Geomorphology 295 (2017) 489–506

Contents lists available at ScienceDirect

Geomorphology

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

Influence of filling-drawdown cycles of the Three Gorges reservoir on deformation and failure behaviors of anaclinal rock slopes in the Wu Gorge

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ARTICLE INFO

Keywords:
Three Gorges reservoir
Filling-drawdown
Anaclinal slope
Deformation monitoring
HM interactions

ABSTRACT

The upper Wu Gorge on the Yangtze River has been the site of tens of reservoir-induced landslides since the filling of the Three Gorges reservoir in 2003. These landslides have been occurring in heavily fractured carbonate rock materials along the rim of the reservoir in the Wu Gorge. A detailed investigation was carried out to examine the influence of reservoir operations (filling and drawdown) on slope stabilities in the upper Wu Gorge. Field investigations reveal many collapses of various types occurred at the toe of the anaclinal rock slopes, owing to the long-term intensive river erosion caused by periodic fluctuation of the reservoir level. Analysis of data from deformation monitoring suggests that the temporal movement of the slopes shows seasonal fluctuations that correlate with reservoir levels and drawdown conditions, with induced slope acceleration peaking when reservoir levels are lowest. This may illustrate that the main mechanism is the reservoir drawdown, which induces an episodic seepage force in the highly permeable materials at the slope toes, and thus leads to the episodic rockslides. The coupled hydraulic-mechanical (HM) modeling of the G2 landslide, which occurred in 2008, shows that collapse initiated at the submerged slope toe, which then caused the upper slope to collapse in a rock topple-rock slide pattern. The results imply that preventing water erosion at the slope toe might be an effective way for landslide prevention in the study area.

1. Introduction

Dam sites are usually located at valley constrictions (Gutiérrez et al., 2010). In a number of cases, high and narrow valleys are usually associated with landslides (Jian et al., 2009; Paronuzzi et al., 2013; Tang et al., 2015). However, engineers and geologists did not fully realize the possible disastrous consequences of reservoir slope failures until the well-known 1963 Vajont Reservoir landslide in Italy (Semenza and Ghirotti, 2000; Kilburn and Petley, 2003; Boon et al., 2014; Crosta et al., 2016).

Mass movements of reservoir-rim slopes can occur during either filling or drawdown of a reservoir (Jones et al., 1961; Schuster, 1979; Gutiérrez et al., 2010; Zangerl et al., 2010; Jiao et al., 2014). The raise in the water level during reservoir filling causes saturation of slope materials, reducing mechanical strength of soil and rock (Záruba and Mencl, 1982; Wang et al., 2007), and decreasing slope stability. However, this decrease might be partly counterbalanced by the buttressing effect (increased lateral confining pressure on lower slopes) of a reservoir (Paronuzzi et al., 2013). The sudden drawdown of a reservoir, on the contrary, may have a debuttressing effect on lower slopes (Gutiérrez et al., 2010). Jones et al. (1961) observed more than 500 slope movements induced by the Grand Coulee reservoir, Washington, USA, from 1941 to 1953. They found that about half of the landslides occurred during filling operations and approximately 30% during drawdown operations. Nakamura (1990) studied reservoir landslides in Japan, and also indicated that about 60% of the landslides occurred due to the drawdown of water level and another 40% due to water filling. Long-term monitoring data for the Geheyan reservoir (Qi et al., 2006) in China and the Canelles reservoir in Spain (Pinyol et al., 2012) show the specific effects of reservoir water levels on slope deformation. For instance, the study of the Maoping landslide along the Geheyan reservoir (Qi et al., 2006) revealed landslide reactivation after the impoundment in 1993. The deformation was due to rapid drawdown rather than rise of water level. Rainfall also triggers landslides on slopes along reservoir (Macfarlane, 2009). Examples along the Three Gorges reservoir include the Qianjiangping landslide (Wang et al., 2008b), which caused 24 deaths, and the Sanmendong landslide (Sun et al., 2016).

The Wu Gorge in the eastern part of Wushan County (Fig. 1a), is one of the famous Three Gorges along the Yangtze River (namely, Qutang,

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http://dx.doi.org/10.1016/j.geomorph.2017.07.028
Received 7 July 2016; Received in revised form 28 July 2017; Accepted 28 July 2017
Available online 04 August 2017
0169-555X/

