A METHOD FOR ESTIMATING THE BACKWARD EROSION SENSIBILITY OF ROAD SLOPES

Nguyen Hong Hai, Nguyen Thi Phuong Khue

The University of Danang, University of Science and Technology; nhhai@dut.udn.vn

Abstract - Erosion is one of the main causes of instabilities within earth structures such as embankment dams, dikes, or road slopes. In this paper, a Jet Erosion Test (JET) and an energy approach to determine the sensitivity of interface erosion are presented. This paper focuses on the assessment the backward erosion sensibility of road slopes by overtopping. The erodibility is characterized by an erosion resistance index (Iα) which is calculated from a relationship with easily measurable physical parameters (degree of saturation, dry density, degree of compaction, water content ratio and clay fraction). The analysis is performed on eleven specimens collected from three cut slopes and one fill slope of four roads located in Quang Nam province and Danang city. In comparison with field observations, the results show that the potential for slope instability by backward erosion may be apparent when the value of the erosion resistance index is lower than 2.

Key words - Jet Erosion Test; backward erosion; erodibility; erosion resistance index; energy analysis.

1. Introduction

The interaction between water and earth structures as embankment dam, or highway slope can cause many damages. Erosion is one of the main causes of these instabilities. Two types of internal erosion processes can be distinguished: suffusion and interface erosion. The suffusion process concerns only the finer particles which are detached and then move inside the soil matrix which is composed of coarse particles. The interface erosion can appear in cracks or concentrated leaks and is then called piping (Fell & Fry, 2007). When the interface erosion appears between two materials with different grain size distributions, it is called contact erosion. In such case and with a seepage flow which is normal to the interface, the process is called backward erosion (Marot et al., 2014). Backward erosion is a phenomenon that usually occurs in road slopes (Figure 1)

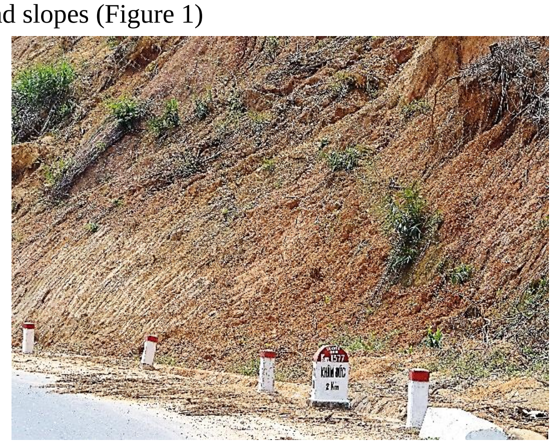

Figure 1. *Backward erosion of cut slope (Ho Chi Minh Highway - East branch)*

The erodibility of cohesive soils depends on many physique parameters of soil. Various researchers have developed different testing devices for characterizing the sensibility of interface erosion of fine soils (Briaud et al., 2001; Hanson and Cook, 2004; Wan and Fell, 2004). Among these testing devices, the Jet Erosion Test (JET) is commonly used because it can simplify studies low plasticity soils or on saturated soils. Another advantage of the JET is that it can be used on site and measure the intact resistance.

With the objective to estimate the backward erosion sensibility of soil slopes, this paper deals with the methodology to determine the sensitivity of slope erosion using JET. Using the erodibility classification proposed by Marot et al., (2011) and comparison with field observations showed that the classification allows estimating the slope instability potential by backward erosion.

2. Apparatus and analysis method

2.1. Principle of Jet Erosion Test

The JET was developed by Dunn (1959) and had been further improved by Hanson and Cook (2004). This apparatus is designed to apply a submerged water jet on the face of a soil specimen. Such an apparatus is described in the A.S.T.M. Standard D5852. In laboratory, soil specimens are compacted in a standard Proctor mold.

Figure 2 shows that the principles of the device. The jet test apparatus consists of an adjustable head tank, a jet tube with a nozzle, a point gage and a jet submerged tank which contains the specimen.

