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# Recent landslide activity in Manaihan, East Belgium

**Abstract** Past landslides have been recognized in the Battice area in E-Belgium. In contrast to the other inactive landslides, the Manaihan landslide responded immediately to heavy rainfall events in the last two decades. This study aims to map its spatial extent and the dominant surface features; to measure surface displacement using GPS; to investigate subsurface structure with Cone penetration test (CPT) and corings; and to determine the depth of the shear surface by inclinometers. Results show a partial landslide reactivation. Surface velocities range between 20 and 40 cm/year and are strongly dependent on winter rainfall. CPT results give clear boundaries between the landslide mass and the undisturbed bedrock in the head scarp. Distinct shear surfaces have been determined with displacement rates up to 15.8 mm in 21 days. Further research should apply geophysical methods for two-dimensional information on the ground, investigate geotechnical properties of the landslide mass, model slope instability, and determine the influence of a sewage pipe crossing the central landslide mass as a potential cause for landslide activity.

**Keywords** Geomorphic mapping · GPS · Cone penetration test · Inclinometer · Manaihan, Belgium

## Introduction

Two regions have been recently recognized as being affected by deep-seated landslides in Belgium — in the Flemish Ardennes to the west (Ost et al. 2003) and the Pays de Herve to the east (Demoulin et al. 2003). The opportunity to map and to study the landslides of the Pays de Herve was provided by a research project funded by the Walloon Region government and launched after a landslide-producing rainfall event in September 1998 (Demoulin and Pissart, personal communication).

Several large ancient landslides extend over the slopes of the main ridges of the moderately dissected Herve tableland, in the Battice area of East Belgium (Fig. 1). Although most of them have been inactive for many years, one landslide near Manaihan was dramatically reactivated by the heavy rainfall of 14 September 1998 (126 mm in less than 24 h). This landslide suddenly moved ~2 m downslope, creating a 1.5-m-high new scarp at the top of the old headscarp. At east two buildings were severely damaged, a gas station had to be immediately turned off and a sewage pipe collapsed in two places within the landslide a few months later. Eyewitnesses have report ground displacements within the landslide for the last ~20 years, especially with a slow movement of the landslide during winter periods.

