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Pinhole test for identifying susceptibility of different horizons in loess-derived soils to piping erosion

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Abstract: The pinhole test is an empirical test based on the qualitative evaluation of the dispersivity (colloidal erodibility) of compacted fined-grained soils. This study evaluates the pinhole test device for the quantitative assessment of the susceptibility of soil horizons to piping. The experiments performed on different loess-derived soil horizons, with different hydraulic head and using distilled water show that the clay-enriched horizon (*Bt* horizon) is less susceptible to piping than the decalcified (*C1*) and the calcareous horizon (*C2*). This study demonstrates that the pinhole test is suitable for assessing the susceptibility of soil horizons to piping in a quantitative way.

Keywords: pinhole test, subsurface erosion, hydraulic head, antecedent soil moisture content, water quality

Introduction

Piping or tunnel erosion is defined as: "the hydraulic removal of subsurface soil, causing the formation of underground channels in the natural landscape" (Boucher 1990).

Gully erosion research in Europe prior 1980 was mainly focused on Hortonian infiltration-excess model for runoff generation, while subsurface erosion was considered of little importance compared to sheet and gully erosion. However, over the last decades it has become clear that piping also plays an important role in gully development, inducing high soil losses (Poesen 1989, Bocco 1991, Poesen et al. 2003). Bocco (1991) noted that subsurface erosion, and particularly piping, was an important factor in gully development and Higgins (1990) regarded piping as a source of "many, if not most" gullies in the Mediterranean climate in California. Nowadays, piping-induced rill and gully development is accepted as a critically important soil erosion process in a wide range of European environments (Faulkner 2006). Several authors have described how piping can play a major role in gully erosion on the collapsible or destructured loess soil (Faulkner 2006). Poesen (1989) and Poesen et al. (1996) have recognised the role of loess in Belgium, particularly in historical gully erosion.

However, quantitative data on the susceptibility of soils and soil horizons to piping and the contribution of piping to sediment yield are scarce. Therefore, this research aims at evaluating the pinhole test device for the assessment of the susceptibility of soils to piping and the hydrological and erosion response of different loess-derived soil horizons (undisturbed samples): i.e. a *Bt* horizon, decalcified loess (*C1* horizon) and calcareous loess (*C2* horizon).

Materials and methods

The pinhole test device is a laboratory test for direct measurement of the dispersibility and erodibility of fine-grained soils, using a flow of water passing through a small hole in a soil specimen (Sherard et al. 1976). Dispersibility is assessed by observing effluent colour and changes of flow rate through the hole, measuring sediment concentrations in the effluent and by visual inspection of the hole after completion of the test. Undisturbed samples of *Bt* horizon, decalcified loess (*C1* horizon) and calcareous loess (*C2* horizon) are taken (steel cylinders were inserted horizontally into the wall) and analysed with the pinhole test device using distilled water (EC, 26 μS cm^{-1}) and 4 hydraulic heads (50, 180, 380 and 1020 mm). Pipe flow discharge (Q_w, cm^3 s^{-1}) and sediment discharge (Q_s, g s^{-1}) are measured and, in this way, the erodibility of the soil horizon is evaluated.

Moreover, initial moisture content (%) and bulk density (g cm^{-3}) were determined for each soil sample (Copecki rings, stainless steel rings, 98.17 cm^3).

A preliminary investigation (Nadal-Romero et al. 2011) indicates that the pinhole test is suitable for assessing the susceptibility of soils to piping in a quantitative way. Moreover, this investigation concluded that it is necessary to use distilled water, to determine realistic values of hydrological and erosion parameters and to compare different soils.

Study sites and loess-derived soil horizons

The study area is located in the Belgian loess belt, which forms part of the large European loess belt. Soil sampling was done in two locations. At site A (Korbeek-Dijle) the *C1* and *C2* horizon were sampled and at site B (Heverlee) only the *Bt* horizon was sampled at 0.40–0.60 m. The grain sizes of the different loess horizons show distinct distributions (Table 1).

Table 1. Texture, gravimetric moisture content (*MC*), dry bulk density (*BD*) and $CaCO_3$content of the undisturbed loess-derived soil horizons studied

Soil horizons	% Clay (0–2 μm)	% Silt (2–63 μm)	% Sand (>63 μm)	MC (%)	BD (g cm^{-3})	$CaCO_3$ (%)
Bt	20	74	6	22.2	1.37	0
C1	20	73	7	21.2	1.34	0
C2	9	88	3	20.7	1.34	14.6

The texture is silty-loam for the *Bt* horizon (clay-enriched horizon) and the decalcified loess (*C1* horizon) and silty for the calcareous loess (*C2* horizon). Calcareous loess contains up to 14% calcium carbonate which is present primarily as detrital grains.

Results

The first results of several pinhole experiments performed on undisturbed samples from different loess-derived soil horizons (*Bt*, *C1* and *C2*) with a high soil moisture content around 20% (Table 1) at different hydraulic heads (*H*) for distilled water are shown in Figure 1 and Figure 2 and mean values are summarized in Table 2.