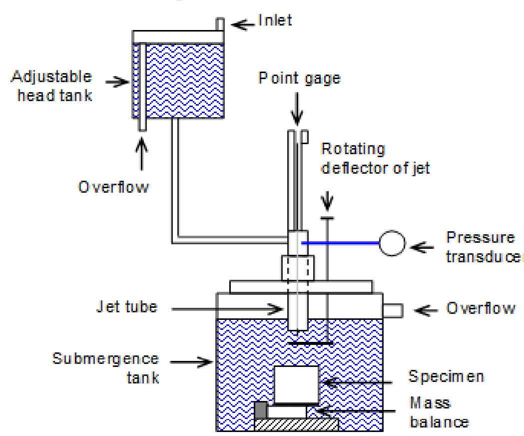

Figure 2. *Schematic diagram of the Jet Erosion Test device (Marot et al., 2014)*

The collected data during the test at specific times include: the depth of scour J measured from a reference level and the head applied to the nozzle, ΔH. Data are recorded at intervals chosen by the operator, depending on the erosion rate. Typical intervals range from 15 s to 30 min, with total test times of 2 hours or less. The device used for this study comprises also a mass balance which is placed under the specimen in order to measure the variations of specimen mass for the experiment duration.

2.2. Energy analysis

For the purpose of characterizing the sensitivity to erosion of soil interface, an erosion resistance index I_α, was proposed (Marot et al., 2011). It is based on the energy dissipation between the fluid and the soil.

$$I_\alpha = -\log\left(\frac{m_{dry}}{E_{erosion}}\right) \tag{1}$$

Where, m_{dry}– the eroded dry mass; $E_{erosion}$- the energy dissipated by erosion.

At J depth, erosion energy is assumed to come from the space defined by lateral distance from jet centerline r ≤ 0.14 J (see Figure 3). The energy dissipated by erosion ($E_{erosion}$) is the time integration of the instantaneous erosion power that can be determined by integrating equation (2) for the test duration.

$$\frac{dW_{erosion}}{dt} = \pi \int_0^{0,14J} \rho_w . u^3(0,J)\left\{\exp\left(-0,693\left(\frac{r}{b_u}\right)^2\right)\right\}^3 .r.dr \tag{2}$$

With: ρ_w- fluid density; r- horizontal distance from the jet axe; b_u- distance from centerline corresponding to a decrease of half vertical velocity [$u(b_u,J) = 0,5.u(0,J)$]:

$$b_u = 0,093(J - J_P) \tag{3}$$

Where: J- distance between soil/water interface and jet origin; J_P- the potential core length.

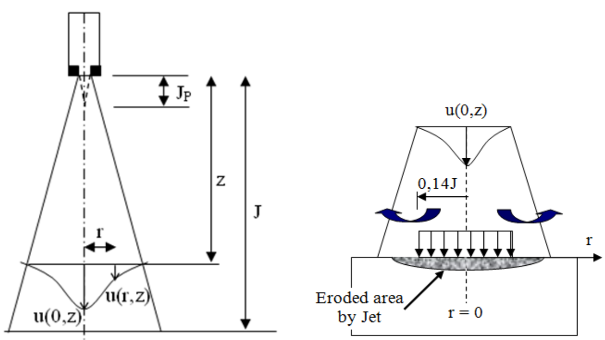

Figure 3. *Geometric description of the jet*

At t=0, the initial distance to the interface is written as J_0. At an infinite time, J tends to a limit the equilibrium depth J_e. For distances smaller than J_p=6.2 d_0, the flow consists of a potential core in which the velocity is equal to the initial velocity u(0,0) at the jet origin, and an outer zone where the axial velocity varies inversely with the distance (Hanson and Cook, 2004):

$$u(0,J) = \left(\frac{J_P}{J}\right).u(0,0) = \left(\frac{J_P}{J}\right).\sqrt{2.g.H} \tag{4}$$

Marot et al. (2011) proposed six categories of soil erodibility: highly erodible for $I_\alpha < 1$, erodible for $1 \le I_\alpha < 2$, moderately erodible for $2 \le I_\alpha < 3$, moderately resistant for $3 \le I_\alpha < 4$, resistant for $4 \le I_\alpha < 5$ and highly resistant for $I_\alpha \ge 5$.