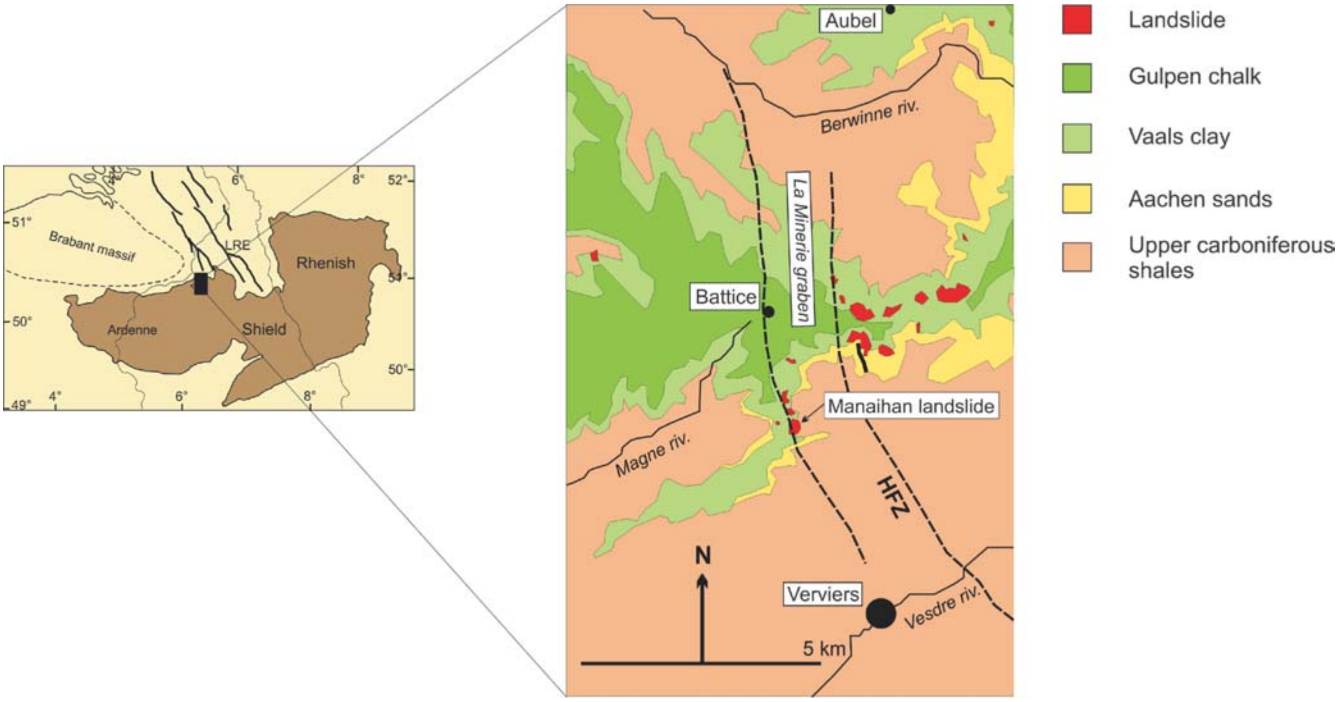

**Fig. 1** Location of study area, generalized geology and distribution of past landslides near Battice, east Belgium (adapted from Demoulin et al. 2003). The Manaihan landslide is indicated

The ridges on which the landslides are located expose subhorizontal upper Cretaceous strata resting unconformably on the upper Carboniferous shales of the basement. At the base of the Cretaceous cover, the sands and silts of the Aachen Formation are 0 to 10 m thick. They are overlain by the 10- to 30-m-thick Vaals Formation, which displays its typical clayey facies, and by some meters of chalks of the Gulpen Formation, locally weathered to clay-with-flints.

The landslides mainly disturb the clays of the Vaals Formation, on slopes ranging from 4 to 10°. They are generally 200 to 600 m across and extend 100 to 400 m downslope, showing a fairly fresh arcuate 5- to 20-m-high headscarp leading down to several backward-rotated masses in the upper part of the slide and then to a very hummocky topography terminating in a ~2-m-high toe. They are thus extended compound (multiple rotational + translational) block slides.

Demoulin et al. (2003) analyzed a series of $C^{14}$ dates suggesting that the landslides investigated in the Battice area might have occurred around 150 A.D. Several periods of reactivation have been identified. Trenches in the toe of the landslides, combined with a geophysical reconnaissance survey, showed that original structures are preserved in the lower part of the slides, which makes it clear that no significant flow occurred. The rotated blocks of the biggest landslides appear to be 10 to 25 m deep, with a basal shear surface systematically located in the Aachen sands. Based on these observations, Demoulin et al. (2003) proposed that the landslides were initiated by liquefaction within the Aachen sands. They suggest a prior translational gliding in the lower part of the slope (where the sands crop out) and then retrogressive rotational block movements. These ancient landslides were probably seismically triggered. Indeed, a climatic trigger is unable to explain the particular spatial distribution of all landslides because they only occurred in a limited part of the outcrop area of combined Aachen sands and Vaals clays around the La Minerie graben, and were especially close to its eastern border fault, the Ostende fault segment of the active Hockai fault zone. Furthermore, a mechanism involving sand liquefaction makes a seismic origin probable, as also do the size of the landslides and the results of slope stability analyses (Demoulin et al. 2003). Nevertheless, the strong Verviers 1692 earthquake, with an epicenter located not far from the landslides and an estimated $M_w > 6.0$ (Camelbeeck et al. 1999), seemingly caused no landsliding or even reactivation of pre-existing slides in the area. This non-failure might be correlated to its occurrence on 18 September, when the water table is commonly very low. A combined seismic + climatic trigger is most probable for the initiation of the ancient landslides. In contrast, the reactivation phases were certainly caused mostly by heavy rainfall, notably during the very humid period of the 13th–14th centuries. Presently, wet climatic conditions amazingly lead to landslide movement only in a single location, i.e., a relatively small landslide where a sewage line crosses the slope. Thus, a coupling with anthropogenic influences might be possible.

