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ORIGINAL PAPER

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Determination of potential landslide shear plane depth using seismic refraction—a case study in Rheinhessen, Germany

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Abstract Landslides on the Rheinhessen cuesta are not only a natural component of slope evolution but also have been influenced by anthropogenic activities such as viniculture. Single landslides as well as the regional occurrence of hundreds of mass movements have a direct and indirect effect on the environment and cause high economic loss.

This study analyses a regionally characteristic landslide, DROM 9, to establish the potential for the use of seismic refraction to determine the change of substrate below the ground surface. In Rheinhessen, landslides commonly occur as shallow translational features in depressions that were probably created as Pleistocene valleys. Seismic field data have been analysed using the "intercept technique" and the "generalised reciprocal method". The depth of the substrate and the divisions within it were confirmed by boreholes. With this information, it is possible to develop a structural model of the subsurface, which leads to a better understanding of landslide kinematics.

Keywords Geophysical technique · Seismic refraction · Landslide dimensions

Résumé Les glissements de terrain, le long de la côte de Rheinhessen, représentent non seulement une caractéristique de l'évolution des pentes mais aussi les conséquences d'activités anthropiques telles que la viniculture. Des glissements majeurs isolés, comme des centaines de mouvements de terrain à l'échelle régionale, ont des effets directs et indirects sur l'environnement et causent des pertes économiques importantes.

Cette étude prend appui sur un glissement caractéristique, DROM 9, pour mettre en évidence l'intérêt de la sismique-réfraction pour identifier un substratum sous des terrains de surface. Dans la région de Rheinhessen, les glissements de terrain sont généralement des glissements plans peu profonds se présentant dans des dépressions, héritages probables des processus d'érosion du Pléistocène. Les données sismiques de terrain ont été analysées à partir de la « Technique des intercepts » et de la « Méthode inverse généralisée ». La profondeur du substratum et sa structure ont été confirmées par des forages. Avec cette information, il est possible d'établir un modèle structural des terrains de surface, ce qui autorise une meilleure compréhension de la cinématique des glissements de terrain.

Mots clés Technique géophysique · Sismique-réfraction · Glissements de terrain

Introduction

Landslide occurrence at the cuesta in Rheinhessen (Fig. 1) is not only caused by the natural constellation of deposition factors which is part of a general slope evolution but also by anthropogenic activities such as viniculture. As demonstrated in the winter of 1981/82, landslides may have a direct effect upon human life and also result in increased economic costs both directly and related to their remediation. Consequently, landslides have become prominent in public awareness and have been investigated with respect to their importance for natural hazard modeling and slope evolution within the project "Landslides in South- and West Germany" (MABIS) (Dikau and Schmidt 2001), funded by the German Science Foundation (DFG).

Since 1995 (Glade et al. 2001), various landslides have been investigated with reference to the distribution, genesis and stability of ground movements on the cuesta of Rheinhessen. One of these landslides, DROM 9, is located within the municipality of Dromersheim, south of Bingen. Based on the surveys of Glade et al. (2001), geophysical investigations have been carried out to examine the subsurface structure of this landslide.

Chorley et al. (1984) note that landslides contribute significantly to slope evolution and are therefore an important component of the slope system. Recent investigations have been particularly focused on either a geomorphological assessment of surface structures, including their temporal and spatial variability, or on geotechnical instrumentation and modeling of localized landslides. Process geomorphology has the task of investigating the functional dependencies between form, material and process within an interdisciplinary environment. It applies methods from other disciplines, such as seismic refraction, as well as models originally developed within engineering geology and soil mechanics (Anderson and Richards 1987; Carson and Kirkby 1972; Selby 1982; Chorley et al. 1984). The basis for the development of kinematic models, applicable for efficient evaluation of geomorphic hazards and for minimizing damage through monitoring and stability countermeasures, is the profound knowledge of the natural causes of each landslide failure, the general movement pattern and the factors controlling the movement (Dikau 1990; Brunsden 1993; Krauter 1998). The application of geophysical methods allows first approximations of subsurface conditions including lithology, bedding conditions and structure, and has the advantage of investigating potential inhomogeneity in large areas with a relatively low time expenditure (Prinz 1997).

