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Reactivation of old landslides: lessons learned from a case-study in the Flemish Ardennes (Belgium)

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Abstract

The number of human-induced landslides is increasing worldwide, but information on the impact of human intervention on slope stability is often lacking. Therefore, this study analyses the Hekkebrugstraat landslide, the best-recorded landslide in the Flemish Ardennes (Belgium). Information obtained from local inhabitants, aerial photographs and newspaper articles enabled a 50-year reconstruction of both the landslide history and the land-use changes at or close to the landslide site. The reconstruction suggests that anthropogenic preliminary factors such as: (i) the absence of well-maintained drainage ditches in the affected area; (ii) the elevation of the surface of the road, i.e. a sunken lane, in the affected area; (iii) increased surface runoff from the drainage area; (iv) the creation of ponds; and (v) the removal of the lateral support at the landslide foot have played an important role in the reactivation of the Hekkebrugstraat landslide. After the reactivation of February 1995, landslide movement was observed for more than 5 years and caused damage to houses, and other infrastructure. However, also natural factors, such as the presence of an impermeable clay layer at limited depth, springs and relatively steep slopes (i.e. 0.14 m m^{-1}), and above normal antecedent rainfall have contributed to the reactivations. Comparison of our reconstruction of the reactivation with precise Digital Terrain Models (DTMs) of 1952, 1973 and 1996, produced by digital stereophotogrammetry, indicated that the reported movements correspond well with the uplifted and collapsed zones found on the DTMs. Hence, this analysis provides valuable information for land-use planners in areas with old, apparently stable, landslides.

Keywords: Old deep-seated landslide, landslide reactivation, anthropogenic causal factors, land-use change, damage

Introduction

In many places in the world, human activities have to face natural hazards (e.g. Berz *et al*., 2001; McGuire *et al*., 2004). Landslides are generally recorded in mountain areas (e.g. Glade, 1998; Dhakal *et al*., 1999; Temesgen *et al*., 2001; Henry *et al*., 2002; Guzzetti *et al*., 2003; Vanacker *et al*., 2003; Ayalew & Yamagishi, 2005; Knapen *et al*., 2006), but also in hilly regions (e.g. Hutchinson, 1967; Marre, 1987; Schmidt & Dikau, 2004). In hilly parts of Belgium, landslides cause damage to buildings and other infrastructure (Halet, 1904; Lefèvre, 1926–1927; Vanmaercke-Gottigny, 1980; Demoulin *et al*., 2003; Ost *et al*., 2003; Demoulin & Glade, 2004; Van Den Eeckhaut *et al*., 2005, 2006). In one of the affected regions, the Flemish Ardennes (Figure 1), more than 150 deep-seated landslides have been recorded (Van Den Eeckhaut *et al*., 2005, 2006), here defined as movements on slopes with a minimum estimated shear plane depth of 3 m and an affected area generally larger than 1 ha. As no historical documents reporting the initiation of one of these landslides has been found, the landslides are assumed to be at least 100 years old, but detailed dating is needed to obtain more information on their age. About 70% of these deep landslides are currently inactive, and are classified as dormant (Van Den Eeckhaut, 2006). They are located under forest relatively far from human intervention, and have brooks or drainage ditches evacuating the water from springs at the base of the main scarp. The other approximately 30% of the landslides have been more active (Van Den Eeckhaut, 2006), i.e. one or more reactivations have occurred over the last few

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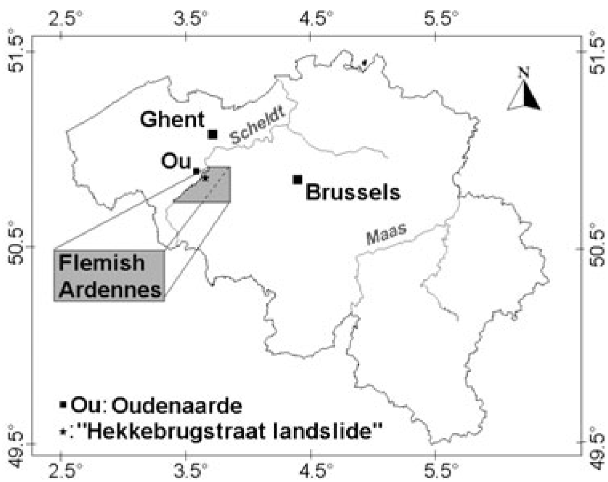

Figure 1 Location of the Flemish Ardennes in Belgium and the Hekkebrugstraat landslide.

decades. Such reactivations were often related to human intervention on the marginally stable hillslope sections, and generally occurred after periods with a monthly rainfall exceeding 100 mm and a 12-month antecedent rainfall exceeding 1000 mm (Van Den Eeckhaut, 2006).

Because of the close location to cities, such as Ghent and Brussels (Figure 1), the Flemish Ardennes, especially its forested hillslopes, has become an attractive residential area. Due to the increasing residential development in the hilly areas, the severity of the problems related to the reactivation of landslides is expected to worsen. Most newcomers are not aware of the presence of landslides in the region, and they do not realize that their intervention may affect the stability of a site. At present, however, little information on the effect of human intervention on the reactivation of deep-seated landslides is available for the Flemish Ardennes.

This study aims at a better understanding of the human influence on the reactivation of landslides. It focuses on the Hekkebrugstraat landslide (Figure 1). From a morphological and lithological viewpoint, this landslide is representative of the majority of deep-seated landslides in the Flemish Ardennes. Its uniqueness is that both landslide activity and land-use changes at and near the affected area are relatively well recorded for the last 50 years. During this period the Hekkebrugstraat landslide has reactivated several times, with a major event in 1995. The main objective of this study was to gain information on the natural and anthropogenic factors that are responsible for the reactivation of the Hekkebrugstraat landslide.

