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ENGINEERING GEOMORPHOLOGY OF THE WIDENTOBEL CATCHMENT, APPENZELL AND SANKT GALLEN, SWITZERLAND. A GEOMORPHOLOGICAL INVENTORY SYSTEM APPLIED TO GEOTECHNICAL APPRAISAL OF SLOPE STABILITY

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ABSTRACT

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The paper presents a method of applied and detailed 1:2000 scale geomorphological and geotechnical surveying, developed in Alpine areas and tested to its engineering consulting value in the Widenbach valley, Appenzell and St. Gallen, Switzerland. The investigation was carried out by a pair of geomorphologists, trained in high relief terrain and well versed in mass movement characteristics.

A programme of "Wildbachverbauung" — the controlling of fluviatile erosion by the erection of dams — was already undertaken in the twenties, but this first generation of wooden dams is now being replaced by concrete constructions.

The Widenbach valley, situated in the marls and sandstones of the folded molasse zone (untere Süsswasserzone) was subjected to glacial scouring and deposition by a branch of the Rhine glacier, transfluencing westwards across the Stosspass, separating the Widenbach valley at 940 m a.s.l. from the Appenzell depression. Postglacially, various earthflows have originated from the instable morainic deposits as well as from the weathered marls and sandstones underlying the glacially oversteepened valley flanks. They have built a two km long earthflow complex filling the Widenbach valley to considerable depth. The townships of Eichberg and Altstätten, situated at the outlet of the system, have since historic times experienced damage to forest and grazing land, houses and roads.

In the midstream and upstream valley sections, the Widenbach is flowing on the earthflow morphology, while the downstream part, already constrained by new dams founded in exposed hard rock, is controlled by fluvial processes. The mass movement dynamics of the midstream and upstream sectors make a completely different engineering approach necessary. When this was made clear by the geomorphological reconnaissance, the lack of data could only be filled by a detailed 1:2000 scale geomorphological site investigation, as time and funds for long-lasting monitoring of the earthflow system were not available.

This geomorphological survey contained the following elements: pre-field airphoto-interpretation, mapping of micro-terrainforms, classification of materials, types and order of movement; it placed emphasis on the behaviour of the various discontinuity planes expressed in the terrain.

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Infiltration zones were singled out and a series of geo-electrical soundings along profile lines selected on the basis of the geomorphological data were made, thus supplementing the surface data with depth information on the earthflow basal contact. The geological structure and lithology exposed in the valley flanks were shown to control the subsurface hard-rock morphology and to induce shear planes in the flow mass over buried hard rock sills, thus expressing themselves at the surface also.

The investigation made expensive exploratory drilling superfluous and was carried out within four weeks and another week of geo-electric profiling. During the complete investigation a close contact between the geomorphological and the engineering teams was effected by common progress meetings and follow-up excursions which led to a fast understanding of the geomorphological maps by the engineering consultants.

A materials map and an instability hazard map were extracted from the geomorphological survey and the profiles. The planning, construction order and engineering design of the midstream sector of the Widenbach are based to a large extent on the produced geomorphological and geotechnical data.

LISTS OF ENCLOSURES (Folded in envelope inside back cover)

1. Geomorphological–geotechnical map, 1986, 1:2500 (3 sheets, format A3).
2. Map of materials, 1986, 1:2500 (3 sheets, format A3).
3. Geotechnical hazards map, 1986, 1:2500 (3 sheets, format A3).
4. Legend

1. INTRODUCTION

Detailed geomorphological mapping (1:2000) formed the nucleus of a geomorphological investigation on slope stability, transport of slope material, activity of several small rivers and nature and composition of gravity transported earth flow material in the Widentobel catchment. It appeared that sufficient measurements and data showing the dynamic nature of the area which might throw light on the complex of geomorphic processes were not available. Site-geomorphological mapping in sufficient detail can bring reliable data for the civil engineer to plan construction work.

Emphasis was on that area where in the near future the Widentobel main channel will have to be trained. This programme of so-called "Wildbachverbauung" has started downstream in the Rhine valley and is now reaching upstream into the most active zone where landslips and mass-flow are feeding the system.

The investigation was carried out after an invitation by the Planungsamt, Sektion Wasserbau der Kantone St. Gallen und Appenzell AR. The actual work schedule was: approximately ten days of pre-field study, aerial photo-interpretation and perusal of previous reports and literature; twenty-five days of field investigation and twenty days of cartographic work and report writing.

1.1. Location and character of the investigated area

The investigated area is situated in the Widentobel valley which drains eastward into the Rhine system (see Fig.1). Highest relief is formed by the Hirschberg (1174 m) to the South and the Sommersberg (1177 m) to the North. The area is underlain by sandstone, conglomerates and marls belonging to the foreland molasse. The highest part is formed by a glacially worked pass, Stoss, where road and rail connections between Altstätten in the Rhine valley and