Within geomorphology, seismic refraction has been successfully applied by Weise (1972) to investigate loose sediments above in situ bedrock. Barsch (1973), Dikau (1978), King (1976, 1984), Ortlam (1991) and Pfeffer (2000) used this method to delineate permafrost within rock glaciers. Caris and Van Asch (1991) investigated a landslide in the French Alps with seismic refraction and a coupled application of geoelectric and geomagnetic methods, and were able to identify the depth of the shear plane. Mauritsch et al. (2000) also successfully used a combination of geophysical methods to investigate landslides. Bogoslovsky and Ogilvy (1977) worked on the subsurface structure and geometry of different landslides on the Krim Peninsula, in Caucasus, at the Black Sea coast and in the Wolga valley. The combination of seismic refraction and geoelectric techniques has also been promising in these investigations. In contrast, Matthesius (1994) concluded from an investigation of the Wißberg landslide in Rheinhessen that seismic refraction methods could not determine the location of shear planes within the bedrock. This suggests that refraction seismic could be applied to landslide investigation only in cases where the landslide material consists of a totally different structure and matrix to the underlying bedrock.

This study used seismic refraction methods to investigate vertical profiles and derive a structural model of the subsurface. Particular emphasis was placed on determining the depth of the potential shear surface and investigating the structure of the base of the landslide.

Study area and environmental setting

The study area (Fig. 1) extends over an area approximately 24 km^2 (Dikau 1990; Glade et al. 2001) and is part of the 1,400 km^2 region of the plateau and hilly country of Rheinhessen, located at the northwestern border of the Upper Rhine Graben in southwest Germany (Leser 1969; Steingötter 1984). The northwestern region of the Mainz basin is characterized by a significant cuesta due to the differing characteristics of the predominately Tertiary clays, marls and fine sand which are overlain by a Miocene limestone (Wagner and Michels 1930; Lauber 1941; Rothausen and Sonne 1984). Since the late Tertiary, the localized uplift has been accompanied by erosional processes (Uhlig 1964; Brünning 1977; Andres and Preuss 1983; Preuss 1983).

The average annual temperature of 6.9 °C and rainfall of approximately 550 mm is below the average rainfall for Germany, making this region one of the most climatically favourable in the nation. Although extreme precipitation events occur particularly during the summer, it is the prolonged rainfall during the autumn and winter that most generally causes widespread landsliding. The landslide described in this paper was related to such a winter event.

Due to the geological-geomorphological and climatic conditions at the cuesta and to the anthropogenic