Materials and methods

Study area

Landslides were investigated in a 430 km^2 study area in the Flemish Ardennes (Figure 1). The region has a maritime temperate climate, with a mean annual rainfall of 800 mm, which is well distributed over all seasons. The regional topography, lithology and hydrology are important environmental factors controlling slope stability. The Flemish Ardennes is a hilly region characterized by altitudes ranging from 10 m a.s.l. in the valley of the river Scheldt to 150 m a.s.l. on the Tertiary hills, located east of the river Scheldt. Hillslope gradients are generally less than 0.15 m m^{-1}. Due to the systematic valley asymmetry, slopes facing from south through to northwest are steeper than the slopes facing in other directions. Several active faults are suspected within and at the boundaries of this region (De Vos *et al*., 1993). The geological deposits closest to the soil surface consist of Quaternary eolian loess underlain by loose Tertiary sediments. Sub-horizontal, almost impermeable clay layers alternate with more permeable clayey sand layers (Jacobs *et al*., 1999). Due to this alternation, perched water tables build up, and springs occur where water tables rise to the surface. Cropland is located on the loess-covered plateaus of the lower hills, and pastures dominate the hillslopes. The highest loess-free Tertiary hills and the steepest hillslopes are forested (IWONL, 1987).

This study focuses on the Hekkebrugstraat landslide (Figures 1 and 2), for which landslide activity over the last 50 years has been recorded through observation by local residents. According to the classification of Cruden & Varnes (1996), the Hekkebrugstraat landslide is a rotational earth slide, which is larger in area than the 'average' deep-seated landslide in the region (Table 1). The affected area is 7.1 ha, and the total volume of debris displaced by the landslide is estimated between 215 000 and 450 000 m^3. At present, the main scarp, located at 70 m a.s.l., is approximately 8 m high and sub-vertical (Figure 2b). The southwest orientation of the landslide and the lithological characteristics are both typical. On a cross-section through the landslide (Figure 3), three Tertiary sediment layers and one debris layer can be distinguished. The main scarp is located in the Tielt Formation (Tt). These consist of alternations of micaceous and glauconitic clayey sands with a clay content of approximately 29% (Van Den Eeckhaut, 2006), and thin clay layers. Below these clayey sands, 10-m thick homogeneous blue massive clays (i.e. clay content of 55%, Van Den Eeckhaut, 2006) of the Kortrijk Formation, Aalbeke Member (KoAa) crop out at an altitude of approximately 55 m a.s.l. This layer acts as an aquiclude giving rise to springs at the interface with the more permeable Tielt Formation above. According to Mercier-Castiaux & Dupuis (1990) the clays of both the Tielt Formation and the Aalbeke Member are rich in smectites. The lowest lithological layer, the Moen Member (KoMo) is a coarse clayey silt or fine sand with small clay intercalations (Jacobs *et al*., 1999). The landslide debris consists of a mixture of materials from the Tielt Formation and Aalbeke Member. Due to persistent soil erosion by water in the upslope contributing area, only a thin layer of silt loam still covers the Tielt Formation on the plateau.

Table 1 Characteristics of the Hekkebrugstraat landslide compared with the 'average' characteristics of 153 deep-seated landslides mapped in the Flemish Ardennes, using the terminology proposed by the IAEG Commission on Landslides (1990)

	Hekkebrugstraat landslide	Average landslide
Landslide characteristics		
Total affected area (ha)	7.1	4.0 ± 4.6
Width of surface of rupture (m)	230	215 ± 160
Total landslide length (m)	380	185 ± 160
Height of main scarp (m)	8	8.5 ± 3.5
Depth of surface of rupture (m)	10–15[a]	10–15[b]
Volume of displaced material (m^3)	215 000–450 000	95 000–143 500
Environmental characteristics		
Average hillslope gradient of total affected area ($m\ m^{-1}$)	0.14	0.16 ± 0.05
Slope aspect	SW	S to NW
Lithology of landslide main scarp	Tt/KoAa	Tt/KoAa
Lithology of landslide foot	KoAa/KoMo	KoAa/KoMo

SW: southwest; S to NW: south to northwest; Tt: Tielt Formation; KoAa: Aalbeke Member, Kortrijk Formation; KoMo: Moen Member, Kortrijk Formation.
[a]Estimate based on geotechnical measurements carried out by Geotechniek (DOV Vlaanderen, 2005).
[b]Estimate based on resistivity measurements (Van Den Eeckhaut, 2006) and geotechnical measurements carried out by Geotechniek (DOV Vlaanderen, 2005)

