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Earthquake-triggered landslides at the Brunssummerheide, Limburg, the Netherlands: preliminary studies following the 1992 Roermond earthquake

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Abstract

Two landslides occurred at the Brunssummerheide during, or shortly after the main shock of the 1992 Roermond earthquake. The Brunssummerheide is located 25 km south of the epicentre. An earthquake can reduce the stability of a hillslope in three ways: firstly, the ground acceleration from seismic waves forms an additional destabilizing force; secondly, the shear strength may be reduced by an increase of the pore pressure, and thirdly, an earthquake may cause the breaking of small cohesive bonds between soil particles, thus reducing the overall cohesion.

Slope stability back-analyses were carried out to reconstruct the forces and processes during the event. Peak ground accelerations as predicted by empirical attenuation relationships are insufficient to cause instability of the slopes. It is concluded that an increase of at least 100% in the pore pressures was required to destabilize the two hillslopes.

Introduction

Two landslides occurred at the Brunssummerheide during, or shortly after, the main shock of the Roermond earthquake, April 13, 1992. The Brunssummerheide (also known as Brunssummer Heide) is located 25 km south of the epicentre (Fig. 1). The soil consists of well-sorted fine grained sands of the Miocene Heksenberg Formation (Fig. 2). Part of the region has been reworked during lignite mining a few decades ago. Nowadays, the region has been landscaped and forested and is used as a recreational area.

Both hillslopes are about 4 m high. The wider landslide, designated as the 'large landslide', is believed to be in part a reactivation of an older landslide. It is about 200 m wide and 25 m long. There are some wide fissures, indicating horizontal block movement. Ground subsidence occurred in a path at one end of the slide. The 'small landslide' occurred at a valley head about 300 m away from the 'large landslide'. With its stepped surface it has an amphitheatre-like form. There are no morphological features present that suggest liquefaction. A profile is given in Fig. 3. For a detailed map of the area see Fig. 3 in Maurenbrecher et al. (1994).

Influence of earthquakes on slope stability

Earthquakes may cause decrease of slope stability in three ways:

- Ground acceleration due to seismic waves adds to the destabilizing forces on the soil mass.
- Seismic waves cause a cyclic loading effect on the soil. The soil tends to compact, thereby reducing pore space. If pore water cannot drain fast enough, pore pressure, u, will increase and effective stress ($\sigma' = \sigma - u$, where σ is total normal stress) will be reduced. Eventually, the soil may lose all its shear strength when $\sigma' = 0$ (i.e. liquefaction). Slope instability will already occur before $\sigma' = 0$ is reached.
- Where cohesion between the soil particles exists, ground displacements due to seismic waves may be sufficiently large to rupture the bonds between soil particles, leading to a loss of cohesion (Ishihara 1986).

Ground acceleration at the Brunssummerheide

Direct measurements of the ground acceleration during the earthquake are not available for the Brunssummer-

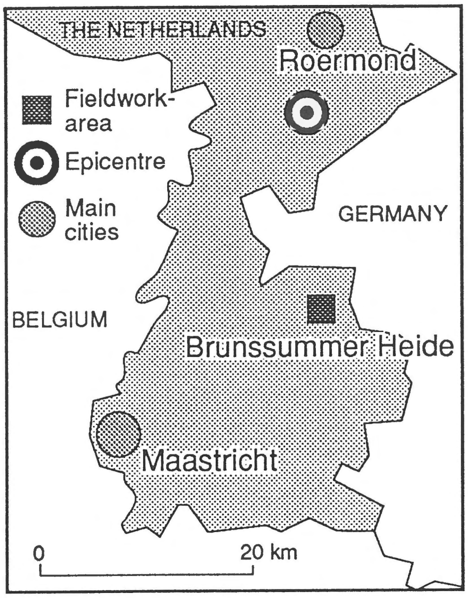

Fig. 1. Location of the Brunssummerheide and the epicentre of the 1992 Roermond earthquake in the southern Netherlands.

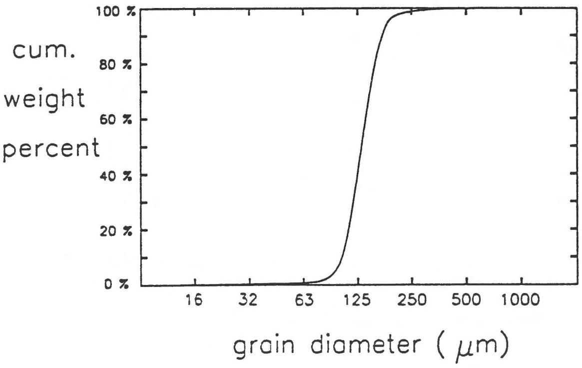

Fig. 2. Grain size distribution of the sands at the Brunssummerheide.

heide. The nearest seismograph stations with unclipped records of the mainshock are found at epicentral distances between 50 and 60 km. The measured peak horizontal ground accelerations (a_{max}) at this distance range between 0.03 and 0.05 g (Ahorner 1992, Berger 1994).