3. Correlation between erosion resistance index and soil physical parameters

It is useful to estimate soil erodibility by physical parameters that may be easily measured. A series of tests using clayey sands and different fine-grained soils was performed by JET. A statistical analysis is performed in order to identify the main parameters for a correlation with erosion resistance index. Based on a parametric study on 114 sets of test data, a correlation between erosion rate index determined by JET and 4 physical parameters was proposed for fine grained soils (Nguyen, 2012).

The predictive equation was realized by XLstat software:

$$\begin{aligned} I_\alpha &= -0,65 + 1,97.10^{-2} S_r + 1,53\left(\rho_d / \rho_{d\max}\right) \\ &+ 1,60\Delta w_R + 1,56.10^{-2} F_a \quad (R^2 = 0,63) \end{aligned} \tag{5}$$

where: S_r- saturation ratio; ρ_d- dry density of the soil; (ρ_d/ρ_{dmax})- degree of compaction; $\Delta w_R=(w-w_{opt})/w_{opt}$- water content ratio; w- water content of compaction; w_{opt}- water content of Proctor optimum; Fa- clay fraction (percentage of fine particles smaller than 2μm).

4. Estimating the backward erosion sensibility of soil slopes

4.1. Study sites

Four soil slopes used in this study are three cut slopes and one fill slopes of four roads located in the province of Quang Nam (Ho Chi Minh Highway, West branch at Km486+887 and Km493+850, named HCM; DT611 road at Km23+670, named DT611) and Danang city (14B Highway named QL14B; DT602 road named DT602). The location map of study sites is given in Figure 4.

Figure 4. *Location map of the study sites*

4.2. Field and laboratory determination of soil properties

The properties of the four soil samples collected from the field are given in Table 1.

According to the classification by USCS and AASHTO, the soils are fine-grained and medium plasticity.

As shown in Figure 5, the values of optimal dry density for the normal Proctor compaction range between 12.07kN/m^3 and 16.10kN/m^3 for optimal water content between 21.2% and 34.3%.

The grain size distributions of the tested soils are plotted in Figure 6.

The natural density of slopes determined by the sand-cone method is given in Table 2. Relative compaction is ranging between 0.73 (DT602-1) and 0.86 (HCM-4, DT611-1)