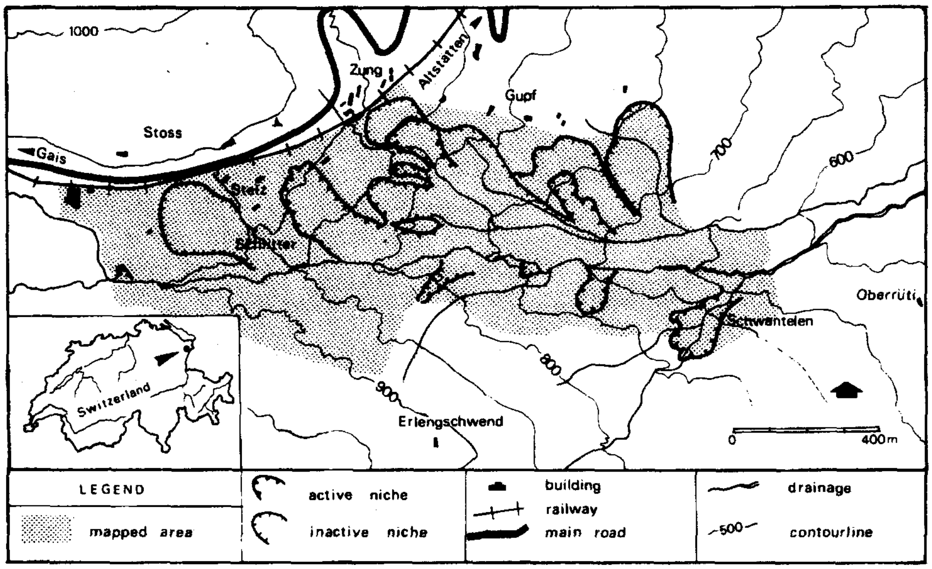


Fig.1. Location of the study area and important slide scars.

Gais in the kanton Appenzell are situated at the northern limit of the most active parts of the northern slopes of the Widentobel valley system (see Swiss Topographic Map 1:25000, no. 1095, GAIS).

The Widentobel valley since historic times has been plagued by mass movement of catastrophic dimensions. The central part of the valley depression is taken up by a large earthflow approximately 2 km long. This earthflow complex is fed by several erosional niches that extend into the valley slopes, endangering construction works, road, railroad and houses as well as degrading productive grassland and forest. Moreover, the production of coarse and fine grained material delivered to the fluviatile system of the Widentobel has reached catastrophic dimensions during flooding, endangering the communities of Altstätten and Eichberg. It is this risk that has led to extensive construction of wooden dams in the past. These have partly been replaced by concrete dams, the section to be controlled in the near future is the most active part of the fluviatile and mass movement transport system.

1.2. Methods of investigation

Prior to the fieldwork a study of available literature and earlier reports was helpful. Next a photo-interpretation was carried out (scale: 1:4600). These data were combined in a pre-field interpretation map at photo scale. Main classification of terrain units, influence of geological denoted parameters i.e. faults, lineaments, formation boundaries and resistant rock units, all influencing the geomorphic evolution of the area, were extracted to a large degree from the air photographs.

During fieldwork mapping, the following activities were carried out: first a general reconnaissance during two days, thereafter a grid was marked at 100 m intervals by painting trees or driving wooden poles to facilitate precise orientation during mapping.

Mapping and developing further detailed geomorphological geotechnical legend on the basis of the Austrian system by Rupke and De Jong (1983) took approximately 28 days. Draughting the final map and extracting final cartographic representations, cross-sections and writing up took another 26 days.

Simple but important necessities used are: detailed aerial photographs flown in a leafless period, altimeter, compass, Abney level, hand auger. Detailed 1:2000 contour maps (1957 and 1979) were extremely helpful, although certain areas had already developed a quite different morphology since 1979.

2. GEOLOGY

2.1. Geological structure (lineaments)

The geological structure of the rock sequence is highly influenced by the effect of the North Alpine boundary fault which rather acts as a zone of imbrication where many faults affect the molasse formations. This leads to many reversals in the stratigraphic sequence but more important, greatly reduces rock strength and, through brecciation, increases the total weathering surface area exposed, also at depth.

The imbrication faults, thrustlike in behaviour, follow the strike of the rock layers and are often near-vertical. Figure 2 shows many different structural units; it is clear that "formational boundaries" are often due to thrusting in this section. In the Widentobel area we may see that the main fault: Stoss-thrust is separating the Forst–Gonten zone containing the granitic molasse from the Kronberg zone built of marl/sandstone sequences. This discontinuity plane is at present morphologically expressed in the backwalls of the Seitenbach (A/B 10/11) and the Schlittertobel (C 7/8) niches.

Apart from the above mentioned NE/SW structures we find especially in the northern part of the catchment different structures with a NW/SE component prevailing (see also Fisch, 1943). This latter lineation is often controlling boundaries of erosional niches and the hydrological network in the area outside the main earth flow. Lineations could be picked out from many details in the pre-field photo-interpretation.

During the field survey a third set of lineations of mainly E–W direction was met. This expressed itself rather in the large scale of surveying then used (1:2000), they are due to tensional fissures controlling micromorphology.

These tensional fissures are well developed at the northern boundary of the main earth flow, recent earthflow material often obliterates the same. The Seitenbach itself is controlled in its mid- and downstream section by an important set of tensional fissures within unconsolidated material.

2.2. Lithology

The area falls entirely within the so-called zone of Folded Molasse. Several NE–SW oriented lithological units are present; boundaries of formations are highly faulted (see Fig.2 after the Geological Atlas of Switzerland, 1960).