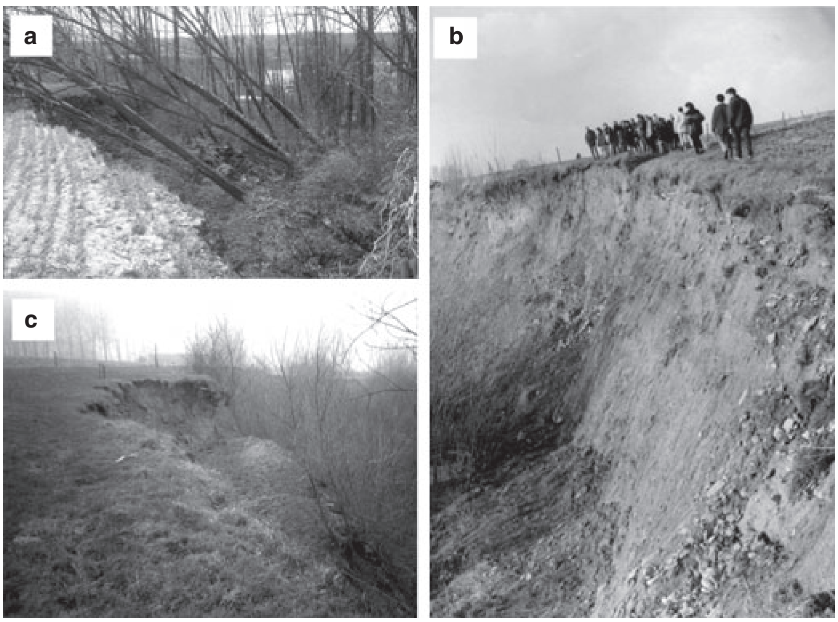

Figure 2 The Hekkebrugstraat landslide: (a) main scarp retreat in February 1995. The loading of the tilted block, indicated by tilted poplar tree stems, reactivated the debris in the accumulation zone. Note the sealed soil surface upslope of the main scarp producing large volumes of surface runoff during the prolonged rainfall events in the winter of 1994–1995; (b) 8-m-high main scarp in March 1999 (photo by J. Reyniers); (c) main scarp retreat in January 2003.

Reactivations of and land-use changes at and near the Hekkebrugstraat landslide

Information on both the reactivation of the Hekkebrugstraat landslide and the human-induced land-use changes was obtained from historical topographical maps, through aerial photo interpretation, by interviewing four local residents and from newspaper articles published between 1988 and 2003. Four historical maps were used in this study, the Ferraris map (1771–1777), the map from 'The atlas of the rural roads' (1841) and the topographical maps of 1948 (1:25 000; NGI) and 1972 (1:10 000; NGI). These maps provided information on the land use and land-use changes in and around the landslide area during the last 230 years. More detailed information on land-use changes over the last 50 years was obtained from analyses of aerial photographs taken in 1952 (1:25 000; NGI) and 1996 (1:20 500; NGI). Additional information came from field observations.

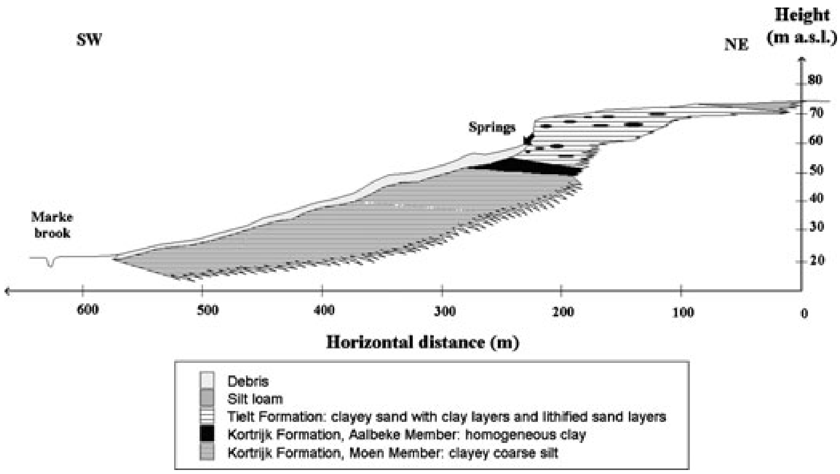

Figure 3 Cross-section through the Hekkebrugstraat landslide with indication of the lithology (after Gulinck, 1966).

The causal factors that have contributed to the reactivation of the Hekkebrugstraat landslide were subdivided into preliminary and triggering factors following Crozier (1986), Popescu (2002) and Glade & Crozier (2005). Preliminary causal factors result in marginally stable slopes, which are susceptible to movement without actually initiating it. For the Hekkebrugstraat landslide natural preliminary factors are topography (i.e. slope gradient and slope aspect), lithology (i.e. relatively permeable clayey sands of Tielt resting on almost impermeable clays of Aalbeke; Figure 3) and hydrology (i.e. presence of springs). However, probably also anthropogenic preliminary factors have contributed to its reactivation. On the other hand, triggering causal factors, such as intense or prolonged rainfall, shift the slope from a marginally stable to an actively unstable state, and thus initiate slope movement.

Microtopographical changes of the Hekkebrugstraat landslide over the last 50 years

Recently, detailed information on the microtopographical changes of the Hekkebrugstraat landslide during the last 50 years was obtained by Dewitte & Demoulin (2005) and Dewitte (2006) from the comparison of precise Digital Terrain Models (DTMs) of 1952, 1973 and 1996. These DTMs were produced by digital stereophotogrammetry using aerial photographs at scales between 1:18 500 and 1:25 000 (NGI, 1952, 1973, 1996). Accuracies (root mean square error) of approximately 65, 55 and 50 cm were obtained for the DTMs of 1952, 1973 and 1996. By subtracting successively the DTM of 1973 from that of 1952, and the DTM of 1996 from that of 1973, maps showing the vertical displacements, i.e. both collapsed and uplifted parts, were obtained for the periods 1952–1973 and 1973–1996. These maps are produced with a confidence interval of 68.3% (i.e. $\pm$75 cm), which means that only differences in altitude of 75 cm or more are considered as significant.

Results and discussion

Reactivations of, and land-use changes at and near the Hekkebrugstraat landslide

This section provides a chronological overview of both the recorded landslide reactivations and the human-induced land-use changes, which are believed to have contributed to the reactivations. As these human interventions affect slope stability by either increasing shear stress or decreasing shear strength (Selby, 1993) the recorded interventions are classified according to their influence on shear stress or shear strength.