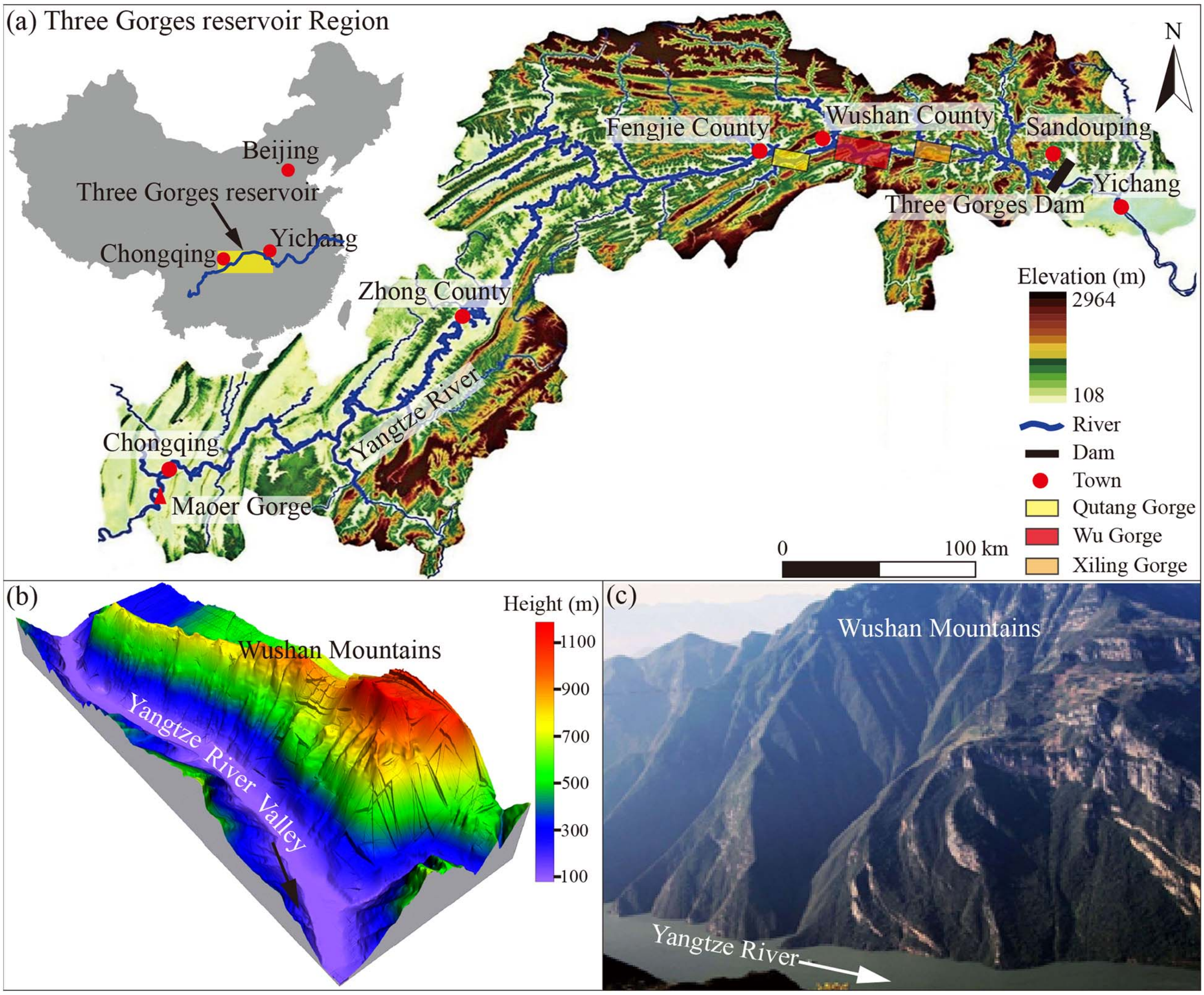

Fig. 1. Geographical and geomorphological setting of the study area. (a) Geographic map of the Three Gorges reservoir and location of the study area. (b) Topography of the Wushan Mountains. (c) Oblique aerial view of steep and high-relief slopes bounded by natural gullies in the upper Wu Gorge.

Wu and Xiling Gorges, as shown in Fig. 1a), surrounded by steep mountains with deep and narrow V-shaped valleys (Fig. 1b). Since the impoundment of the Three Gorges reservoir in 2003, many large scale landslides have been induced in the Wu Gorge, such as the Baizhangpo and the Gongjiafang landslides (Fig. 2a). These landslides, including both reactivated old instabilities and newly triggered ones, have threatened Wushan Town, shipping along the Yangtze, and dam stability (Deng et al., 2000; Wang et al., 2008a; Huang et al., 2012; Sun et al., 2016).

Although several studies have been performed on the Gongjiafang landslide (Huang et al., 2008; Huang et al., 2012; Gu and Huang, 2016), most of which focused on its geological and geotechnical features or induced waves. The influence of filling–drawdown cycles of the reservoir on slope stability has not been well documented and analyzed. Simplified analyses by Gu and Huang (2016) indicated that river erosion at the slope toe triggered a rockslide, they did not consider actual seepage processes at the slope toe in relation to changing reservoir water levels. The present work more thoroughly examines the influences of reservoir operations on the stability of the anaclinal slopes in the upper Wu Gorge. Measurements of surface displacement are integrated with geological data to develop a geometrical and kinematic model of the slope system. In addition, kinematic analysis of the G2 rockslide, a typical landslide in the study area, is carried out using a numerical model of slope seepage. The results allow us to understand the variation of slope stability during the reservoir filling–drawdown procedures.

2. Geological and geomorphological settings

2.1. Physiographic descriptions

The Three Gorges Dam was completed in 2006 and formed a reservoir longer than 660 km, extending from the dam site in Sandouping Town to the Maoer Gorge in Chongqing City (Fig. 1a). The reservoir area can be divided into two parts. The eastern part is from Sandouping Town to Baidicheng in Fengjie County (Fig. 1a), with a length of 193 km. In this part, the Three Gorges have been formed by severe river incision into the massive limestone of the Lower Palaeozoic and Mesozoic, along a narrow fault zone in response to episodic tectonic uplift during the Quaternary (Li et al., 2001; Liu et al., 2004; Fourniadis et al., 2007). The mountain height at the gorge ranges from 600 to 1200 m a.s.l. (Fig. 1b), whereas the river width is only 200–300 m. Between the three gorges are two portions consisting of clastic rocks forming wider valleys with slope angles gentler than in the gorges. River bank erosion, terrain dissection and slope failure tend to be