## Aims and goals

The respective interaction between humans and nature are one of the main concerns in the present study, which was begun in September 2001. Focusing on the reactivated Manaihan landslide, the work is performed in a first part to assess,

- the spatial extent of movement,
- the rate of displacement,
- the internal structure of the landslide mass,
- the location of the landslide shear plane.

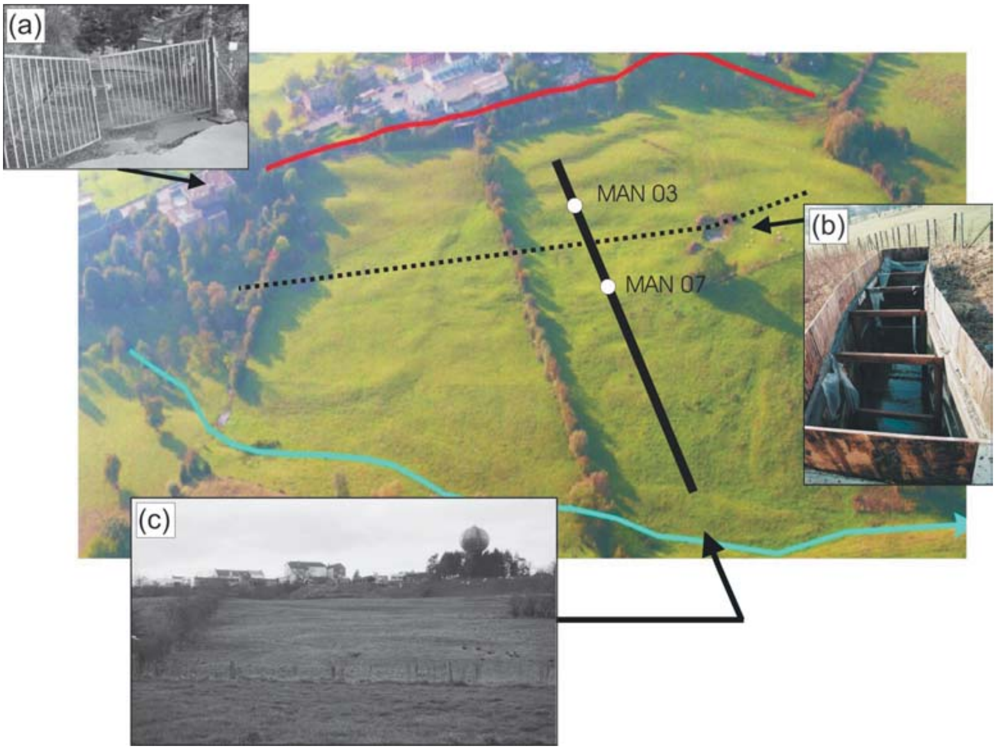

**Fig. 2** An oblique aerial photograph of the Manaihan landslide looking west. The headscarp is located by a *red line*, and the *blue line* shows the drainage line. **a** A tilted gate; **b** an open part of the sewage pipe, as a *dashed line* on the photograph; **c** the headscarp from the landslide toe upwards. The *bold line* refers to the location of the CPT profile including the two locations of inclinometer MAN 03 and MAN 07. Photograph by Albert Pissart; **a–c** by Thomas Glade