Landslide history prior to 1950

Although the emphasis is put on the landslide history during the last 50 years, a short overview of the available information on both the Hekkebrugstraat landslide as well as the land use prior to 1945 is relevant. For this purpose, two historical maps, the Ferraris map of 1771 (Figure 4a) and the map from 'The atlas of the rural roads' (1841) were analysed. On the Ferraris map, there is no indication of a landslide (Figure 4a). At the end of the 18th century, the area currently affected by the landslide was forested, while the upslope contributing area was under cropland or pasture. The fact that the Hekkebrug road is indicated by a thick brown line on the Ferraris map suggests that the road was a sunken lane, and that the hillslope was well drained preventing topsoil saturation. Although the landslide is not shown on the Ferraris map, there are three reasons to believe that the hillslope had already failed at that time. The first is that none of the 152 other large landslides mapped in the study area are shown on this map. Secondly, there is a lack of historical documents describing the initiation of the landslide. As it is located only 2 km from the city of Oudenaarde (Figure 1), and as in 1771 there were already six houses within less than 500 m of the present-day landslide (Figure 4a), it is very unlikely that the

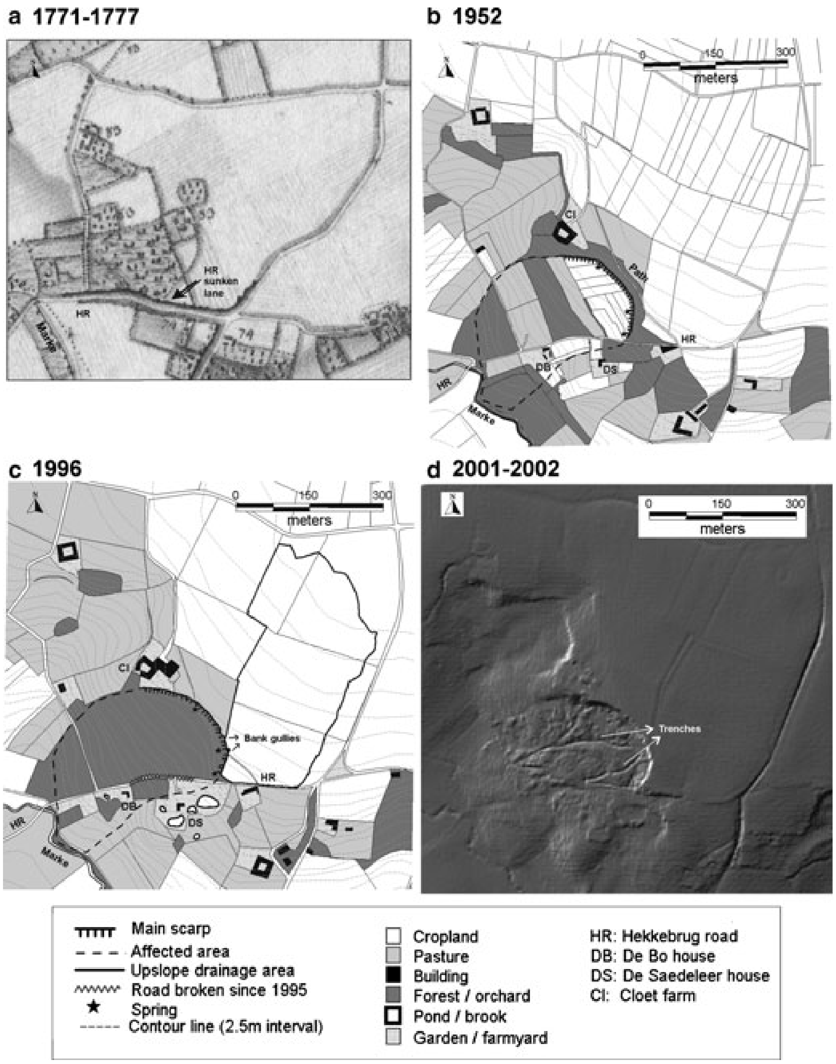

Figure 4 The Hekkebrugstraat landslide site: (a) excerpt of Ferraris map (1771–1777); (b) situation around 1952 based on aerial photograph interpretation; (c) situation around 1996 based on aerial photograph interpretation; (d) topography around 2001–2002 shown on LIDAR-derived hillshade map (DEM of Flanders, 2005).

initiation would have post-dated 1771 without having been reported. The third reason is that, in contrast to most surrounding hillslope sections, which were used as either cropland or pasture, the site itself was forested. This strongly indicates that the microtopographical or hydrological conditions of the site were not suitable for agricultural activities.

The map taken from 'The Atlas of the rural roads' (1841) only shows roads and field plots. The curved shape of both the plots downslope and the footpath upslope of the present-day main scarp location, suggest the presence of a main scarp which means that the hillslope had already failed by that time. The affected area was at least partly cultivated as the depletion area was divided into small plots.

Influence of human activities prior to landslide reactivation of 1995

From 1950, more detailed information is available from aerial photographs and interviews with local inhabitants. Undoubtedly, there was a landslide, and the affected area was partly cultivated (Figure 4b). However, cultivation within the depletion area was only possible because of a judicious system of well-maintained ditches draining the water from the springs at the base of the main scarp. Also the pastures in the accumulation area, downslope of the small plots, were drained by small subsurface drainage pipes. In 1955, the agricultural activities in the depletion area stopped, together with the maintenance of the drainage channels, and the entire affected area was planted with poplar trees. The reduced drainage resulted in the build-up of pore water pressures in the debris above the shear plane (Figure 5; Table 2).

