Engineering Geology 159 (2013) 20–30

Contents lists available at SciVerse ScienceDirect

Engineering Geology

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

Engineering aspects and time effects of rapid deterioration of sandstone in the tropical environment of Sabah, Malaysia

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A R T I C L E I N F O

Article history:
Received 16 July 2012
Received in revised form 19 February 2013
Accepted 2 March 2013
Available online 21 March 2013

Keywords:
Weathering
Intensity
Rate
Intact rock strength
Sandstone
Sabah

A B S T R A C T

Cut slopes in rock masses start to deteriorate directly after excavation due to stress relief and weathering. The deterioration is a time dependent process that depends on the local climate and the rock mass including its history, and the environment. The amount of deterioration per time unit ('the weathering intensity rate') is not a constant over time, but is for most rock masses larger when the mass is less weathered and becomes smaller with further progressing weathering. A study has been carried out to establish the relationship between weathering intensity rate and exposure time for the *intact rock strength* (*IRS*) of sandstone in humid tropical areas. The data set for the study was collected in and near Kota Kinabalu, Sabah, Malaysia, which has a humid tropical climate. The geology in the area consists of thick sequences of sandstone and shale beds of the Crocker Formation. Results show that the best relationship between intact rock strength (*IRS*) and exposure time (t) is by a logarithmic function; $IRS\ (t) = 105 - 34 \log (1 + t)$. This relationship can likely be used for prediction of the intact rock strength development of similar sandstone over the engineering lifetime of man-made slopes in tropical areas.

1. Introduction

Road construction in mountainous areas with a humid tropical climate is often plagued by slope instability. In Malaysia, especially in the state of Sabah a large increase in development and population density has triggered the expansion of housing and infrastructure in hilly areas during the last decennia. This requires extensive numbers of road cuts and embankments for road construction. A number of the road cuts show deterioration and instability within relatively short time spans of a couple to tens of years.

Road cut slopes in Sabah Malaysia are designed to be stable over a certain time span, normally more than 30 years, which is the 'serviceable lifetime' (Chua, V.; personal comm. June 1, 2012). The 'serviceable lifetime' of the slope is achieved by using a higher *Factor of Safety* (*FoS*) than required for a stable design at the time of construction. Although the design is supposed to result in a slope to be stable for more than 30 years, many slopes or parts of slopes fail within 30 years after construction. The reasons for failure sometime after construction but before the design 'serviceable life' time ends are likely stress relief and weathering. Throughout the world, stress relief and weathering are often marginally quantified or simply neglected in slope design (Wong et al., 1998; Huisman et al., 2006). The lack of understanding and appreciation of these processes also resulted in improper design of man-made slopes in Malaysia (Gue and Tan, 2006). A proper design of a slope for the entire engineering lifetime of the slope should include quantitative factors accounting for the degradation of the rock mass over its lifetime. However, quantified relations over engineering periods are seldom in the published literature and do not exist for the tropical climate and environment of Malaysia. Most of the published studies on rock weathering concern the influence of weathering on the geotechnical properties of the intact rock in engineering applications, and the development of weathering profiles and soil layers over long (geological) time spans (e.g. Raj, 1985; Mohamed et al., 2007; Mohamad et al., 2008, 2011; Ghiasi et al., 2009; Chigira et al., 2011). In this paper, a study is described to develop quantitative factors for incorporation in the design of slopes to account for stress relief and weathering in humid tropical areas.

2. Slope material deterioration mechanism in slope

Stress relief and weathering are the dominant deterioration processes that affect the durability of a man-made rock slope after excavation. These cause the physical, geotechnical and chemical properties of the slope material to change in response to the new environment and are considered a major cause of future geotechnical engineering problems (Hack and Price, 1997).

2.1. Stress relief

The excavation of a slope causes a change in stress regime in the rock mass forming the slope; generally, stresses will become less

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0013-7952/$ – see front matter
http://dx.doi.org/10.1016/j.enggeo.2013.03.009

due to the removal of material, however, stress increases and stress concentrations may occur as well. Stress reduction allows opening of existing discontinuities, and stress increase and concentrations may lead to new discontinuities as may be stress relief fracturing in shaly type of rocks (Price et al., 2009). Moreover, the change in stress field may cause new discontinuities because of reduction of confining pressure (Anon., 1995; Hudson and Harrison, 1997; Hencher and Knipe, 2007). The new and more opened existing discontinuities allow for a higher permeability and hence an increase in water permeating into and flowing through the rock mass. Weathering will then increase and be faster as water is one of the main agents involved in weathering (Bland and Rolls, 1998; Huisman, 2006).

2.2. Weathering

Weathering is the chemical and physical break down of minerals due to physical, chemical, and biological processes. The weathering affects intact rock but also the fabric and nature of discontinuities in the rock mass (Gupta and Rao, 2001; Nicholson, 2004; Gurocak and Kilic, 2005; De Mulder et al., 2012). Weathering depends on local conditions such as local climate, surface and groundwater conditions, chemicals dissolved in groundwater, land and fertilizer use, etc. (Saunders and Fookes, 1970; Fookes et al., 1988; Semhi et al., 2000). The rates with which the processes take place are also very dependent on local conditions such as temperature and presence of water (White and Blum, 1995; Bland and Rolls, 1998).