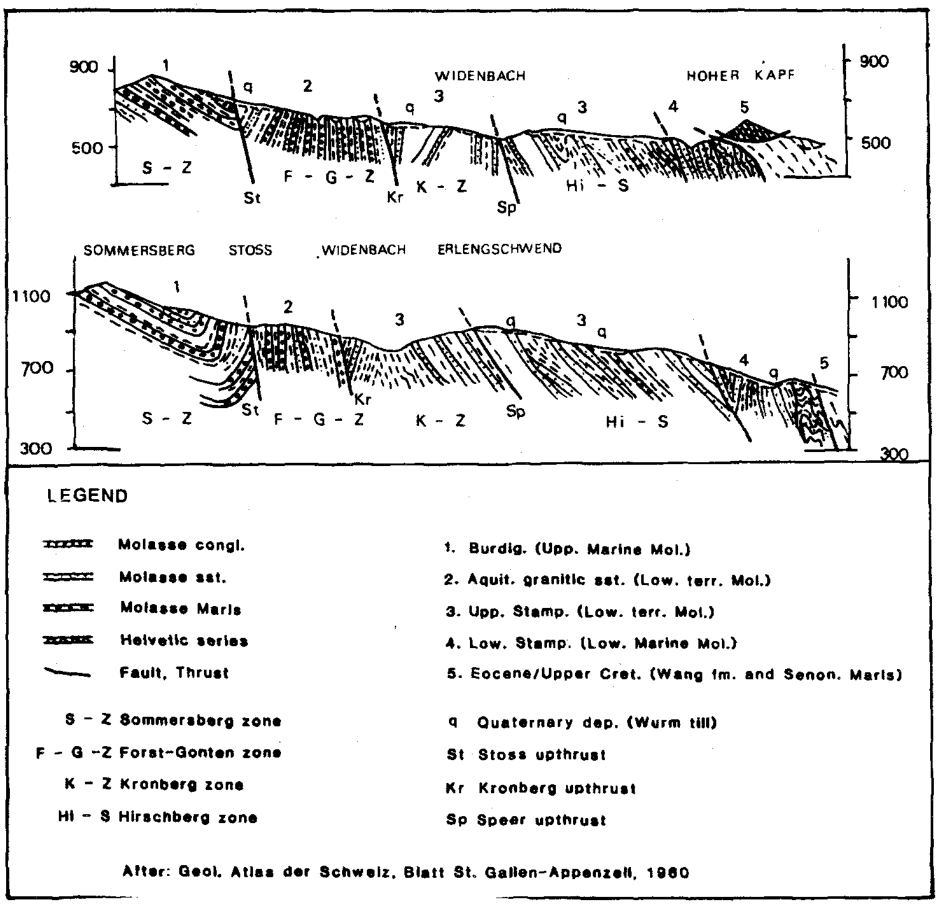


Fig.2. Geological sections, after: Geological Atlas of the Schweiz, St. Gallen — Appenzell, 1960.

The investigated area is underlain by two formations, both belonging to the "Untere Süsswasser Molasse".

The Mergel–Sandstein Formation belongs to the Upper Stampian and contains calcareous sandstones and siliceous marls both yellow and grey coloured. Red, rather clayey marls and shales occur locally. The marly layers are incompetent and extremely impermeable for water, they produce on weathering a type of solifluction clay that flows readily after saturation and easily transports large chunks of other material. In volume the marly sequences are the most important rock type, which fact explains largely the size of the earthflows in the Widentobel valley.

The calcareous sandstones are intercalating with the marly members; they show a massive, fine or coarse grained texture without clear bedding or grading. Due to the fact that most of the area shows high dip values, the sandstone outcrops are forming elongated raised spurs in the area. They produce large amounts of debris due to weathering and lead to a form of mass-movement that can be described as "slow toppling". Tensional fissures occur especially in these more competent rock units. This feature develops even more readily as the incompetent intercalated marl sequences are removed due to solifluction and the like. When sandstone masses are thus exposed, it is observed that they are strongly tectonised. This expresses itself in slickensiding and a multitude of fissures and joints which lower the internal cohesion and rock strength and allow deep penetration of the weathering front. At certain localities the sedimentary contact between sandy and marly material is characterised by load casts. The sandy layers represent sudden incursions of up to five metres thick sandy facies into the clay facies. As these volumes of arenaceous materials are restricted, the resulting hydrological properties are controlled by the marly fine-grained weathering products.

Conglomeratic members present the most resistant lithology in the area, the stability provided by these is the only support of the rail- and road connection at Stoss (see map).

To the south no more conglomerates are found but only marls and sandstones. Conglomerates are exposed E of Stelz in the backwall of a niche below the railway, where they are intercalated with massive sandstone layers and thin sandy marls ("Leberfels"). This formation being more coarse-grained forms a large aquifer and, as the conglomerates extend northwards under the Sommersberg in a synclinal structure, part of the water destabilising the Widentobel area stems from there (see Fig.2).

2.2.1. Primary materials (numbering as in map materials Annex 4D)

1. Nagelfluh, conglomerates This formation is represented by a vertically arranged outcrop in the backwalls of the denudational niches directly south of the railroad, and represents a backbone resistant to backwearing in the slope. In combination with the high conductivity for water this material as such is rather stable. However, due to the presence of the active niche just below, the future slope development will lead to a dramatic sliding of this portion of the slope (A/D 10/11; C 7/8), taking sections of rail- and road connections with it.

2. Calcareous sandstones This type of rock is rather weakly lithified, grains are not well cemented, the matrix weathers easily due to the high carbonate content. Nevertheless the sandstone sections do appear as longitudinal steep-sided spurs in the relief.

Sandstones are characterised in morphology by:

— steepsided spurs standing in relief;
— tensional fissures reducing formational outcrops, through:
— production of blocky debris to relict hills and thus
— feeding large block streams (C 10);
— exerting pressure/strain on the surrounding marls in those cases where the sandstone bodies have become sheared and rootless.