Figure 1 shows pipe flow discharge (Q_w, cm^3 s^{-1}) through the specimen during an experiment lasting for five minutes:

1. during a test with a constant *H*, Q_w increased due to pipe erosion;
2. an increase in Q_w was also observed with increasing *H*.

Figure 2 shows the sediment discharge (Q_s, g s^{-1}) through the specimen during an experiment lasting for five minutes:

1. an increase in Q_s was observed during a test and also with increasing *H*;
2. significant differences between different horizons were observed.

Figure 3 shows the relationships between hydraulic head and mean flow discharge (*A*) and mean sediment discharge (*B*):

1. a linear increase in mean Q_w and Q_s was observed when increasing *H*;
2. the relationship between *H* and Q_w was stronger for *C1* (R^2 = 0.9958) than for *Bt* and *C2*;
3. the relationship between *H* and Q_s was much stronger for *Bt* (R^2 = 0.9232) than for *Bt* and *C2*.

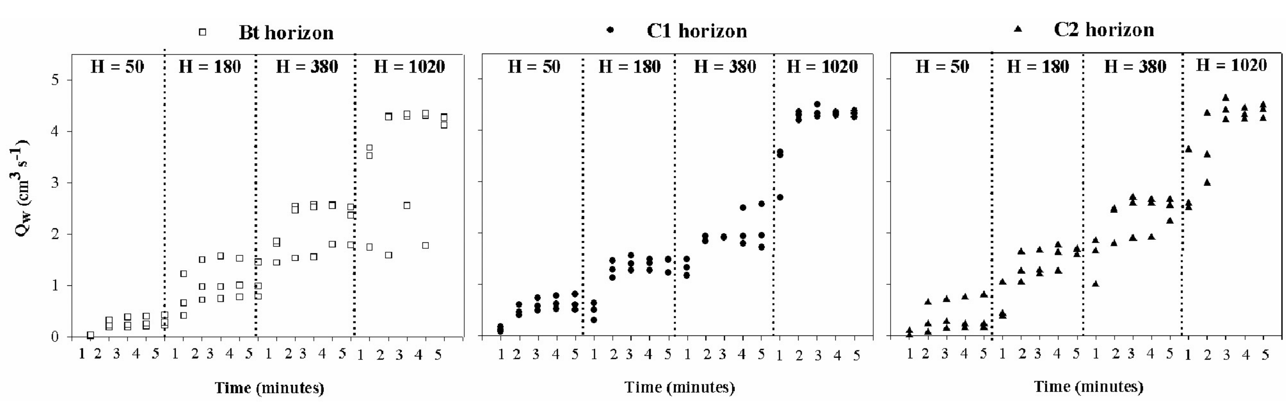

Fig. 1. Pipe flow discharge (Q_w) at different hydraulic heads (*H*) for different loess-derived soil horizons during a five minute experiment

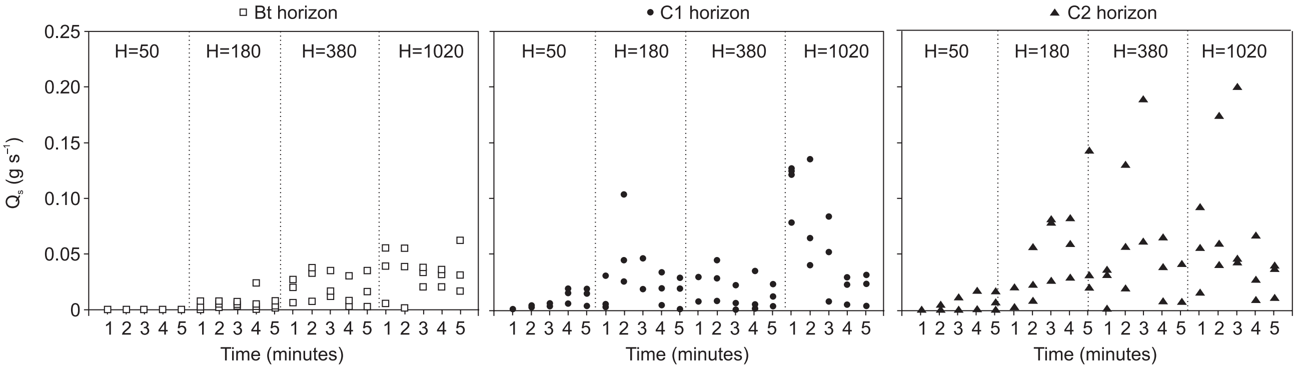

Fig. 2. Sediment discharge (Q_s) at different hydraulic heads (H) for different loess-derived soil horizons during a five minute experiment

Table 2. Mean pipe flow discharge (cm^3 s^{-1}) and sediment discharge Q_s (g s^{-1}) at different hydraulic heads (H)