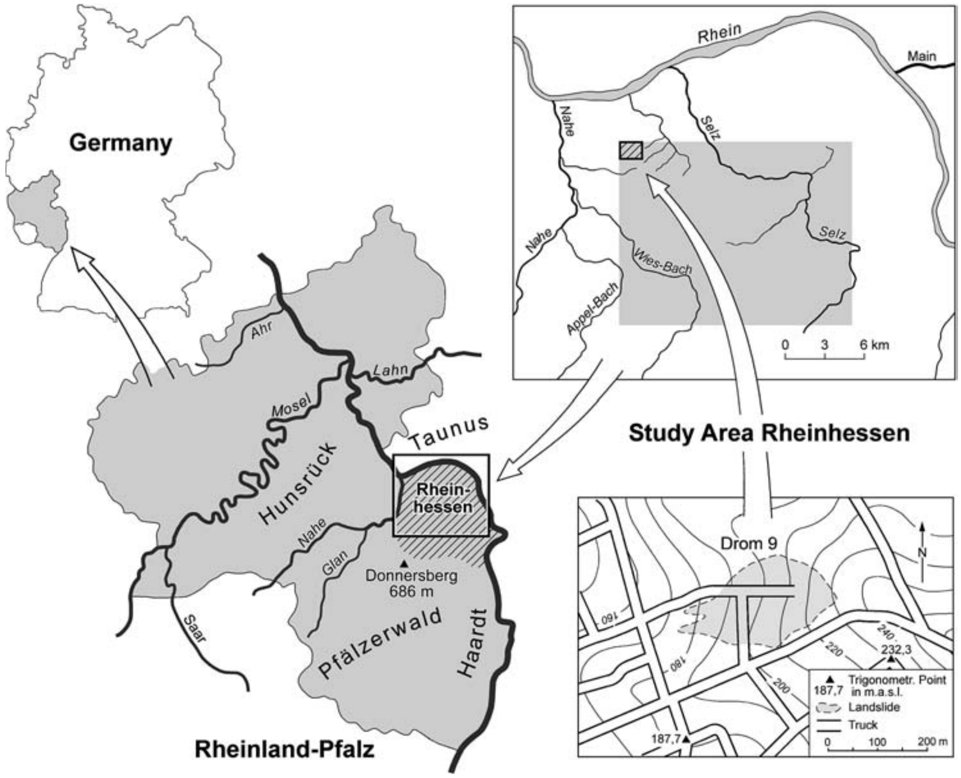

Fig. 1 Location of the study area in Rheinhessen, southwest Germany (based on Glade et al. 2001)

impacts (in particular viniculture and building activities), the slopes are particularly susceptible to landsliding (Steingötter 1984, Krauter et al. 1985). During the winter of 1981/82, for example, when an extensive snow cover thawed following an influx of warm air, approximately 240 landslides were triggered within this melt period, affecting an area of roughly 230 ha (Preuss 1983; Steingötter 1984; Krauter et al. 1985; Jäger 1997; Krauter 1998). In total, approximately 10 million m^3 of slope material moved, causing considerable damage to vineyards, farm tracks and residential buildings (Steingötter 1984; Krauter et al. 1985; Krauter 1998). The main areas affected were those formed of a superficial layer, a weathered bedrock mantle and redistributed sediments (colluvium) in the higher slopes (210 m a.s.l.) where the angles exceeded 7° (Jäger 1997). At this elevation, the stratigraphy changes from the limestones known as the ‘‘Corbicula-Layers’’ (Lower Miocene) to the impermeable, marly clay fresh-water horizons of the Upper Oligocene (Wagner and Michels 1930; Lauber 1941; Rothausen and Sonne 1984) (Fig. 2). According to Krauter et al. (1985), the majority of the landslides are reactivated Pleistocene failures, a phenomenon which accounts for 90% of the landslides in the Mainz basin. These were probably initially reactivated during the widespread deforestation that accompanied the urbanization of the Middle Ages, and more recently by the influence of various anthropogenic activities.

Landslide activity comparable to that of the 1981/82 winter is known to have occurred in 1880/81, 1940/41 and 1941/42 (Steingötter 1984; Krauter et al. 1985) and in the spring of 2001; again, widespread landslides occurred following prolonged rainfall. In addition to the numerous localized landslide investigations at Wißberg (Matthesius 1994; Steingötter 1994) and Jakobsberg (Steingötter 1984), landslides within the municipality of Ockenheim and Dromersheim have also been investigated in detail by Glade et al. (2001).

The DROM 9 landslide

Detailed investigation has been carried out on the DROM 9 landslide located on the northwest slope of the Rheinhessen plateau above the municipality of Dromersheim, south of Bingen (Fig. 1). This landslide is typical of many such bodies in the Rheinhessen area (Jäger 1997), being located in a slight hollow between two ridges (Fig. 3) where colluvium has accumulated. Based on Varnes (1978), Cruden and Varnes (1996) and Dikau et al. (1996) terminology, this landslide can be classified as an active, complex failure. The landslide is divided into shallow and small rotational blocks in the upper part and compressions with flow structures in the lower part. It can be assumed that the landslide is a regressive multiple failure with compounded shear