Drainage was also hampered by road works. As mentioned before, the Hekkebrug road has been a sunken lane for centuries. Until the first half of the 20th century, this sunken lane acted as a drainage channel evacuating the water from the springs. Especially during winter, the road was muddy and inaccessible for vehicles. To increase road accessibility, improvement works were carried out among other

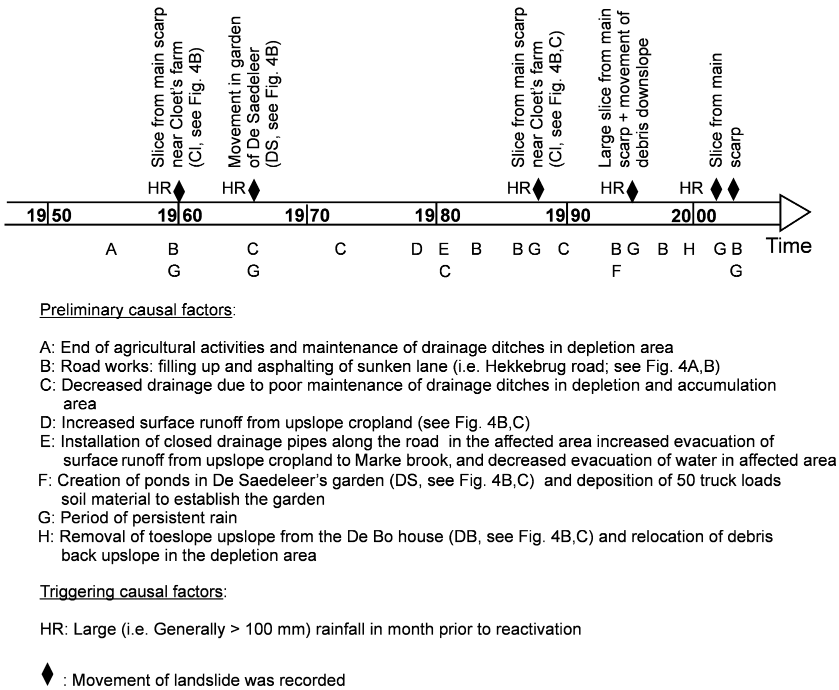

Figure 5 Preliminary and triggering causal factors responsible for reactivations of the Hekkebrugstraat landslide during the last 50 years.

dates in 1947, 1960, 1982, 1988, 1994 and several times after the reactivation of 1995. On each occasion, a new layer of stone bricks or asphalt was put on the previous one. In total, all these road improvements resulted in a road fill with a thickness of approximately 2 m. As a consequence, the Hekkebrug road lost its drainage function, and the excess water was stored in the debris layer in the depletion and accumulation area north of this road (Figure 5; Table 2).

After the cessation of agricultural activities in the depletion area in 1955, the trees along the main scarp were cut down. Because the roots were not removed, the root cohesion was conserved for a few years. According to O'Loughlin & Ziemer (1982), Selby (1993), Watson *et al.* (1999) and Sidle *et al.* (2006) half of the root cohesion is lost in 2–10 years after tree removal. It is probably not a coincidence that after several wet months in 1960, about 5 years after tree removal, a small slice fell off the main scarp (Figure 5) near the farm of Cloet (Figure 4b).

Comparison of Figure 4b,c indicates that in the area upslope of the Hekkebrugstraat landslide average plot size increased from 0.8 ha in 1952 to 2.6 ha in 2005. During intense rain storms, this increase in plot size and the growing of maize, which is characterized by higher runoff curve numbers (i.e. 88) than wheat (i.e. 84; Soil Conservation Service, 1972) caused an increase in surface runoff from the upslope drainage area towards the main scarp. This runoff was collected in the depletion area, because of the absence of effective drainage. In 1980, attempts were made to improve this drainage by installing closed 0.40-m diameter drainage pipes along the Hekkebrug road from the southern limit of the main scarp to the Marke brook (Figures 4c and 5; Table 2). These closed pipes replaced open drainage ditches alongside the road, so that the already limited drainage of water in the debris layer was even more restricted. The presence of two bank gullies in the main scarp (Figure 4c) and the occurrence of at least two muddy floods, covering De Bo's garden, indicated that the problem of the excess surface runoff from the upslope croplands had not been solved after the installation of the closed pipes.

Land-use changes at the site were not limited to changing farming practice and road improvement. In 1993, three large ponds, each having a diameter ranging from 10 to 40 m, were dug in De Saedeleer's hilly garden (Figures 4c and 6a,b). To establish the garden, the excavated soil was deposited on the hillslope together with about 50 truck loads of additional soil. As excavations result in oversteepened slopes, and addition of extra soil material causes overloading (Keaton & Beckwith, 1996; Figure 5; Table 2), the creation of ponds on inherent unstable slopes is not recommended. The water supply system was also inappropriate as it consisted of a series of cascades transporting the water from an upslope spring through the ponds without any provision for draining the water that was leaving the third pond. This water flowed freely into the meadows downslope, creating a wetland.

Apart from the reactivation of 1960, reactivations were also recorded in January 1966 and March 1988 (Figure 5). The 1988 event was similar to the one in 1960, and consisted of a limited reactivation of the main scarp. The 1966 event was located in the accumulation zone and caused only limited damage (i.e. cracks) in De Saedeleer's garden and to

Table 2 Factors contributing to the instability of the Hekkebrugstraat landslide by increasing the shear stress or lowering the shear strength

Factors contributing to	Type
High shear stress	**Overloading**
	Road fill (B)
	Weight of water (C, F)
	Weight of additional soil (F, H)
	Removal of lateral support
	Removal of toeslopes by human activity (H)
	Creation of ponds (F)
	Windblow of trees on main scarp
	Lateral pressure
	Water in ponds (F)
	Water in cracks
Low shear strength	**Composition and texture of lithology**
	Weak clayey material of Aalbeke Member Kortrijk Formation rich in smectite, and with low permeability
	Successive sub horizontal layers with different infiltration rates (i.e. surface layers with higher infiltration rate than underlying clays of Aalbeke Member Kortrijk Formation)
	Increase in pore water pressure
	Long periods of persistent rainfall (G)
	Intense rainfall (HR)
	Poor maintenance of drainage ditches (A, C)
	Land-use changes that reduce the effect of the original drainage (A, B, D)
	Vegetation
	Removal of trees

The letters A–H and HR refer to the preliminary and triggering causal factors reported in Figure 5.

the section of the Hekkebrug road located immediately upslope of this garden. Both reactivations occurred in periods with antecedent rainfall depths favourable for landslide reactivation (Van Den Eeckhaut, 2006; i.e. monthly rainfall >100 mm and 12-month cumulative rainfall >1000 mm; Table 3).