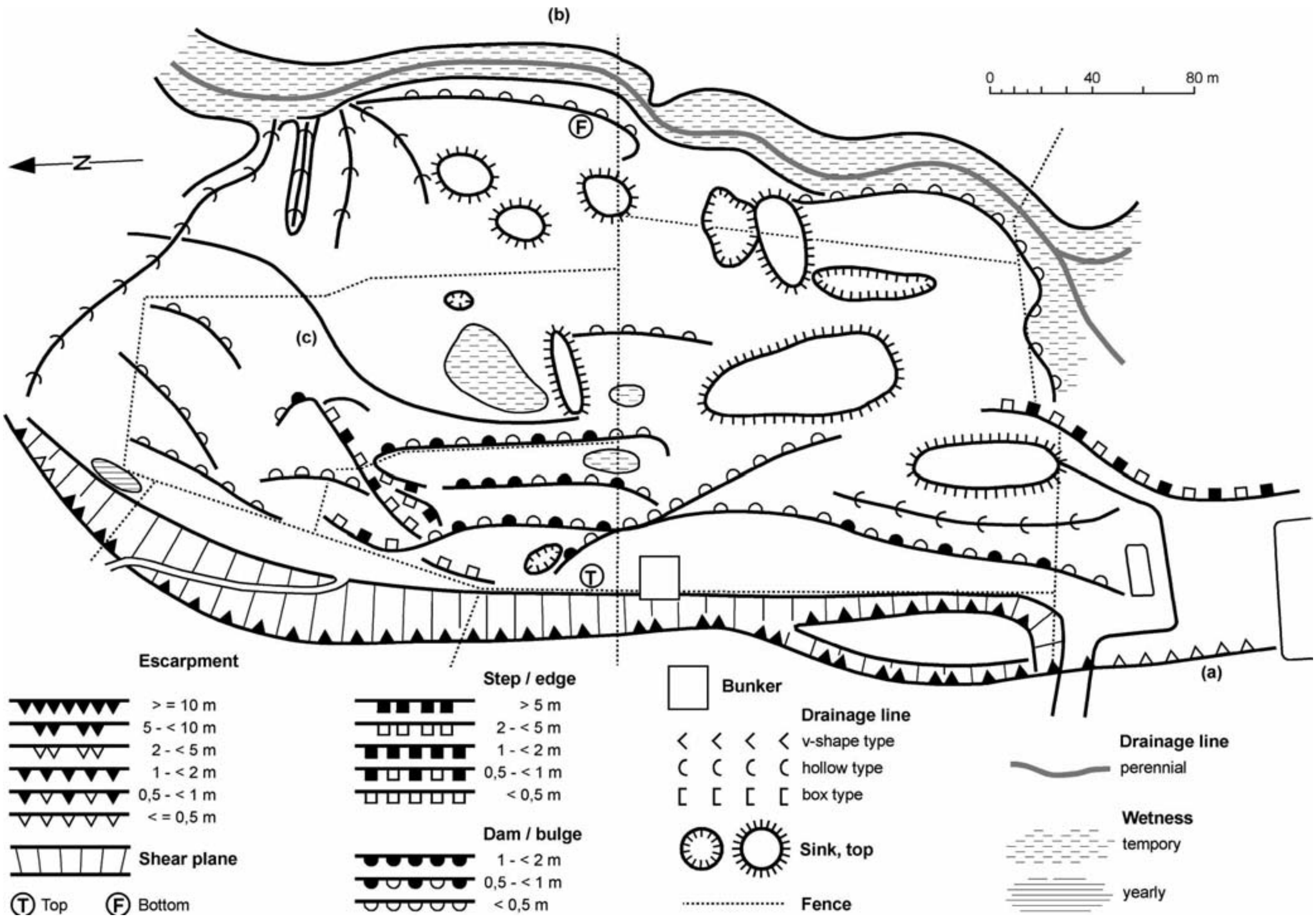

**Fig. 3** Geomorphic map of the Manaihan landslide. *Letters in parenthesis* refer to the inserted photographs given in Fig. 2

In the next section, the applied methods are briefly reviewed, followed by an introduction to the study area and followed by the results. The paragraph of conclusions summarizes the findings and identifies future research needs.

## Methodology

Spatial assessment of the landslide employs two methods. First, geomorphic mapping was carried out from both aerial photographs and field surveys. The map symbols are related to the mapping legends proposed by Leser and Stäblein (1980) for geomorphic maps for scales of 1:25,000. A legend for detailed mapping of landslide features is suggested by Terhorst and Kirschhausen (2001) at scales of >1:10,000. Both legends were combined for this project and led to the presented legend, which differentiates between landslide scarps, sharp edges and bulges, drainage lines, depressions and crests, and hydrologic features.