3 and 4. Yellow and red grey marls. These series are extremely incompetent and impermeable, sensitive to weathering and liquefaction. They form areally the most important rock type of the Widentobel catchment.

The relation of the lithology with the geomorphology leads to:
— formation of large slump and slide masses, even in non-saturated condition of the material,
— subsidence along activated shearplanes without appreciable internal deformation, and
— liquefaction upon saturation, production of mudflows.

5. Subglacial till, "Grundmoräne" This diamict material consists of a densely compacted sandy clay matrix containing subrounded glacially striated erratic boulders and pebbles, distributed at random in the matrix. Where encoutered, the till is smeared out by the Rhine glacier system as a mantle over the molasse/rock substratum. The till cover may vary in thickness from one to several metres in thickness; in fresh state this material is relatively dry and impermeable, due to the glacial compaction.

2.2.2. Secondary materials

Under this heading we classify those materials that have originated by mass movement of fluviatile processes from all available primary material or from earlier deposited earthflow or fluviatile material (see Fig.3).

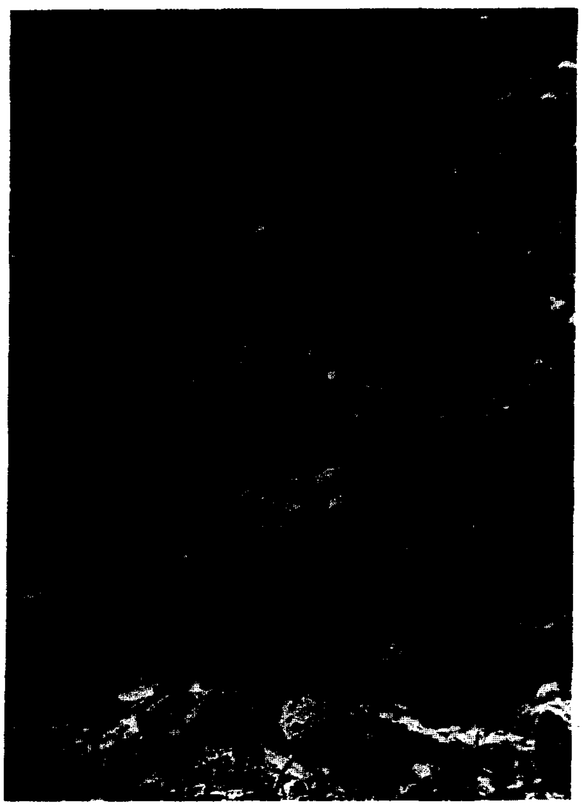


Fig.3. Earthflow material resting on in situ marls. The material consists of a poorly bedded mixture of lodgement till, wathered marl and solifluction material. West of Schwantelen outlet; Map quadr. F 19.

We have recognised a series of secondary materials composed of weathering products of the rock formations mentioned above and of the morainic materials. These secondary products show a great variety in composition, grainsize and water content. Most of these are highly mobile due to the high percentages of clay minerals supporting the various other components. In the materials map these secondary products are presented in a continued numbering system (6–15). By comparison with the geomorphological map and the geotechnical risk map it will be clear that the mobility of the flow complex is primarily stemming from the clayey mass movement materials. (Note: Hatched (striped): areas denote waterlogging in B/C. Non-hatched: relatively dry areas within B/C; this is often due to primary porosity of the material or to secondary porosity due to tensional fissuring.)

2.3. Influence of the last glaciation

During maximum ice-fill of the Rhine system, a lobe of the Rhine glacier succeeded in advancing over the Stoss pass invading the Appenzell region. This has led to glacial erosion as well as deposition of glacial sediments. At places (see map) several metres of subglacial till are present covering the Molasse sequence (see area B14 or D3). In the lower central part of the Widentobel valley no till has been encountered.

The till is rather high in stone content while the matrix is sandy, probably due to local subglacial erosion immediately prior to lodgement. Most coarse material stems from southern and western production areas of the (Upper) Rhine catchment.

As to morphological development: during the Pleistocene slopes may have been steepened in certain localities, in general the present relief is taking advantage of:

— instability and impermeability of till producing slide masses, and
— the predisposition of valley depressions between sandstones already excavated earlier and partly filled-in by till.

2.4. Airphoto-interpretation

Important results of the pre-field interpretation were:

Insight in the grouping of individually very complex earthflow masses and their morphology. The need for detailed study in the field was clear if relevant insight into the mechanism of earthflow and its spread over the area were to lead to a helpful diagnosis in terms of engineering.

A striking lineation influencing the geomorphology is the NW–SE direction recognizable in all northern niches. It can be extended across the rail-road influencing the area to the North (hydrology, weathering). This latter important lineation appears to coincide with a slightly changed direction in the Nagelfluh conglomerates, in a NNW–SSE direction as already noted by Fisch in 1943.

A prominent lineation controlling morphology is due to the strike of the sandstone beds to the South of the Widentobel (see Fig.2).

3. HYDROLOGY

The influence of water in the Widentobel area can be split into the following components: atmospheric water, local precipitation, infiltration and groundwater.

3.1. Atmospheric water

Atmospheric water, including snowmelt water, partly drawn from the periphery, is brought by several "channels" into the area (see C 4, D 6, E 6/7, CDE 8/E 9, B 9/10/11/C 12, C 14, BCD 17). Only part of the drainage network is the result of erosive action, many surface channels are following low zones left over between earthflow masses, other drainage lines are caught in tensional fissure systems (e.g. Seitenbach) with ensuing water infiltration (see Fig.4).