The 1995 reactivation and the human interventions following the failure

All anthropogenic interventions reported in the previous section (i.e. absence of drainage ditch maintenance, road fill, surface runoff from upslope and excavation of ponds; Figure 5) were important preliminary factors that put the Hekkebrugstraat landslide in a marginally stable state during the winter of 1994–1995. The resultant reactivation of the landslide started in early February of 1995. Rainfall was the most probable triggering factor (Table 3). The winter of 1994–1995 was the wettest of the 20th century. Compared with the long-term averages of 69 and 62 mm, respectively, 127 and 168 mm of rainfall were recorded in December 1994 and January 1995. These values are well above the threshold of 100 mm for landslide reactivation found by Van Den Eeckhaut (2006). The 12-month cumulative rainfall depth prior to the reactivation also exceeded the threshold of 1000 mm, but this was more a preliminary than a triggering factor. These unusually large rainfalls probably saturated the hillslope material above the Aalbeke clay (Figure 3) causing a decrease in the shear strength (Table 2). The rainfall would also have caused large volumes of surface runoff on the upslope croplands to flow towards the depletion area. Figure 2a, a photograph taken in February 1995, illustrates the sealed soil surface of these fields at the time of the landslide reactivation. Figure 2a also shows overloading of the main scarp by large 40-year-old, shallow rooting (USDA Natural Resources Conservation Service, 2001) poplar trees. The reactivation occurred during strong winds when some of these trees were blown out, dragging a slice of the main scarp about 140 m long (as measured along the main scarp; i.e. white area on Figure 6a) and approximately 15 m wide, 8 m downslope together with the footpath along the scarp (Figure 2a). The slice of land added approximately 25 000 t to the poorly drained debris layer. This increase in load together with the

Table 3 Rainfalls recorded at Oudenaarde (RMI, 2006) in the months prior to the recorded reactivations of the Hekkebrugstraat landslide

Reactivation recorded in	Normal (mm)	1-month (mm)	2-month (mm)	3-month (mm)	$\sum$ 6-month (mm)	$\sum$12-month (mm)
January 1966[a]	69	168.1	80.2	24.4	544.4	945.2
March 1988	53	135.6	84.2	131.9	479.1	1088.7
February 1995[a]	62	168.2	126.7	29.9	582.5	1014.8
March 2002	53	65.0	130.7	71.1	440.5	910.7
January 2003[a]	69	130.0	121.5	88.3	607.3	1081.2

Normal: long-term normal monthly rainfall recorded for the period 1951–1979; *i*-month: monthly rainfall depth recorded during the *i*th month prior to reactivation; $\sum j$-month: cumulative rainfall depth recorded during *j* months prior to reactivation.
[a]Rainfall analysis starts from month prior to month in which reactivation was recorded, because landslide reactivation occurred during first days of the month.