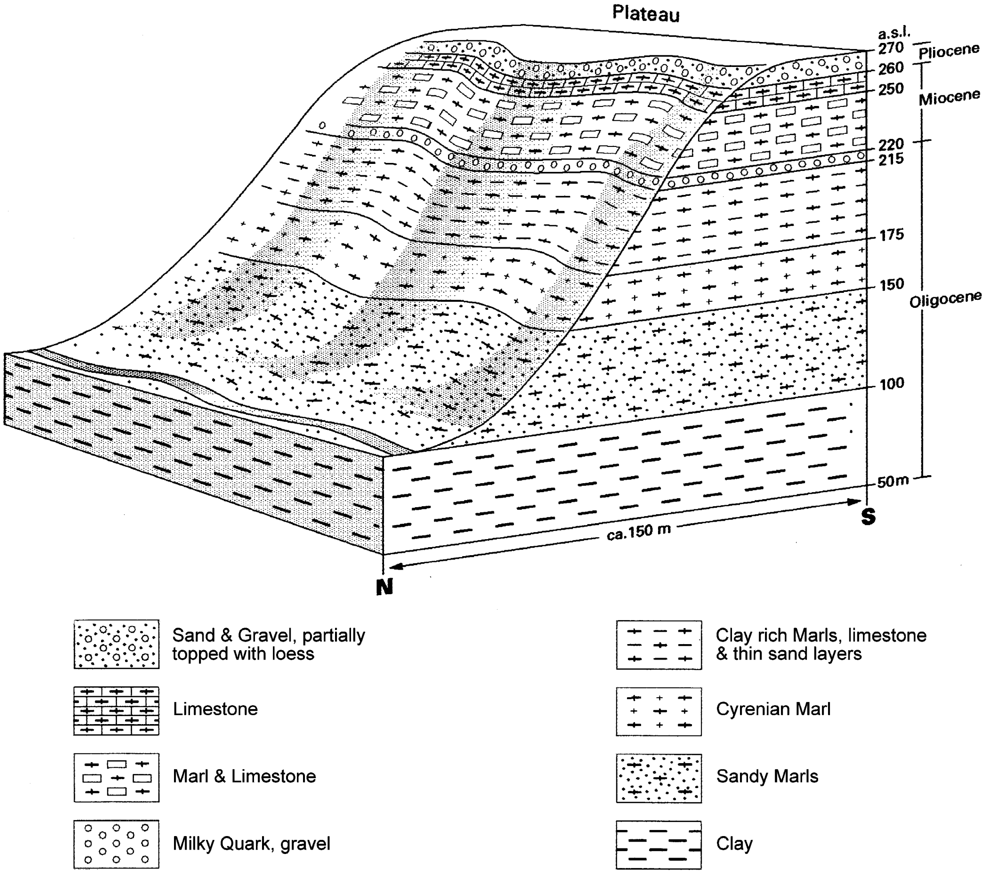

Fig. 2 Generalized lithology of the region (Glade et al. 2001)

planes of primary and secondary blocks (Glade et al. 2001). The landslip mass is comprised of calcareous clays of partially loess-derived colluvium and disturbed Tertiary marls, which in some areas still retain some bedding. The horizons include interbedded fine sand and silt layers together with quartz and calcareous concretions originating from the milky-quartz gravel and Miocene limestone that crop out upslope (Barsch and Dikau 1995a, 1995b).

Although Gers et al. (2001), using dendrogeomorphological investigations, proved some parts have moved sporadically since DROM 9's reactivation during the winter of 1981/82, the initial cracks and sag structure at its top are still identifiable. These sections are currently vegetated with shrubs of various rose plants (Rosaceae) and juniper trees, while the lower area of the landslide is still in use for viniculture (Barsch and Dikau 1995a, 1995b; Dikau and Kuntsche 2000).

Methods of Investigation

Two-dimensional subsurface exploration has been carried out using seismic refraction, the results of which require verification through other techniques (Prinz 1997). The basic assumption of the applicability of seismic refraction measurements is the existence of a distinct boundary between two lithological horizons or layers (P1 and P2) defined by a rapid change in material density which results in an increase in wave velocity ($V_{P2} > V_{P1}$); see for example Bryant et al. (1992). Additional information on the principles of measurement, data analysis and interpretation of wave velocities is given by Bison Instruments 1976; Stein and Zikur 1979; Palmer 1980, 1981; Prinz 1997; Milsom 1996; Scheller 1996; Kirsch and Rabbel 1997; Knödel et al. 1997; Reynolds 1997; Sandmeier and Liebhardt 1997; Pullan and Hunter 1999.