For the Roermond earthquake Ahorner (1992) proposes to use the empirical formula of Joyner & Boore (1981) to estimate a_{max} in the distance range of 50–400 km:

$$\log a_{max} = -1.02 + 0.249M_W - \log R - 0.00255R$$

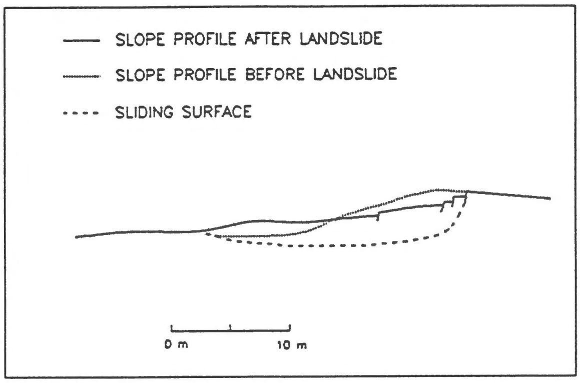

Fig. 3. Schematic cross-section of the 'small landslide' on the Brunssummerheide. Horizontal scale equals vertical scale.

Table 1. Peak horizontal ground acceleration (a_{max}) at the Brunssummerheide, located 25 km from the epicentre of the 1992 Roermond earthquake (M_L = 5.9), estimated from empirical attenuation relationships, here cited by reference to the original publication

Source	a_{max} (g)
Ambraseys (1990)	0.07
Chiaruttini & Siro (1981)	0.14
Campbell (1981)	0.05
Campbell (1985)	0.05
Joyner & Boore (1981)	0.07
Joyner & Boore (1988)	0.07

where M_W = Moment magnitude and R = hypocentral distance.

Estimates of a_{max} at the Brunssummerheide from different empirical formulae fall in the range 0.05 to 0.14 g (Table 1). The actual a_{max} may differ somewhat from these values. For example, local site effects are not considered. Furthermore, most empirical formulae are based on North American data. Only the formula by Ambraseys (1990) is based on European data, while Chiaruttini & Siro (1981) use data from the Alpine belt.

Slope stability analyses for the Brunssummerheide landslides

Cross-section profiles were made in both landslide areas to enable a reconstruction of the original slope surface and the most probable plane of failure. Fur-

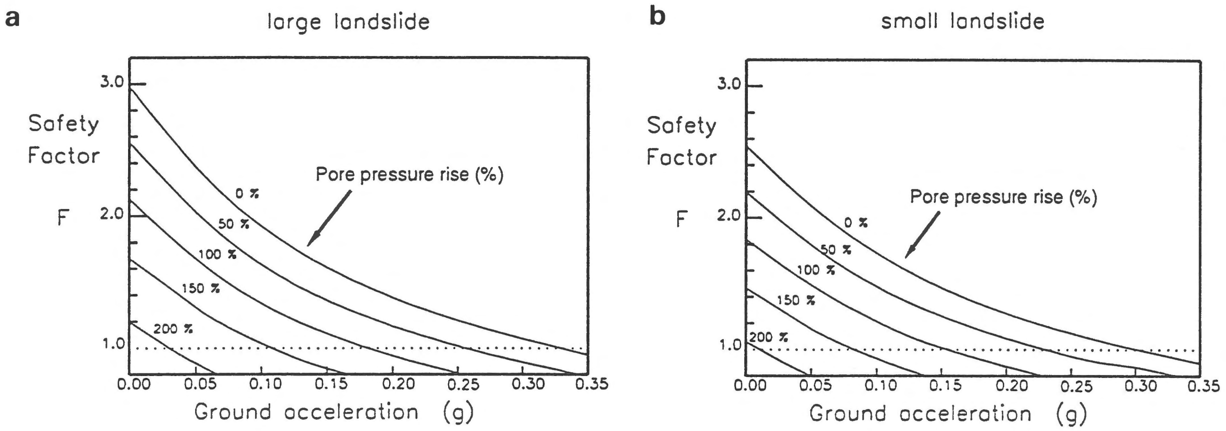

Fig. 5. The safety factors obtained using Janbu's simplified method with Fredlund correction for the large (a) and the small (b) landslide at the Brunssummerheide, calculated for different combinations of earthquake ground acceleration and pore pressure rise.