Secondly, surface displacements were determined using high resolution GPS surveys, which have been proven by many authors to be suitable for detection of surface displacements (e.g., Cornelius et al. 1994; Malet et al. 2002). Installation of 32 marks within and around the landslide allowed displacement monitoring by repeated GPS measurements. An assumed fixed reference frame was comprised of three marks located out of the slide and encompassing it, and measurements were carried out in rapid static mode with SR9500 Leica receivers about every 6th week from October 2001 to May 2002. The field conditions and the data processing allowed for an uncertainty of ~2 cm in all three components (north, east, and up) of relative positioning, i.e., an uncertainty of ~3 cm in the components of relative motion.

Subsurface investigations were based on the results of drop penetration tests (CPT) along a vertical profile and on the installation of two inclinometers. The drop penetration tests were performed with a heavy drop-hammer (50 kg) using the portable equipment manufactured by ABOVO Geotechnics. The tests were carried out according to the German Industrial Norm DIN 4022, which has its equivalent in the EU regulation ISO 14688. The inclinometers were installed along the same profile in two locations above and below the sewage pipe. Plastic inclinometer tubes, manufactured by GLÖTZL Geotechnics, were installed at depths to 9.5 (MAN 07) and 6.0 m (MAN 03), respectively (Fig. 2). Both inclinometer tubes were repeatedly surveyed until the tubes were broken.

## Study area

The Manaihan landslide is located on the gently sloping (~ 4°) eastern flank of a south-striking secondary ridge of the Herve tableland, where it extends over 6.8 ha of meadows at 290 m altitude. A row of houses is present along and, for some, on top of its headscarp, while a gas station was recently set close to this

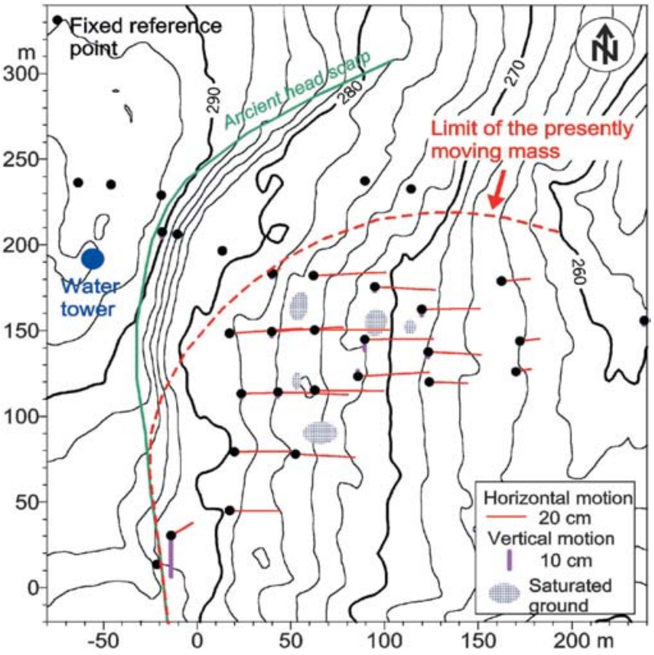

**Fig. 4** Distribution of horizontal and vertical motions recorded by repeated GPS surveys during the period from 2 October 2001 to 10 May 2002 within the Manaihan landslide

scarp. A water tower is also located less than 50 m from the scarp and a sewage pipe passes through the landslide (Fig. 2).

The Manaihan landslide is situated in the upper Cretaceous Vaals clays, which can be 12 m thick in places. Some silt levels, occasionally somewhat indurated, are present within the clays, which are underlain by 4 m of fine sands of the Cretaceous Aachen Formation. Where it is not covered by the landslide deposits, the shaley upper Carboniferous basement crops out at the base of the ridge. The western border fault of the small La Minerie graben follows the strike of the ridge on which the Manaihan landslide is located.

With regard to hydrology, the main aquifer of the Herve tableland lies within the Gulpen chalks, above the Vaals clays. Here, only a small aquifer is contained in the Aachen sands, trapped between the clays resulting from the Mesozoic weathering of the Paleozoic basement and the Vaals clays. Present-day yearly rainfall is 900 mm with two peaks in June–August and November–January, and two lows in March–April and September–October.

## Results

The geomorphic map clearly identifies the head scarp, the bulged surface on the landslide top, the wet places in the middle part of the landslide and the depressions and crests on the landslide toe (Fig. 3). The map gives first information on the landslide characteristics, e.g., ridges and depressions in the top, flow-like structures on the toe and shear and tension cracks along the northern limit of the reactivated slide.