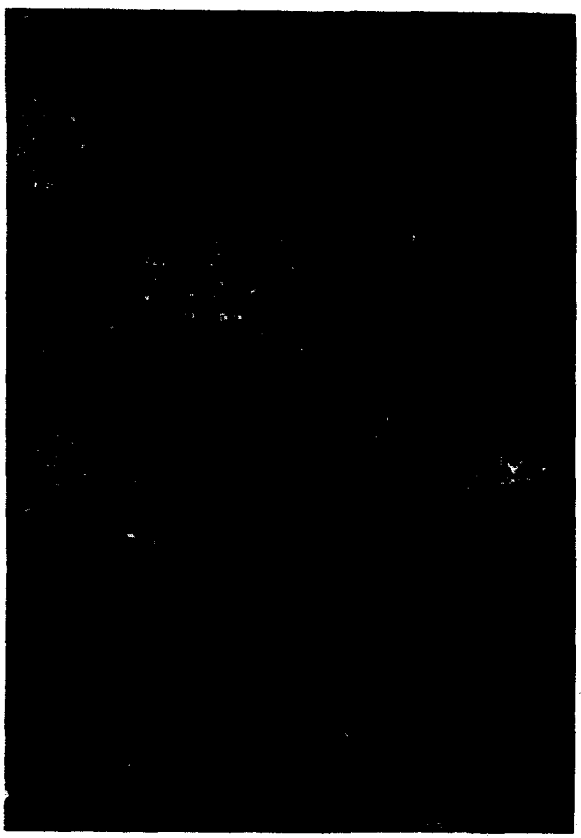


Fig.4. Tensional fissures in partly dried out earthflow material, at Hau; Map quadr. E 12.

3.2. *Local precipitation*

The local precipitation and snowmelt water are taking advantage of the "cracked" micromorphology, the result is a lack of concentrated runoff and spread-out internal drainage through the secondary shear-induced permeability.

3.3. *Infiltration*

The Seitenbach infiltration zone (D 13, D 14) is of special interest. Disregarding local (less than 2 m deep) relief and moisture differences, we may consider the materials in the intervening sector between Seitenbach and the present Widentobel as a fully saturated homogenized earthflow mix. The water table will show a gradient and flow direction from the Seitenbach area to the exfiltration zone in the Widentobel channel SE-wards. Any removal of material from the N bank by undercutting erosion of the river, or due to artificial excavation, will lead to enhanced instability of large masses. The N bank between Schwantelen and Hau is exclusively built of this material; this is the Widentobel section under planned construction in future years.

The southern embankment of the Widentobel is formed by locally different material, not yet homogenized to a degree as found in the northern bank material. Here in the sector Schwantelen-Hau we still find in situ rock with varying strength. In the intervening active slope parts or niches, local groundwater conditions are comparable to those in the northern bank material. The precise selection of a location for dam construction is directly controlled by this factor.

3.4. *Groundwater*

It is known that deeper groundwater flow from the Molasse Nagelfluh underlying the area to the NW (Sommersberg; Behrli, 1985) is feeding springs just to the N of and outside the Widentobel. Earlier hypotheses regarding groundwater flow from the pass area W of the Widentobel are refuted by earlier reports; besides, this supposed part of the catchment is well covered by a closed mantle of compact till. Groundwater is feeding the Schlitter itself and is tapped in the gallery (D 7) of the Schlittertobel niche. Flow of seepage (groundwater) at the base of the till in these northwestern reaches of the Widentobel is often not recognized when the till cover is still relatively intact.

4. GEOMORPHOLOGY

4.1. *Geological factors*

Lithology: this zone of the molasse is characterised by a suite of marls, clays and minor poorly lithified sandstones. These rocks weather readily, have a low resistance to shear and are subject to rapid mass wasting.

Structure: this zone is relatively close to the boundary Molasse/Helvetic nappe, which is rather tectonised. Attitude of the formations is near-vertical and many faults, joints and tectonic planes are developed leading to reduced rock strength (see Fig.5).

4.2. Hydrological factors

High precipitation is added to considerable throughflow from the North where the next synclinal structure containing sandstones and Nagelfluh conglomerates looses deep groundwater to the Widentobel catchment (see also Behrli, 1985).

4.3. Geomorphological factors

Glacial erosion and the accompanying "oversteepening" of rock slopes during the last glacial epoch with ensuing rebound of the rock walls after unloading is an important geomorphological factor. So is the deposition of a mantle of impermeable and instable material in the form of subglacial till (see Fig.6).

Strong fluviatile and denudative "excavation" has worked since the disappearance of the glacier. The geological and hydrological factors make the area susceptible to mass wasting; once it has been started, this development is rather accelerating than diminishing.