Thirteen seismic refraction profiles were undertaken on DROM 9. One of these, which was composed of three smaller, overlapping profiles, is discussed in this paper. The overlapping approach has a distinct advantage over the single profiles (Kirsch and Rabbel 1997) as the gaps between shots can be avoided. For this study a geophone distance of 3 m was chosen based on the recommendation of Sandmeier and Lienhardt (1997). In order to determine the topography, geophone layout and shot points, the ground surface along the line of the seismic profiles was surveyed using the Laser-Tachymetre TPS-System 1000 from Leica Geosystems.

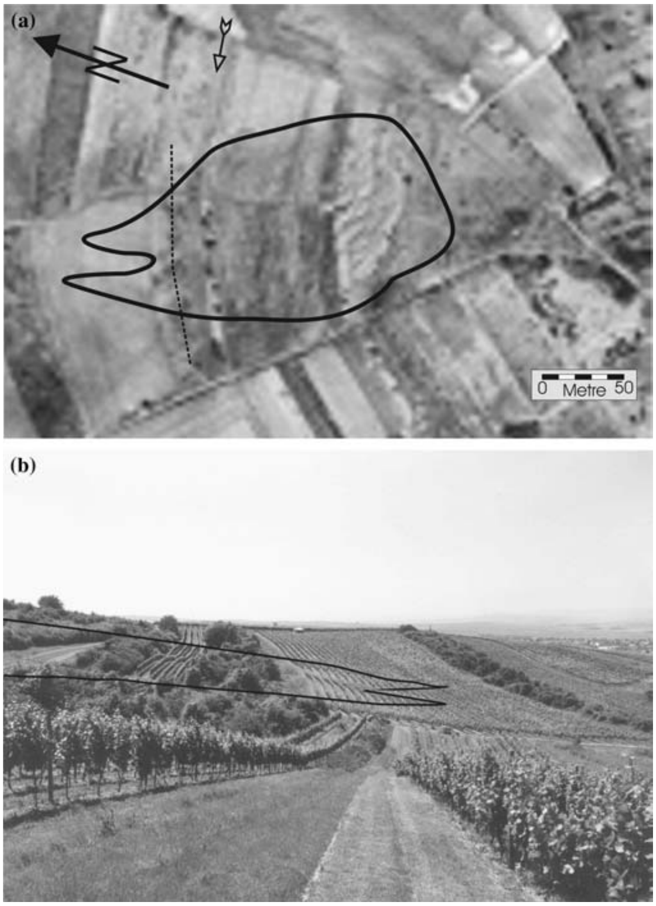

Fig. 3 a Approximate landslide location identified on an aerial photography including seismic refraction profile line (*dashed line* between A and B) and view direction (*arrow with open front*) of (b). **b** Bottom part of DROM 9 in an oblique view to west with approximate landslide boundary

Field work was carried out using a 24-channel digital seismograph (Bison Instruments, Inc.) with a frequency range of 4 to 100 Hz. Due to the low energy of the hammer blows, impulses of three blows have been stacked (accumulated). The analysis of the field data used the software REFRA (Version 2/94–98), developed by Sandmeier and Liebhardt (1997). This procedure allows an optical-interactive handling of seismic refraction data, time-distance data and the development of seismic models through the implemented 'intercept' and 'GRM' techniques ('generalized reciprocal method' based on Palmer 1980, 1981). The GRM technique has been successfully applied in preliminary investigations on the DROM 9 landslide (Dikau and Kuntsche 2000) and hence was also used in this study to determine the seismic wave velocities of the subsurface strata.