H	Bt horizon		C1 horizon		C2 horizon	
	Q_w (cm^3 s^{-1})	Q_s (g s^{-1})	Q_w (cm^3 s^{-1})	Q_s (g s^{-1})	Q_w (cm^3 s^{-1})	Q_s (g s^{-1})
50 mm	0.29	0.00008	0.23	0.007	0.48	0.004
180 mm	1.29	0.006	1.02	0.03	1.19	0.04
380 mm	2.19	0.02	2.13	0.02	1.86	0.05
1020 mm	3.91	0.03	3.56	0.05	4.11	0.06

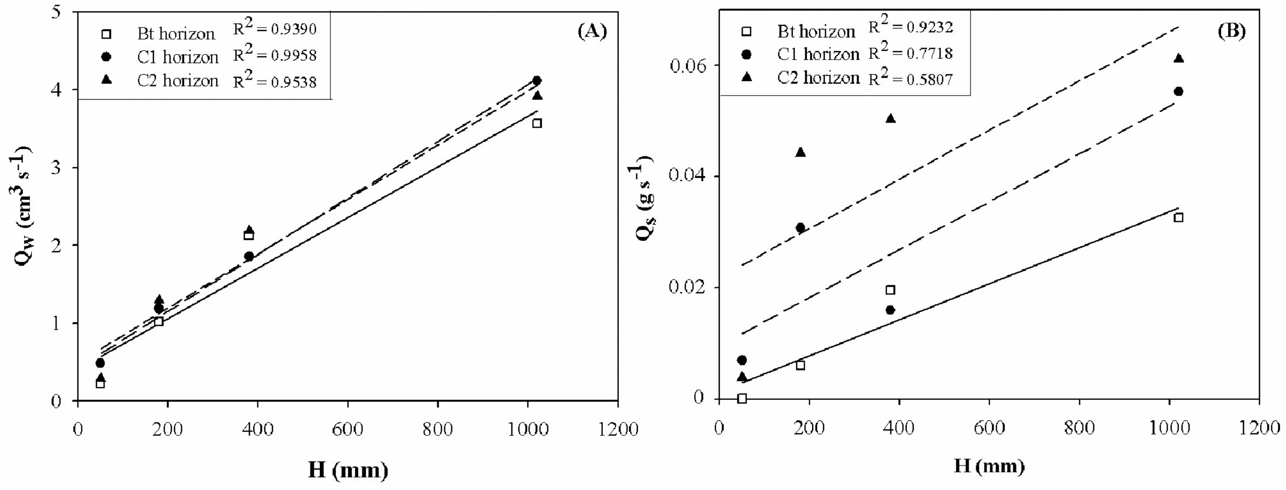

Fig. 3. Relationships between H, and mean Q_w (A) and mean Q_s (B) for different loess-derived soil horizons during a five minute experiment

The statistical analysis (ANOVA) undertaken using the mean Q_w and Q_s values suggests that:

1. statistical significant differences (0.05 level) are observed between mean Q_w and Q_s values and the different hydraulic heads used (p-value are 0.000 and 0.042 respectively).
2. no major differences are observed between mean Q_w values corresponding to the different loess-derived soil horizons.
3. for mean Q_s values, although values are not statistically significant (0.05 level) smaller differences exist between mean Q_s values corresponding to loess-derived soil horizons (p-values = 0.351).

Discussion and conclusions

In a wide range of European environments, piping is considered to be a critically important soil erosion process (Faulkner 2006), and it is known to play an important role in gullying, including high soil losses (Poesen 1989, Bocco 1991, Poesen et al. 2003). However, little or no quantitative information is available on the resistance of various loess-derived soil horizons to piping erosion. This preliminary investigation indicates that the pinhole test is suitable for assessing the susceptibility of loess-derived soil horizons to piping in a quantitative way.

The first results of several pinhole experiments performed on loess-derived soil horizons (*Bt* horizon, decalcified loess *C1* horizon, and calcareous loess, *C2* horizon) on undisturbed samples indicate an increase in mean pipe flow discharge and sediment flow discharge with increasing hydraulic head. Quantitative data on the susceptibility to piping erosion of different loess-derived soil horizons indicate that the *Bt* horizon is at least two times more resistant than the *C1* and *C2*. In this way, the analyses showed that the calcareous loess (*C2* horizon) and decalcified loess (*C1* horizon) tested have a high susceptibility to piping as they could be ranked as *D2* (dispersive), showing high susceptibility to piping, more than the *Bt* horizon, ranked as *ND4* (non-dispersive) based on the classification of Sherard et al. (1976).

Susceptibility to piping is influenced by soil texture (e.g. Jones 1971). Field observations reveal that the presence of $CaCO_3$ in the silt and clay fractions of the loess increases its susceptibility to gully erosion which is in accordance with observations made by several investigations (Peele et al. 1938, Barahona et al. 1990, Nachtergaele & Poesen 2002).

This study provides quantitative information on the piping erosion resistance of a typical soil profile developed on loess. These results and the validation of the findings help to better predict where future piping may occur.

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