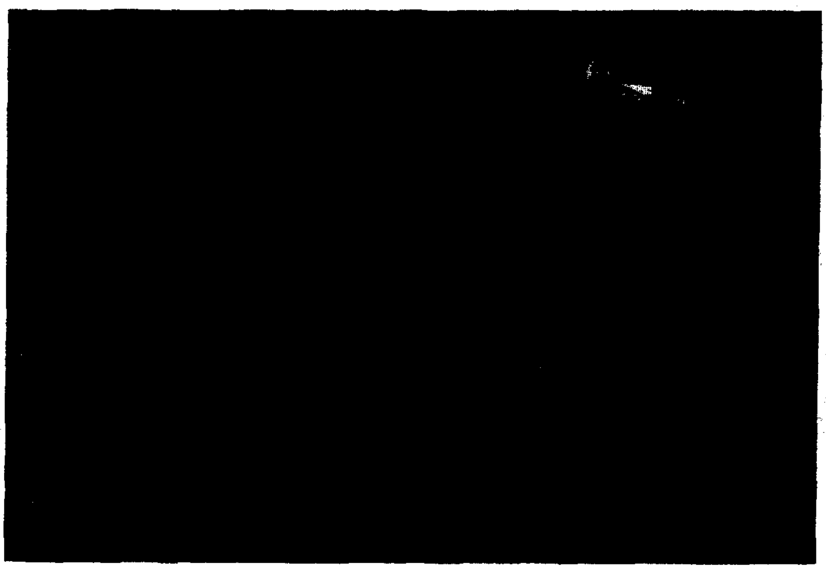


Fig.5. Large slump system developed in marls with 3–6 m thick till cover, 250 m E of Stärchenmühli; Map quadr. D 4.

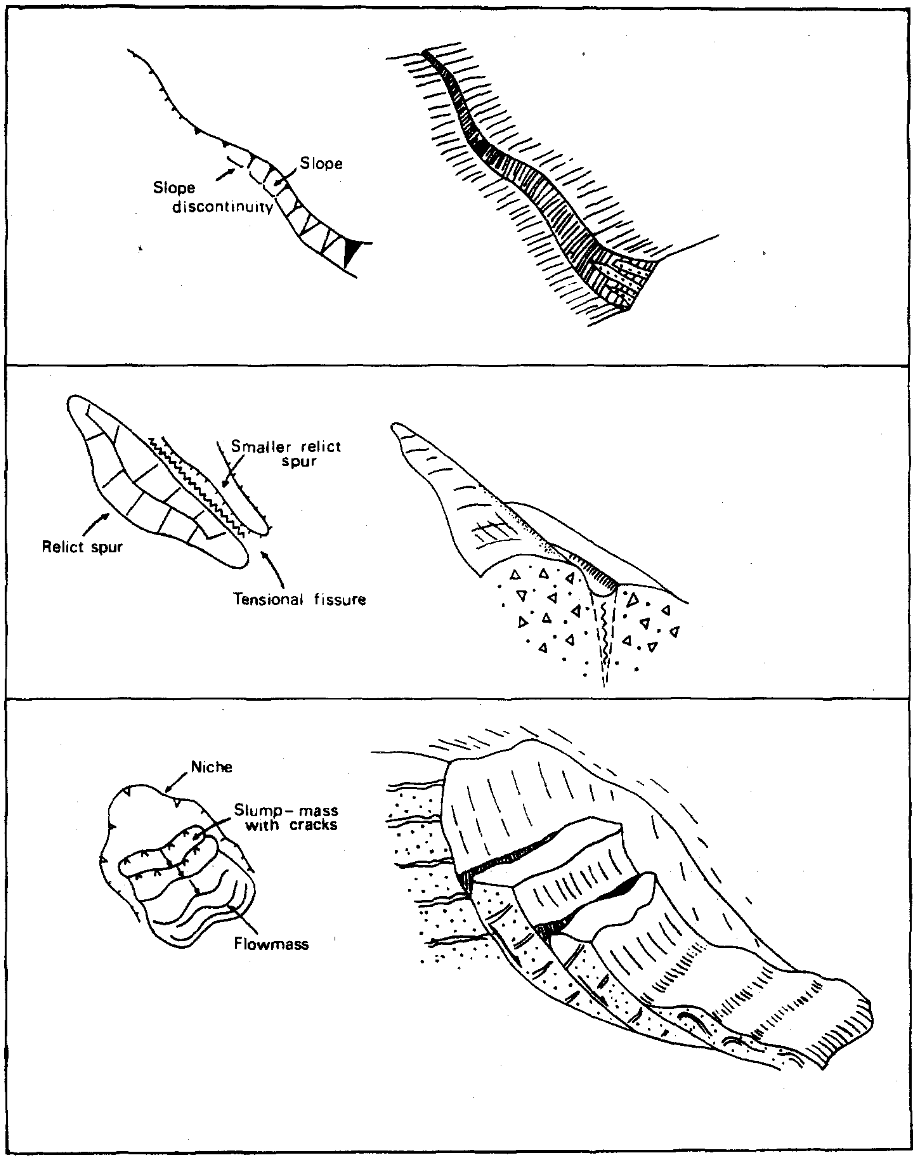


Fig.6. Relation between form and material complexes (at right) and the relevant geomorphological cartographic symbols (at left).

4.4. Basic concept

The following overall concept of the Widentobel catchment in analogy with other catchment areas must be borne in mind.

Within a catchment area containing instable materials, normally three subareas can be recognised.

(A) Downstream sector: deep river incision, a high river erosion rate, a large volume of eroding water leading to a narrow cross-profile; the channel is in a rather fixed position, there is less mass movement.

(B) Midstream sector: river incision is active but not yet deep; here bank erosion is an important sediment producing process and instability in adjoining terrain becomes very important. All forms of mass movement are highly active, here large volumes of earthflow material are ready for activation, especially by bank erosion. The drainage state of the material in this section is poor and large volumes of water also derived from the upstream sector are present in sector B. The cross profile of the valley is much wider than in A.