The GPS points were equally distributed covering the whole landslide surface. The surveys were carried out at regular intervals during the winter of 2001–2002 (2 October 2001–15 November 2001–17 January 2002–5 March 2002–10 May 2002). Up to 40 cm of horizontal ground motion for the main moving mass was measured within this period (Fig. 4). No movement occurred during the autumn, the first displacements (~5 cm) took place between 15 November 2001 and 17 January 2002, probably in the first half of January, as a consequence of two periods of very rapid snow melting. The main slip event (~30 cm) was associated with exceptional rainfall during most of February (198.7 mm), the landslide coming to rest after 5 March 2002.

It was observed that not the whole landslide was moving. Its northern part, separated from the central mass by overstepping scarplets and a small graben, which developed in September 1998 oblique to the headscarp, has not been reactivated. In this area, the old headscarp shows no significant displacement. To the south of this limit, the landslide mass moves downslope as a whole, with highest amounts of motion in its upslope, which half decrease in amount towards the valley bottom. Only minor vertical displacements are observed within the landslide. By contrast, the

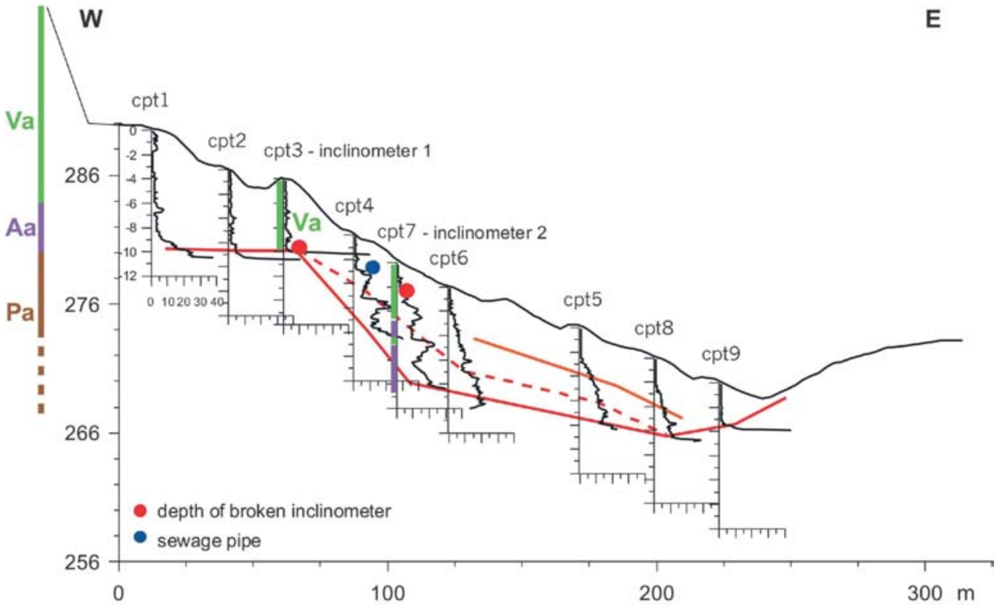

**Fig. 5** Vertical profile through the Manaihan landslide with CPT locations (CPT 1–CPT9). The CPT3 corresponds to inclinometer MAN03 and CPT7 to inclinometer MAN07, respectively (refer also to Fig. 2 for location, and to Fig. 6 for inclinometer readings). *Green bar* labeled with *Va* on the left and in the graphic refers to the Vaals clay, the *violet Aa bar* to the Aachen sand, and the *brown Pa* to the underlying upper carboniferous shales

southern part of the old headscarp is clearly rejuvenated, inducing a strong subsidence (~25 cm during the winter 2001–2002) of the uppermost slipped blocks. The motion data collected during the winter 2001–2002 confirm previous results from GPS measurements carried out in 1999–2000 on a more limited part of the landslide.

