjo et al. [25], the initial FoS of the slope is determined by the slope geometry and initial water table while the actual rainfall-induced failure conditions are greatly influenced by rainfall characteristics and soil properties. The nature of the rainfall, such as intensity, duration, spatial distribution and antecedent characteristics, significantly influences the occurrence of rainfall-induced landslides by affecting the pore water pressure distribution and increases the self weight of the slope material [21,24,26–28]. Based on several studies performed in Hong Kong, Lumb [29] and Brand [30] indicated that antecedent rainfall has a negligible effect on local rainfall-induced landslides. They concluded that rainfall intensity and duration had the most profound influence on the slope failure

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* Corresponding author.

[1] Australian Height Datum.

http://dx.doi.org/10.1016/j.compgeo.2014.08.012
0266-352X/

Nomenclature

AHD	Australian Height Datum
ARI	average recurrence interval
b	fitting parameters of unsaturated Fredlund model that have a value close to unity for sands and increasing with plasticity
c'	effective cohesion
c_{top}	cohesion at the top of Silty Clay
c_{ratio}	rate of increase of undrained shear strength with depth for Silty Clay
c_{max}	maximum value of cohesion in Silty Clay
CH	Silty Clay, high plasticity
CL	Sandy Clay, low plasticity
CPT(u)	piezocone tests with pore water pressure measurements
CRLM	constant river level model
$D_{\%}$	grain diameter related to the percentage of passing in mm
DEM	digital elevation model
DFW	Department for Water
DEWNR	Department of Environment, Water and Natural Resources
FEM	finite element method
FoS	factor of safety
G_s	specific gravity of solids
GISs	Geographic Information Systems
HM	historical model
I_{thr}	threshold rainfall intensity
K	unsaturated hydraulic conductivity
K_{sat}	saturated hydraulic conductivity
LIDAR	light detecting and ranging
MRM	magnified rainfall model
P_{200}	percentage of soil passing US standard sieve #200
PI	plasticity index
PSD	particle size distribution
RS	remotely-sensed
SM	Silty Sand
SC	Clayey Sand
SWCC	soil water characteristic curve
w	moisture content
wPI	weighted Plasticity Index
θ_{sat}	saturated volumetric water content
ρ	dry density
ρ_w	density of water at 4 °C
ϕ'	effective internal angle of friction
γ	unit weight of soil

due to localized high conductivity soils [29,30]. Later, Rahimi and Rahardjo [26,27,31] implemented a series of more detailed studies along the Sieve River in Italy in relation to rainfall associated with soils of different conductivities. Their work showed that the rate of decrease in FoS, the time corresponding to the minimum FoS and the value of the minimum FoS are all controlled by the rainfall distribution. In comparison, rainfall can induce up to a 45% reduction in the FoS of soil slopes with lower fines content and higher saturated permeability ($K_{sat} \geqslant 10^{-5}$ m/s) than those with a high fines content and low permeability ($K_{sat} \leqslant 10^{-6}$ m/s) [26]. These geotechnical properties greatly influence the behavior of rainfall-triggered slope failures because they affect rainwater seepage and infiltration. Rahardjo et al. [25] examined the relationship between K_{sat}, soil suction, FoS and the magnitude of rainfall. Their work found that, under modest rainfall intensity (10 mm/h), soils with $K_{sat} = 10^{-6}$ m/s were associated with the lowest FoS, followed by soil with $K_{sat} = 10^{-5}$ m/s. In contrast, under relatively intense rainfall (greater than 200 mm/h), soils with $K_{sat} = 10^{-5}$ m/s were associated with the lowest FoS.

River level fluctuation has been shown to influence riverbank stability in two important ways: (i) its effect on reducing negative pore water pressure and, hence, its consequent reduction in soil strength, and (ii) the hydrostatic pressure it applies to stabilizing the riverbank [8,9,15]. Due to the limited models available at the time, studies in the 1980s typically proposed simple hypotheses on pore water pressure conditions of the riverbank (dry or total saturated) and adopted relatively simple solutions for slab failures [10,16–18,32]. Later in the 1990s and 2000s, with developments in unsaturated soil mechanics theory, the effect of pore water pressure on unsaturated riverbanks and confining pressure became more widely accepted and included into drawdown analysis and research of riverbank stability [8,9,11,12,14,15,19,20,33–35]. It is generally accepted that when rivers experience an initial high-flow period, the riverbanks are stable due to the supportive effect of the hydrostatic pressure of the water. However, the processes of erosion and soil saturation during high flow events weaken many parts of the bank by undermining it and reducing the effective strength, respectively [10,16,17,36,37]. Berilgen [33] indicated that the stability of a submerged slope during drawdown greatly depends on the rate of pore water drainage. While during initial low-flow periods, the matric suction (the suction due to capillary action and water surface tension) occasionally allows the riverbank remain stable at steep angles [8]. However, subsequent rainfall increases the dead weight of the bank material and reduces the matric suction which might be sufficient trigger a mass failure [34].

A very limited number of studies modeled the coupling of climatic factors and river level fluctuations. Casagli and Rinaldi [8] used tensionmeters, piezometers and a rain gauge on the Sieve River to monitor the matric suction evolution and riverbank stability in a semi-arid climate with daily river flow changes over a 16-month period. Later, based on these monitoring works they performed transient modeling on a drawdown failure which occurred on 14 December 1996 [34]. In their transient model they divided the research period (13–18 December 1996) into 24 time steps to examine the behavior of the riverbank under different rainfall and flow events. Their work indicated that the minimum FoS always occurred after the peak level of the Sieve River, and no later than 5.5 h after. The result suggests that riverbank collapse on Sieve River is dominated by river level fluctuations, primarily due to the reduction in the stabilizing influence of hydrostatic pressures due to river level drawdown, and marginally due to rainfall. This is further supported by the work of Twidale [38], Thorne [17,18,37], Springer [16] and others.

Geographic Information Systems (GISs), which are well known for their efficient and effective processing of spatial data, have greatly facilitated the research of natural hazards, especially with respect to slope instability studies [6,38–47]. With the integration of high-resolution, remotely-sensed (RS) data, such as LIDAR (light detecting and ranging) images and aerial photographs, the GIS framework is adopted in the present paper to facilitate riverbank stability analyses in the following three ways: (a) the topographic information of the site is obtained from data extracted from the digital elevation model (DEM); (b) the collapsed regions are examined by visual interpretation of high resolution aerial images; and (c) the dimensions of the simulated collapsed regions are validated against high resolution aerial images.