(C) Upstream sector: Incision of river channels is not developed or poorly developed, large volumes of relatively dry instable material are present, bank erosion is less important than in (B).

In the case of the Widentobel valley drainage system construction work has been progressing from D (the alluvial fan area) through A (see Fig.7). At the moment, 1985, zones B and C, which have a comepletely different and much less predictable geomorphological nature than zone A, are to be analyzed as to possible geotechnical solutions.

4.5. Summary of the history of mass movements

4.5.1. Prehistoric and early historic mass-movements

Seitenbach niche Zung–Gupf (B/C 10–13). This amphitheatre or denudational niche must have been an important producer of "earthflow material", considering the giant size of the niche.

The northern slopes of the Widentobel catchment are displaying many oval-shaped denudational niches at various levels down till the Rhine valley floor. The southern slopes have a younger and, due to geology, different development.

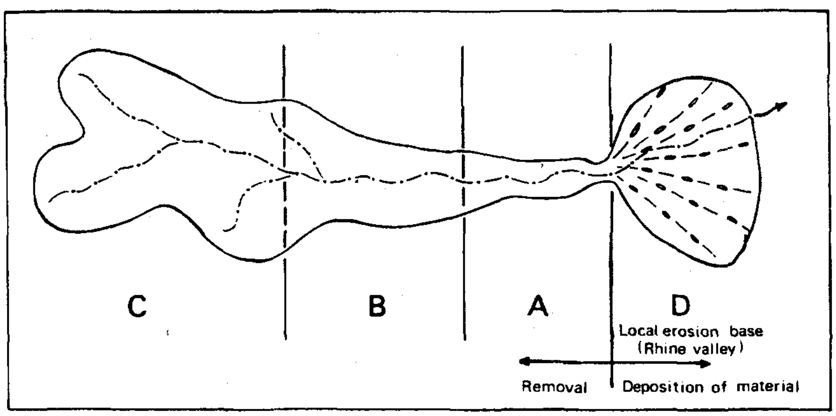


Fig.7. Concept of fluvial transport system: Compartments D: depositional area; A: fluvial deep incision predominant; B + C: geomorphology controlled by massmovements.

4.5.2. Historic and recent mass movements

There have been several accounts of mass movement, for example:
— Schlittertobel" Schlipf, 1910–1930—1945 (C/D 7–8);
— Seitenbach niche (Zung-Gupf), 1955 to present, several localities;
— SSE Gupf, birth of a new niche? to present (C/D 15);
— "Hau," 1960 to present (EF 12–11);
— Schwantelen", 1968–1982 to present (F/G 18–20);
— Several localities in the main earthflow as a result of internal pressure due to differential loading, undercutting and oversaturation (E 11–12; EF 17–19). (The presence of swelling clays has not yet been established);
— newly developing niche E of Rossfelsen, southern part (F 14);
— active niche E of locality 734, southern part (F 15–16); and
— newly developing niche W of Schwantelen, southern part (F 17).

It may be stated that prior to 1960 the development of earthflow morphology and feeding of the main mass transport system was controlled to a high degree by formation, reactivation and extension of niches in the northern valley side. This asymmetric development and the consequent production of earth-flow material in turn pushed the Widentobel to the South, now undercutting the southern slope. As a reaction, since 1960 recent unstable masses originate from the southern slope, partly pushing the Widentobel to the North again.

4.6. Development and dynamics of the geomorphic units of the Widenbach catchment

4.6.1. Central part of the Widentobel-Seitenbach valley system

This area is an active earthflow zone in its lower and midstream sector up to the 820 m contour. The degree of activity is varying.

Characteristic is a rather small slope angle (mean value 11°–12°), interrupted by steeper tracts which form the boundaries of lobes higher in the total earthflow complex. The earthflow complex receives its material from several smaller and larger flows and slides mainly from the northern slopes. The original properties of the parent rock such as layering, sorting, permeability and cohesion have been completely obliterated. A new stratification has not developed.

The material in the earthflow has a very high volume percentage of silt and clay particles, a minor volume is taken up by coarse erratic and sandstone debris components.

The following morpho-units can be recognised:

(1) Flat, near-horizontal (0°–5°) parts in the earthflow complex, swampy waterlogged surface without clear fissuring or cracks. No appreciable slumping activity (E 15). Low "open" vegetation: grass and reeds. In these units the groundwater level is at or near the surface; internal drainage, primary and secondary, are insufficient.

(2) Flat, near-horizontal (0°–5°) parts in the earthflow complex with high bushes and fir tree vegetation. Generally dry areas because of extensive tensional fissuring creating secondary permeability (E 13/14). Slumping in the form of narrow elongated slices is active, the percolation of water into the open fissure system maintains lubricated sliding planes.

(3) Margins of Widentobel water course. Due to fluviatile undercutting of the bank material and the exfiltration of shallow groundwater lowering shear strength of the older earthflow material, active slumping and fissuring is seen. At the contact with the Widentobel itself many small debris flows deliver large amounts of material to the river. The slumping is characterised by very narrow and small slices (30 cm–2 metres) of material. Each slice is situated at a level of 10 to 100 cm lower, boundaries are all active without vegetation and are often waterlogged. The limit between these active margins and the "more stable" surface is conspicuous: it forms a vertical step in the terrain 1–2 m high, without vegetation accompanied by a clear fissure (sliding plane) often with stagnant or slowly infiltrating water. As stated, water-filled trenches 30–40 cm wide and 1–2 m deep occur between slump units (EF 17). Comparable micromorphology is present where an active flow-mass pushes against the central less active temporarily stabilised mass (E 11–E 12).