The analysis of the refraction data results to provide a cross section was used to determine the optimum location of drop-hammer cores in order to verify the geophysical results. The appliance of drop-hammer cores and documentation of core results was based on the German Institute of Standardization (DIN 4021; 4022). Soil description and documentation was conducted following the recommendations of the German Working Group on Soils (Arbeitsgruppe Boden 1994).

Results of Investigation

Seismic refraction

The NNW- to SSE-trending profile crosses the landslide (Fig. 3). The cross section QP01 has a total length of 165 m, and includes the profiles QP01a to QP01c (Fig. 4). For the section between 0 (geophone 1 of QP01a) and 33 m (geophone 13 of QP01a), no refraction data are available, since it was only possible to analyse the results between geophone 13 of QP01a and geophone 24 of QP01a—a distance of 132 m. The highest point on the left side (geophone 24 of QP01a) is at 187.67 m a.s.l., while the highest point on the right (geophone 24 of QP01c) is at 183.48 m a.s.l. The main channel is at 93 m (geophone 12 of QP01b), at a height of 178.56 m a.s.l. Thus, the section across the depression is characterized by a change of concave and convex shapes. The terrain steps between 30 and 50 m and the convex forms of both landslide tongues at 115 and 137 m can be identified (Fig. 4). The profile is within the Upper-Oligocene horizons.

For the colluvium, an average wave velocity V_{P1} of 370 ms^{-1} was determined. The calculation of V_{P2} for the refractor results in an average of 1,100 ms^{-1} (Table 1), similar to values given in the literature for the respective substrata (Knödel et al. 1997; Reynolds 1997; Pullan and Hunter 1999).

The surface of the refractor has a basin shape, similar to the ground surface, and is marked by alternating concave and convex forms. The average thickness of the landslides towards the middle of the depression is 2.2 m, and decreasing towards the lateral ridges. Near the terrain steps, the refractor appears at the ground surface (45 m).

Drop-hammer drillings

Drop-hammer drillings were used to investigate the depth of the strata change between the colluvium and the underlying bedrock. In total, seven cores (RKS 01 to 07) were taken along the profile QP01 using 22-mm diameter sounding rods reaching a depth between 2 and 3 m (Fig. 3a). These depths were used to establish a correlation with the analyzed refractor depths.

Below the humous-rich A-horizon in RKS 01, the underlying clayey sediment is not defined as colluvium, due to its compact structure and its increasing

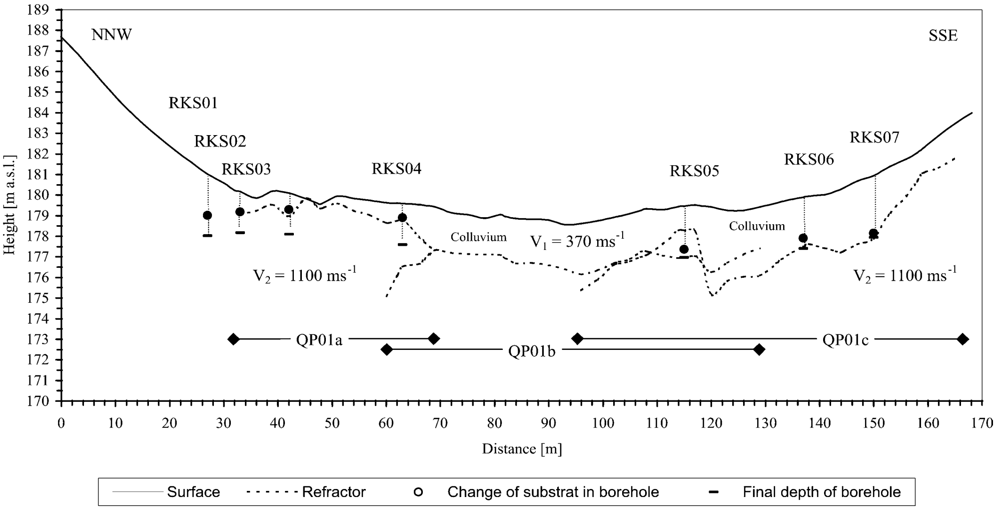

Fig. 4 Results of refraction seismic including locations of boreholes in cross profile QP01 on the lower part of landslide DROM 9 (refer to Fig. 3a for location; *dashed line* between A and B)

Table 1 Analyzed wave velocities VP [ms-1] for the overlying stratum as well as the refractor of the cross sections QP01a to 01c

	Qp01a	Qp01b	Qp01c
Superficial layer [V_1 in ms^{-1}]	390	390	320
In situ bedrock [V_2 in ms^{-1}]	1,200	1,000	1,000

consistency with depth. Its clayey-calcareous characteristic suggests that it is the weathered part of the intact horizons.