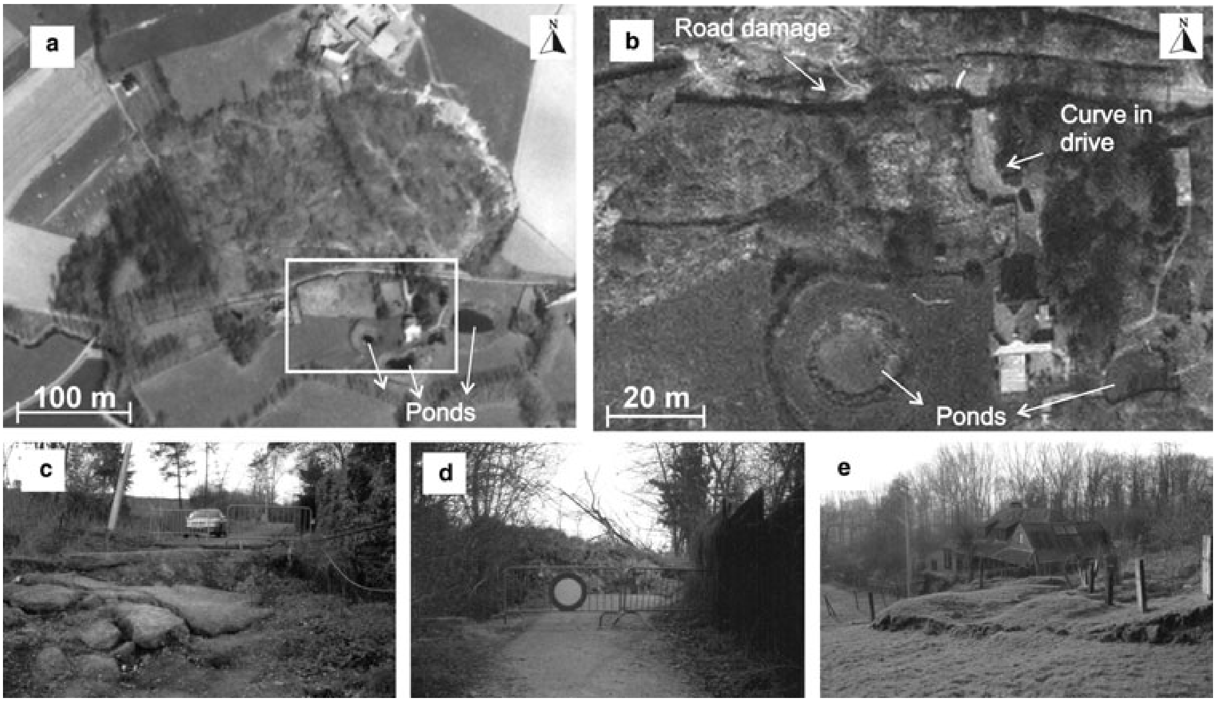

Figure 6 The Hekkebrugstraat landslide: (a) aerial photograph (NGI, 1996). White rectangle indicates enlarged area of De Saedeleer's garden (DS in Figure 4b,c) shown in (b); (b) detail of orthophoto (OC-GIS Vlaanderen, 1998) showing part of De Saedeleer's garden. In the north the road is damaged by debris. The curve in the drive is caused by the downslope movement of the debris. This movement occurred after April 1996, because the curve is not present on (a); (c) damage to the road and electricity lines (2001). In the back, the 8-m-high main scarp can be distinguished; (d) the downward movement of the debris blocked the road (2001); (e) since 1999, the landslide foot has been located only a few metres from De Bo's house (DB in Figure 4b,c).

high February rainfall (115.3 mm) was responsible for the reactivation of the movement in the affected area. By the end of February, the Hekkebrug road was destroyed (Figure 6c,d). The asphalt, stone bricks and drainage pipes had been pushed several metres downslope. Apart from the Hekkebrugstraat landslide, at least three other large, deep-seated landslides were reactivated in the Flemish Ardennes during the wet spring of 1995.

In September 1995, the 800 large poplar trees in the accumulation zone were cut and replaced by young poplar trees. As a consequence of the landslide reactivation, two buildings were threatened. Due to the scarp retreat a barn of the Cloet family became located only a few metres upslope from the main scarp, and De Bo's house was threatened by the foot of the approaching landslide (Figures 6e and 4).

In 1996, an attempt to dig a drainage channel in the affected area, from the base of the main scarp to the Marke brook, failed. As no other control measures were taken, movement of the landslide continued, and in 1997 the landslide foot expanded downslope. A mixture of clayey debris, asphalt and stone bricks covered the pasture between the De Saedeleer and the De Bo houses (Figure 6b,e). In the upslope cropland area, the farmer had dug drainage channels towards the two bank gullies already mentioned (Figure 4c), so that the evacuation of runoff towards the affected area continued. Once in the affected area, this runoff water was not evacuated, but contributed to soil saturation, and hence to the movement. In 1999, the landslide foot was threatening De Bo's house (Figure 6e). The 2-m high toe was only a few metres from the house. Although the toe did not reach the building, the lateral pressure of the debris caused several cracks to develop in the house. To stop the movement, two 2-m deep trenches were dug in the affected area in 2000 (Figure 4d). As the trenches were dug from the base of the main scarp to the Marke brook, the water of both the springs at the base of the main scarp and the runoff water flowing down through the bank gullies was effectively drained from that moment. Together with the digging of the drainage ditches the material of the foot threatening De Bo's house was removed to its original location, upslope in the poplar wood. But by taking away the lateral pressure at the landslide foot (Table 2), the debris located immediately upslope of the excavation was reactivated and 1 day later the material had already slid forward over 1 m. After several years of large movements, little happened in 2001. Against the advice of geomorphologists, the debris between the De Saedeleer and the De Bo houses (i.e. 1.5–2 m over an area of 0.2–0.25 ha, or 3000–5000 m^3) was removed to the upslope poplar wood a second time. As predicted by the geomorphologists, the foot reactivated and a new soil mound arose between the two houses.

To the present day, it seems that the drainage trenches in the wood have drained most of the water from the affected area to the Marke brook because little movement has been observed in the accumulation area since 2001. However, the main scarp has not yet stabilized because both in March 2002 and in January 2003 slices of about 15 m long and 3 m wide fell from the main scarp (Figure 2c). Especially for the January 2003 event (Table 3), the antecedent rainfall was high. In the summer of 2003, the most downslope of the three ponds in De Saedeleer's garden was filled, and the wetland, which developed in the downslope pasture after the creation of the ponds in 1993, disappeared.

Comparison of the reconstructed history of the Hekkebrugstraat landslide with the changes in microtopography over the last 50 years

Figure 7 shows the vertical displacements of the Hekkebrugstraat landslide between 1952 and 1973, and