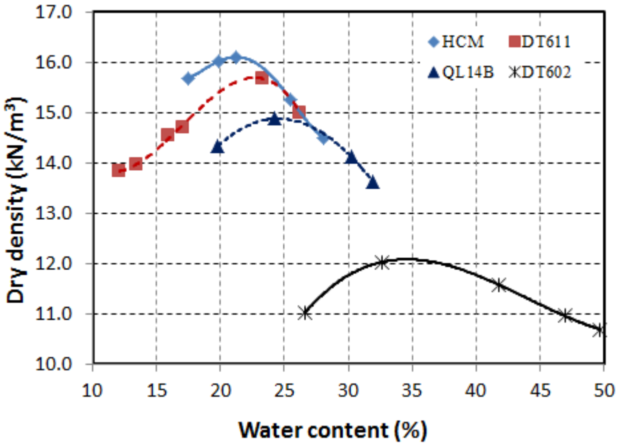

Figure 5. *Grain size distribution curves of soils tested*

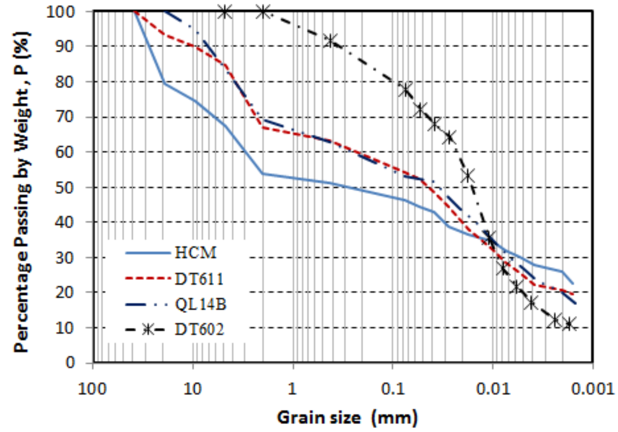

Figure 6. *Grain size distribution curves of soils tested*

Table 1. *Classification and properties of soils tested*

Soil reference	USCS (ASSHTO) classification	Atterberg limits		Normal Proctor state	
		LL (%)	PI (%)	ρ_{dmax} (kN/m^3)	wopt (%)
HCM	CL (A-7-6)	46.5	19.9	16.10	21.2
DT611	ML (A-7-5)	42.2	11.9	15.71	22.8
QL14B	ML (A-7-5)	44.8	13.4	14.88	24.2
DT602	ML (A-7-5)	54.5	13.8	12.07	34.3

Table 2. *Density of soil samples in-situ.*

Nb test	Sample reference	w (%)	γ_d (kN/m^3)	K=γ_d/γ_{dmax}	S_r (%)	I_α	*Classification	Field observations
1	HCM-1	13.0	13.66	0.85	37.56	1.21	erodible	Erosion
2	HCM-2	20.5	12.84	0.80	52.27	1.72	erodible	Erosion
3	HCM-3	25.7	13.29	0.83	70.17	2.16	moderately erodible	Not erosion
4	HCM-4	24.3	13.87	0.86	72.44	2.11	moderately erodible	Not erosion
5	DT611-1	32.8	13.56	0.86	93.36	3.54	moderately resistant	Not erosion
6	DT611-2	27.6	13.27	0.84	75.13	3.14	moderately resistant	Not erosion
7	QL14B-1	21.8	10.93	0.74	41.51	1.45	erodible	Erosion
8	QL14B-2	20.1	11.71	0.79	43.15	1.41	erodible	Erosion
9	QL14B-3	25.0	12.02	0.81	56.32	1.77	erodible	Not erosion
10	DT602-1	36.8	8.76	0.73	49.19	2.21	moderately erodible	Not erosion
11	DT602-2	31.6	9.05	0.75	44.40	1.90	erodible	Not erosion

**Classification according to Marot et al. (2011) soil erodibility system.*

4.3. Results and discussion

The erosion resistance index (I_α) calculated by equation (3) for eleven samples are given in Table 2. The values range between 1.21 (HCM-1) and 3.54 (DT611-1). Using the soil erodibility classification proposed by Marot et al. (2011), six specimens are classified erodible, three specimens are classified moderately erodible and two specimens are classified moderately resistant.

In comparison with field observations, a similarity is found between the erodible classification system according to Marot et al. (2011) and visual observation of erosion processes on the natural slopes.

Four samples collected from Ho Chi Minh highway cut slope, two specimens classified as erodible and two others classified as moderately erodible. Field observation shows that the erosion occurs at two positions classified as erodible and the erosion does not occur at two positions classified as moderately erodible.

For DT611 road cut slope, two specimens tested are classified as moderately resistant and the field observation shows that the erosion did not occur on the slope.

For the 14B highway fill slope, all the three positions tested are classified as erodible. However, by means of field observation we find that it has one position where the backward erosion process (QL14B-3) does not occur. It may be explained by effects of degree of saturation with water content at wet side of optimum (Nguyen, 2014). A similar result is obtained on the test of DT602-2 specimen of the DT602 road cut slope.

5. Conclusion

Backward erosion is one of the main causes of slope instabilities resulting from overtopping flow. In order to characterize the sensitivity to backward erosion of road slopes, a classification system based on the erosion resistance index proposed by Marot et al. (2011) is available. The erosion resistance index may be determined directly by Jet Erosion Test and an energy approach. For the engineering practice, the correlation between the erosion resistance index and soil physical parameters is also efficient in the case of preliminary study.

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