The subsurface investigations show a clear pattern (Fig. 5). The first three CPTs show a material with low resistance down to a horizontal boundary at approx. 280 m a.s.l., which corresponds to a depth below surface of 10 (CPT1), 7 (CPT2), and 6 m (CPT3). CPT4, CPT7, and CPT6 have a different pattern. In all three cases, resistance is very low for the first 2 m: in one case, one blow was enough to push the top down for 1 m. From there downwards, the number of blows increased with some interruptions until it reached a depth below surface of 8.3, 10.3, and 10.1 m, respectively. The general graphs for CPT 5 and CPT 8 are similar, with the exception that the number of blows increased continuously. At location CPT9, the material is characterized by very low resistance with a clear and immediate boundary at a depth of 3.8 m below the surface.

In Fig. 5, three additional lines are presented. The red line indicates the maximum depth of the landslide based on the CPT readings, and the dashed red line might differentiate between the landslide mass (above the line) and the bedrock, which is decreasingly weathered with increasing depth. The orange line indicates a potential surface of the previously undisturbed valley. It is evident that CPTs cannot be used alone to demonstrate the valley development at this section and the landslide size. Further analysis using other methods is indispensable before drawing a final conclusion. However, these investigations suggest that the landslide mass is deep at the head, and probably more shallow above the landslide foot.

In order to determine the depth of movement, two inclinometers were installed at the already mentioned locations. At location MAN 03, the landslide down-slope displacement was 13.4 mm within 119 days, of which nearly 9 mm fall in the period between 15 November 2001 and 17 January 2002 (Fig. 6a). A following reading in February was not possible because the tube was already broken. The readings of the inclinometer MAN 03 show a shear plane at a depth of 5.5 to 6 m, which corresponds to the depth of the bedrock as determined by CPT3. Therefore, it can be concluded that the whole mass of unconsolidated Cretaceous material moves downslope on the Paleozoic bedrock. The slight sidewards movement of 2.7 mm over the total period can be neglected.

At location MAN07, the figure is rather different. First, the inclinometer tube was installed to a depth of 10.5 m and the detected shear plane is at a depth of 2.5 m (Fig. 6b). Furthermore, as the tube was rapidly destroyed by the ground displacement, only one reading was possible, i.e., at 3 weeks after the inclinometer was installed. The down-slope displacement was 15.8 mm in 21 days, with a more significant side-wards component of 4.4 mm. Whether there are internally different movement velocities within the 2.5 m of the main landslide mass cannot be derived precisely.

One interpretation of the MAN07 inclinometer readings is that, in this place, the landslide moves onto the former surface of the valley. Some support for this hypothesis can be derived from the CPT measurements, which give an increase of resistance from 2 to 2.7 m below the surface. Accordingly, at location CPT9, the landslide filled the former valley floor, which might explain the sharp increase of resistance at a depth of 3.8 m. However, one should also keep in mind that the sewage pipe located just a few meters upslope of MAN07 is at a depth of ~2.5 m too. If this pipe lets water seep continuously in the landslide, increased pore pressure and lubrification could explain the development of a shear plane at this shallower depth.