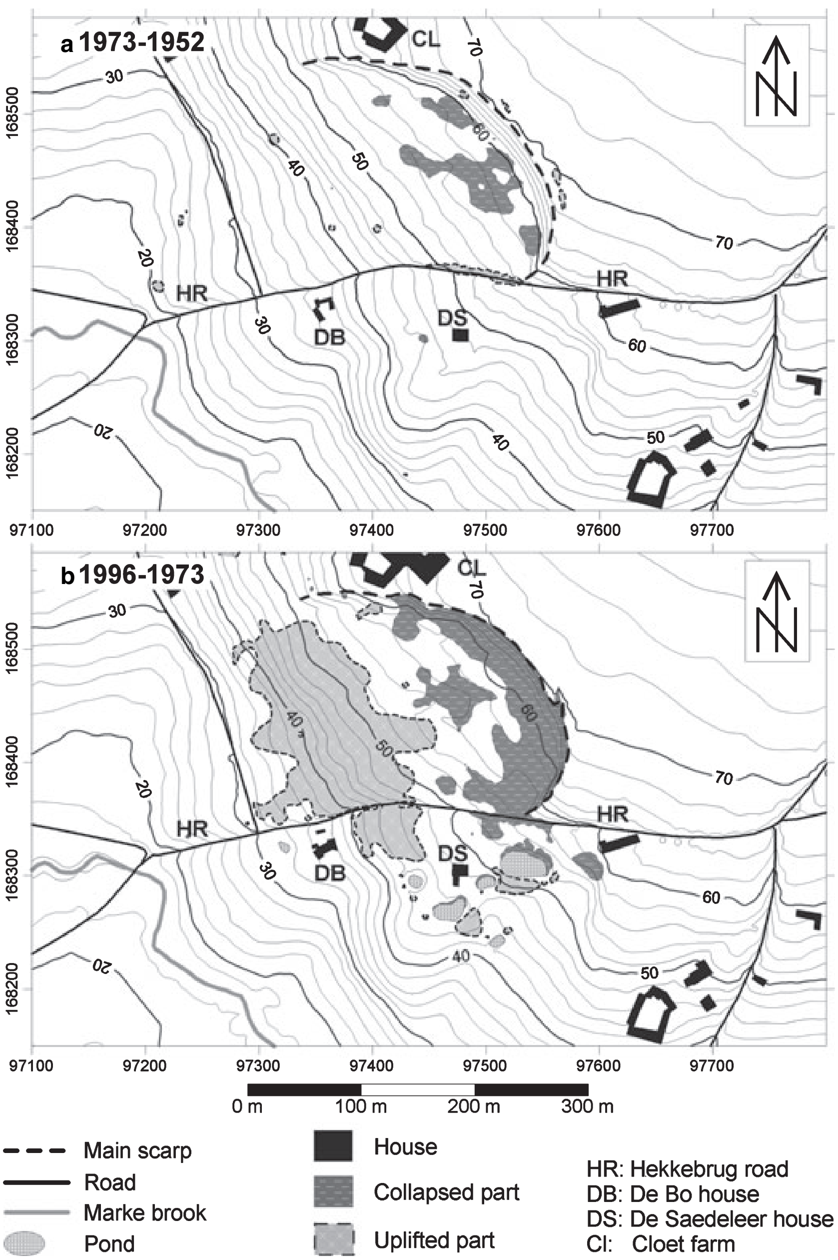

Figure 7 Uplifted and collapsed parts (maxima +4 and −7 m, respectively) within the Hekkebrugstraat landslide obtained by subtraction of detailed DTMs produced from aerial photographs of (a) 1973 and 1952 and (b) 1996 and 1973. The maps are produced with a confidence interval of 68.3% (i.e. 75 cm). Only differences in altitude of 75 cm or more are considered significant (Dewitte, 2006).

between 1973 and 1996 obtained from DTM comparisons by Dewitte (2006). In contrast to limited topographical changes found between 1952 and 1973, major displacements occurred between 1973 and 1996. Immediately downslope of the 1996 main scarp a large collapsed zone with vertical movements of up to −7 m can be distinguished, whereas in the accumulation area debris was uplifted by up to 4 m. The displaced landslide foot threatening De Bo's house (Figure 6e) is also clearly visible. After 1996, this landslide foot moved progressively downslope, until it was located only 3 m from De Bo's house. This analysis of Figure 7 corresponds well with the historical records presented above, showing that the reactivations of 1960 and 1966 affected only limited areas, whereas the reactivation starting in February 1995 affected almost the complete landslide. Some of the vertical displacements shown in Figure 7b correspond well with locations of human interventions discussed earlier. Examples are the uplifted parts along the Hekkebrug road north of De Saedeleer's house (DS; between 34 and 54 m a.s.l.) resulting from successive road improvement (Figure 5), and the vertical soil surface displacements around the ponds dug near De Saedeleer's house.

Conclusions

This study shows that in hilly areas, old landslides can be reactivated by a combination of natural and anthropogenic causal factors. During the last 50 years, the Hekkebrugstraat landslide has been reactivated at least six times. The reactivation of 1995 was the most catastrophic event, because a 140-m long × 15-m wide slice fell off the 8-m high main scarp, and reactivated the whole accumulation area causing considerable damage to houses, roads and other infrastructure.

Most reactivations of the Hekkebrugstraat landslide were triggered after monthly rainfall depths above 100 mm during the previous months. Long periods of high rainfall, and the presence of relatively steep slopes, impermeable clays and springs are important natural preliminary causal factors. Equally important, however, are anthropogenic preliminary factors. Interventions that decreased the shear strength of the hillslope material were mainly the result of poor water management causing large quantities of surface runoff flowing from the cropland above to the landslide depletion area, digging of ponds within the landslide area and poor maintenance of drainage ditches (Table 2). Shear stress on the surface of rupture was increased by overloading with road fill and soil material, and by removal of lateral support at the toe of the landslide (Table 2). Owners of land affected by old landslides, and authorities should be informed about the detrimental activity observed in this study, because by preventing such intervention, problems can be avoided.

Because the movements in the accumulation area have been stopped by the digging of deep drainage trenches in 2000, the Hekkebrugstraat landslide can probably be kept in a more or less stable state provided the intensive drainage of the depletion and accumulation area is maintained, and human intervention contributing to slope instability is avoided. Detailed, qualitative analysis of information on landslide history and land-use changes provided by local inhabitants, aerial photographs and newspaper articles, coupled with quantitative analysis of detailed DTMs, are valuable and complementary approaches for the reconstruction of conditions leading to reactivation of old landslides.

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