The top layer of the cores RKS 04 to 07 is also a humous A-horizon reaching a depth of 0.2 m beneath which is a loamy horizon reaching to depths of between 0.65 and 2.7 m. This has been identified as colluvium, having a layered structure of silts and clays that are remarkably stiff and wet and in which positive pore water pressures are developed during prolonged rainfall events. The underlying, impermeable clay is interpreted as the bedrock over which the landslide moved (Table 2). It is concluded that only a minor amount of additional soil moisture would be necessary to trigger the movement of the colluvium above the shear surface, which is already at residual strength (Veder 1979; Rothausen and Sonne 1984; Krauter et al. 1985; Kany and Hammer 1984).

Discussion

The analysis of the seismic refraction investigations resulted in the profile QP 01, which is composed of the sections QP01a to 01c, indicates V_{P1} velocities of 370 ms^{-1} for the colluvium and weathered mantle and V_{P2} of 1,100 ms^{-1} for clayey marls and calcareous sediments of the Upper-Oligocene.

Comparing the analyzed refractor depths with the positions of the stratum change from colluvium to bedrock determined in the cores indicates a deviation of 5 to 16% (Table 3). This difference is much higher than the error of 6% given for the GRM analysis of Knoedel et al. (1997). However, in addition to errors within the geophysical analysis, the quick and cheap method of drilling will also have resulted in some inaccuracy in the depth determined for the various horizons. Together, these errors could explain the observed inaccuracy such that the drop-hammer drillings can be considered to have supported the analyzed refractor line and

Table 2 Results of drop-hammer drillings RKS01 through RKS07 on landslide DROM 9

RKS	Position within the profile (m)	Height (m a.s.l.)	Potential sheer plane (m b. terrain surface)	Potential sheer plane (m a.s.l.)	Final depth (m b. terrain surface)	Final depth (m a.s.l.)
01	27.00	181.01	-	-	3.00	178.01
02	33.00	180.18	-	-	2.00	178.18
03	42.00	180.09	-	-	2.00	178.09
04	63.00	179.60	0.70	179.90	2.00	177.60
05	115.00	179.47	2.10	177.37	2.50	176.97
06	137.00	179.90	2.00	177.90	2.50	177.40
07	150.00	180.95	2.80	178.15	3.00	177.95

Table 3 Comparison and difference in percent between analyzed refractor and the potential shear plane derived through drop-hammer cores

RKS	Final depth (m b. terrain surface)	Potential sheer plane (m b. terrain surface)	Refractor (m b. terrain surface)	Deviation (%)
01	3.00	2.00	-	-
02	2.00	1.00	1.10	5
03	2.00	0.80	1.10	15
04	2.00	0.70	0.80	5
05	2.50	2.10	2.50	16
06	2.50	2.00	2.40	16
07	3.00	2.80	3.10	10

confirmed that seismic refraction can detect the subsurface structure of this particular type of landslide.

As the refractor position relates to the surface between the colluvium and in-situ bedrock—the basal shear plane of the landslide—this information can be used to establish a more detailed structural model of DROM 9.

It is concluded that this technique can be used where the shear plane is located on the boundary between two materials with significantly different properties, such as colluvium and in-situ Oligocene marls and clays. In the future we hope to establish the depths of this landslide in more detail by undertaking additional profiles and, by using other geophysical methods such as geoelectric techniques, develop a detailed three-dimensional structural model of the shear plane of the DROM 9 landslide, which could be used for slope stability modeling.

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