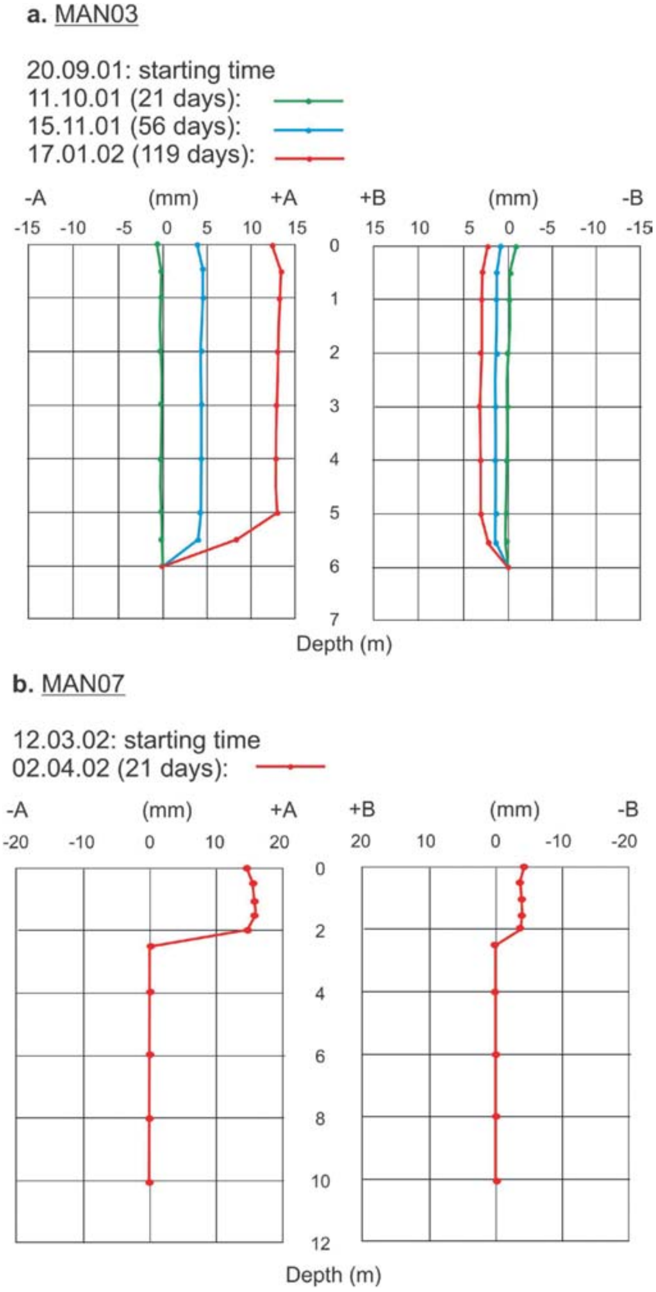

**Fig. 6** **a** Inclinometer readings between 20 September 2001 (first reading after installation) and 17 January 2002 (last measurement before destruction) at MAN 03. **b** Inclinometer readings between 12 March 2002 (first reading after installation) and 2 April 2002 (last measurement before destruction) at MAN 07. Note: –A to +A are along slope measurements (+A being downslope); +B to –B are measurements perpendicular to the slope. Refer to Figs. 2 and 5 for positions on the slope

## Provisional conclusions and perspectives

We have defined the size and limits of the presently moving mass within the ancient landslide. GPS measurements show that, beyond a limit marked by the small oblique graben, which appeared after the rainfall event of September 1998, the northern part of the landslide remains inactive. By contrast, the headscarp seems to have recently developed southward. As derived from the CPT results and core samples collected at the inclinometer locations, it can be surmised that the ancient landslide filled a pre-existing valley and pushed away the creek, which is now flowing about 50 m to the east of its former position. The currently displaced masses correspond to the whole thickness of the rotated blocks in the upper part of the slope (6–10 m depending on the place), with a shear plane at the Aachen sands–Paleozoic shales contact. However, in the lower half of the landslide, where the motion was mainly translational and the valley was filled with up to 12 m of slipped material made of two superposed units, the chief current shear plane is at a depth of 2.5 m, which is also the depth of the sewage pipe passing across the landslide some 10 m higher in the slope. GPS measurements indicate that the motions taking place during a "normal" winter may reach 30–40 cm horizontal displacement, with the whole mass moving en bloc, mainly in response to periods of prolonged heavy rainfall. The headscarp is being rejuvenated only in its southern half and, fortunately, not where a water tower is located.

The remaining question is why the Manaihan landslide has been reactivated and continues to move while the other landslides with similar environmental conditions are inactive. First, indication of a complex trigger is given by the depth of the active shear plane in the lower part of the slide, similar to that of the sewage pipe located upslope, and by the juxtaposition between the reactivated part of the headscarp and that part of the scarp undergoing anthropogenic loading. In addition, there is a marked correlation of the movements with periods of prolonged rainfall. To better understand the trigger(s) and mechanism of the present-day motions, it is planed to determine the geotechnical properties of the material involved in the slide, visualize the structure of the landslide by 2D geophysics, precisely time the incidences of reactivation, and note the total amount of recent displacement. Finally, there is a need to perform slope stability analyses in order to define the conditions required for reactivation.

## Acknowledgements

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