2.2.1. Weathering at surface versus subsurface

Weathering processes in the subsurface are different from those in an exposure at surface. In the first situation weathering is mostly governed by chemical weathering whereas physical weathering is largely absent, while in exposures where weathering takes place under the direct influence of the atmosphere, it is a combination of chemical and physical weathering. In an exposure, biological agents may be of influence too (Hinsinger et al., 2001), and stress relief may be more pronounced at surface than in the subsurface. Many parameters are of influence on weathering rates in the subsurface such as the stress regime, the depth of the rock mass below surface, the hydrological regime (Day et al., 1980; Katongo, 2005), and chemicals dissolved in groundwater. These parameters may change over time. Back-calculating weathering rates in the subsurface are mostly done from mass balances of chemicals dissolved in groundwater (e.g. Moreira-Nordemann, 1980; White et al., 1998; Olvmo, 2010) although many studies include necessarily also weathering at surface, as it is mostly impossible to differentiate between chemicals derived from surface and subsurface weathering.

2.2.2. Intact rock weathering

Many studies have been done to the weathering of intact rock. Most concern ornamental stone, which mostly implies that the rock is freely exposed to weather influences. For example, many studies have been done on tomb- grave- or head-stones (among many studies: Dragovich, 1987; McNeill, 1999; Inkpen and Jackson, 2000; Williams and Robinson, 2000; Wells et al., 2008), natural rock blocks mounted on the outside of buildings (Warke et al., 2006; Ruiz-Agudo et al., 2007), or natural rock in and on monuments, such as Cleopatra's Needle in New York (Winkler, 1980; Storemyr, 2012), Medieval castles and churches in Spain (Sancho et al., 2003; Sebastián et al., 2008), and ancient temples and monuments in Asia (Lee et al., 2005; Siedel et al., 2010). The weathering effect on construction materials especially rock aggregates has been discussed in detail by Fookes et al. (1988). Rates for weathering vary widely depending on rock material and climatic environment. A decrease of weathering rate is observed by many authors when the weathered material stays on the surface, and then protects the underlying material. If the weathered material is removed i.e. falls off by gravity or is flushed away by water, weathering starts again with a weathering rate comparable to the weathering rate of the original material. In the Mediterranean area, the rates of weathering for building stone depend strongly on the way the building stone is used, i.e. in how far the building stone is isolated from coastal i.e. marine, influence (Al-Agha, 2006). Measured weathering rates for similar types of intact rock can be a factor 3.5 times faster in a humid tropical area compared to a cool humid temperate environment (Day et al., 1980).

2.2.3. Rock mass weathering

Although weathering rates vary widely, the determination of the weathering rate of intact rock is straightforward compared to determining weathering rates for rock masses. Natural rock masses contain intact rock but this rock is neither exposed to the atmosphere at all or only one site of a block if it is on the outside of an exposure or cut. The influence of the atmosphere has to be transferred through other blocks or through discontinuities by water or air. This temporizes and moderates the effects of the outside environment on the inside of the rock mass. The rates obtained for weathering of exposed intact rock are hence not applicable to intact rock that is imbedded in a rock mass. Rock mass weathering is described by Gutiérrez Elorza (2005) albeit rates are mainly given for ornamental stone (Section 2.2.2).

Rock mass weathering in tropical environments has been described for most intact rock and rock masses that occur in Malaysia, i.e. granite (Komoo, 1985; Raj, 1985; Ghiasi et al., 2009; Chigira et al., 2011; Mohamad et al., 2011), sandstone/shale (Mohamed et al., 2007; Mohamad et al., 2008), limestone (Pauzi et al., 2011) and schist (Zauyah and Stoops, 1990). Most of the studies are related to the weathering effect on the physical and geotechnical properties of rock (such as durability, modulus of elasticity, compressive strength), mineralogical changes, and characterization of the weathering profile. Generally, they conclude that weathering has a significant effect on the rock geotechnical and physical properties, and results in deep weathering profiles. Relations between weathering and time are not mentioned in these studies. Mohamed et al. (2007) compare physical deterioration differences between sandstone and shale, and Rodeano et al. (2006) and Ismail et al. (2009) describe engineering properties of fresh and weathered sandstone in the Kota Kinabalu area.

3. Slope rock mass weathering with time

Rock mass weathering affects the durability of a rock slope after excavation (Hack and Price, 1997; Yokota and Iwamatsu, 2000; Hack et al., 2003; Borrelli et al., 2007; Hencher and Knipe, 2007). Weathering in cut slopes is controlled by internal, external and geotechnical parameters (Bland and Rolls, 1998; Huisman, 2006). Internal parameters are referring to the properties of rock materials, whereas external parameters are the environmental conditions, fluid chemistry, hydrodynamics of the site and biogenic activities. Slope design parameters (e.g. slope aspect, angle and height), method of excavation and drainage measures also influence the degradation of geotechnical properties.

3.1. Weathering intensity and weathering intensity rate

The relationship between rock mass response to the process of weathering and exposure time is expressed in two different terms; i.e. 'weathering intensity' and 'weathering intensity rate'. Weathering intensity refers to the degree of decomposition or amount of alteration from the original state shown by rock mass material at a certain point in time, whereas the weathering intensity rate refers to the amount of change in this weathering intensity per unit time (Bland and Rolls, 1998; Huisman, 2006). The weathering intensity and weathering intensity rate of a rock mass respond to the particular combination of conditions controlling weathering at the site of