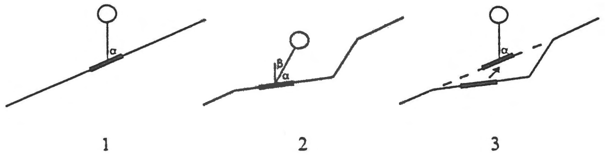

Fig. 4. Use of tilted trees to reconstruct the original slope surface (schematized): 1) Original slope surface with tree (slope angle = 90°–α). 2) Observed slide surface with tilted tree (β is tilting angle). 3) Reconstructed slope surface.

thermore, the tilting angles of trees on the slides were measured, assuming that this tilting was caused by block-rotation. The back-rotated block should fit with the original slope surface (Fig. 4). A few weeks after the earthquake, groundwater levels were measured to be 3 m below the surface at the scarps of both landslides, and near the surface at the toes. We assumed that the groundwater level at the time of the event was about the same. The permeability of the sands is quite high and no significant variations in the rainfall occurred in the period before and after the earthquake. Consolidated drained triaxial tests of the sands of the Brunssummerheide show: a) no significant difference between peak and residual strength of the sands, b) an angle of internal friction (φ') of 33°, and c) no cohesion.

Slope stability is usually assessed by evaluating the equilibrium of destabilizing and resisting forces or force moments in the slope. The safety factor (F) is defined as:

$$F = \text{available shear strength/shear stress}$$

We analyzed slope stability using spreadsheet calculations and the computer program SLIDE, with the methods of 1) Fellenius, 2) Bishop, and 3) the simplified method of Janbu with the Fredlund (1974) correction, respectively (Graham 1984, Nash 1987). In Fig. 5 we present the results for the third method. Near equilibrium, i.e. F approaching 1, the difference between the results of the three methods becomes negligible.

The safety factors of the original slopes of the large and the small landslide are 3.0 and 2.6, respectively. Both slopes would have remained (marginally) stable even with a groundwater level at the terrain surface in the whole slope: F = 1.5 and F = 1.2, respectively. The effect of seismic waves on the slope stability at both sites has been calculated in terms of F for several combinations of a_{max} and pore pressure increases (Fig. 5). With no pore pressure increase a horizontal acceleration of minimally 0.3 g would be necessary to destabilize the slopes. This horizontal acceleration is unlikely, as estimates of a_{max} at the Brunssummerheide range between 0.05 and 0.14 g (Table 1). For a horizontal acceleration of 0.14 g a pore pressure rise of at least 100% is needed to destabilize the slopes. Konstantinov et al. (1991) suggest to multiply a_{max} in slope stability analyses by a reaction coefficient of 0.4 in order to account for the short duration of the peak acceleration. This approach would suggest that the minimum pore pressure increase for destabilization should be 200%. Furthermore, in our model we assume that peak acceleration and maximum reduction of effective normal stress coincide in time, which is not necessarily true. Therefore we believe our results represent minimum values for the pore pressure increase.

Liquefaction susceptibility at the Brunssummerheide

From the above we conclude that a pore pressure rise was necessary to destabilize both slopes. This pore pressure increase may be either attributed to the cyclic loading at the depth of the plane of failure, or to dissipation of increased pore pressures from a deeper liquefied zone shortly after the earthquake.

The liquefaction susceptibility of a saturated deposit depends on

a) the ability of the material to densify during shaking,

b) potential for pore pressure increase caused by this densification.

Youd & Perkins (1978) give threshold magnitudes for the occurrence of liquefaction as a function of epicentral distance. The lowest magnitude at which liquefaction occurs is $M = 5.0$ (Kuribayashi & Tatsuoka 1975, Keefer 1984). In Youd & Perkins (1978) the largest epicentral distance to significant liquefaction features is 6 km for $M = 5.9$. Their threshold magnitude for liquefaction at 25 km is 6.7. Therefore, the Brunssummerheide sands would not be expected to be within the liquefaction field for the Roermond event.

These sands were originally deposited in a Miocene beach environment. Liquefaction of deposits older than Pleistocene is not likely to occur (Youd & Perkins 1978), as they are already well consolidated. However, the sands seem to have been reworked during surface lignite mining a few decades ago. Soil samples of the landslide material still have a high porosity of about 0.5. The measured grain-size distribution at the Brunssummerheide is shown in Fig. 2. The material consists of well-sorted fine sands, with 90% of the material having a diameter between 100 and 200 μm. This grain size distribution is generally considered highly susceptible to liquefaction. Maurenbrecher et al. (1994) give the first results of a quantitative in situ liquefaction susceptibility assessment based on soil parameters derived from post-earthquake site investigations.

Conclusions

Our investigation shows that the two landslides which affected the Brunssummerheide, 25 km south of the epicentre of the Roermond earthquake, could not have occurred without the triggering effect of the earthquake. The direct effect of the ground acceleration from the seismic waves is unlikely to have played a major role in lowering the stability of the slopes. Because the peak ground accelerations predicted by empirical formulae are too low for triggering the landslides, a pore pressure increase of at least 100% is required. Further research is required on peak ground accelerations in north-west Europe and on the in situ liquefaction behaviour at the Brunssummerheide.

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