(4) The margins of the central earthflow complex; these are conspicuous by the intensive development of tensional fissures, especially the northern margin. These fissures can be followed for hundreds of metres parallel to each other. They also serve as boundaries between morpho-units, e.g. restricting older flow masses to a narrower spread, reducing the original positive microrelief (5–15 m) to elongated relict hills (D 12–15, E 16–18).

The fissure systems are interpreted as the expression of discontinuity planes due to pressure differences within the flow mass and asymmetric unloading. In cases they may represent deeper seated faulting or buried relief.

Attention is asked for the parallellism of the main water course and the major tensional fissures (D 12–15, E 16–18).

Here, the cross-sectional profile shows a peculiarly broad and stretched configuration. The fissure system mentioned (D 12–15) is responsible for the diffuse infiltration of surface water from the Seitenbach catchment (Fig. 11).

Important to visualise: the complementary result of the fissuring is the enhancement of narrow steep-sided relict spurs (see also 4.6.1 under 4; DE 11 through 17).

4.6.2. The southern valley side

As stated earlier, the Widentobel including its undercutting erosive power has been shifted rather recently to the South, i.e. pushed away by the giant volumes of earthflow material from the North. This means that since 1960 and in the near future the southern valley side has been and will be under heavy attack by the river and most catastrophic breakouts will be expected here. When observed in more detail we note a rather steep slope, generally ranging from 20°–40°, interrupted by several NE–SW stretching elongated spurs, each containing a backbone of molasse sandstone. The intervening initial subvalleys represent incompetent rock in the form of clays and marls. These are easily triggered to produce giant volumes of earthflow material directly dumped into the Widentobel.

The following morpho-units can be recognised:

Sandstone spurs. These show, along their local water divide, a relatively gentle gradient (15°–25°), which steepens to near-vertical next to the Widentobel. In cross-section the spurs have steep flanks (30°–90°), illustrating their hard rock nature. Massive and fresh sandstone is exposed in such flanks, due to the fan-like opening up of vertical shear planes or, due to tensional fissuring, large slices become detached producing active local rockfall.

Depressions and niches between sandstone spurs. These complex depressions correspond with less resistant lithology more easily excavated by erosion and mass movement. Two of the recently developed and most active mass wasting areas are thus situated.

The "Schwantelen" flow mass. (FG 18, 19, 20) reaches a dimension of about 17.700 m^2 after reactivation since 1982 (see Fig.8). The backwall is still retreating fast and has a size of 100 m across in the headwall niche, where we find a number of very large slump masses. The material exposed in the niche consists of reddish, grey and yellow marls, intercalated with few thin sandstone layers. All of the area has been covered by a 1–3 m thick mantle of subglacial till by the Rhine glacier.

In the adjoining terrain a number of tensional fissures are seen; they are indicative for the extension of the future expansion of the Schwantelen niche. One of these has been put to use as a drainage ditch!

Characteristic in the Schwantelen unit are the following observations: the material in transport becomes homogenised over short distances (100–200 m). The earthflow tract narrows near its confluence with the Widentobel; the earthflow shows as a large debris flow or homogenised accumulation, with steep-sided margins up to 32° and a gradient of the surface of approximately 20°. At the surface and at the foot the Schwantelen flow is rather blocky (up to

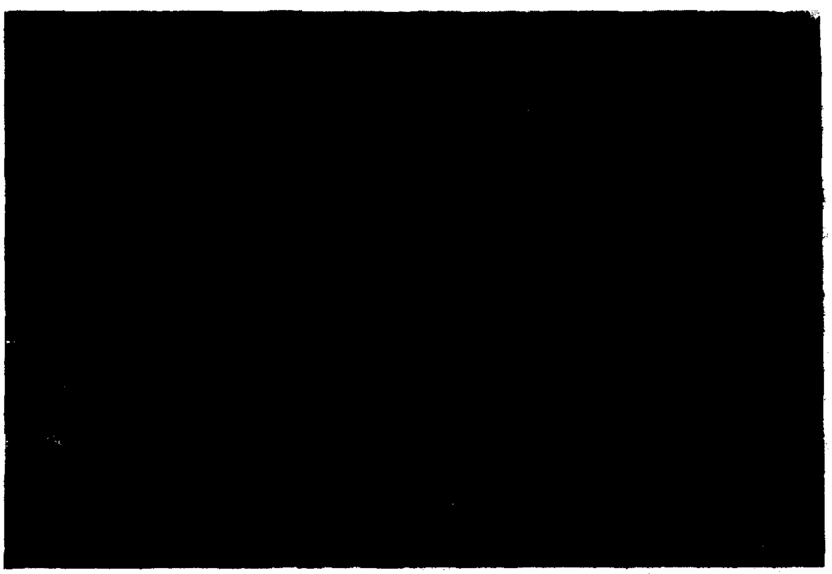


Fig.8. Large slumping complex, western rim of the Schwantelen niche; Map quadr. F/G 18/19.

several cubic metres), floating in and on top of the fine-grained marls and muds.

This debris flow is extremely active and gives rise to mudflows at its margins. Internal movement prevents the estabishment of a proper water coarse in the Schwantelen mass; this endangers the flow-mass even more. A particular risk is the gradual overpushing of the frontal slope (see below).

At the mouth of Schwantelen into the Widentobel the input of debris into the fluviatile system is extremely heavy, the space behind the recent dams (1982) has been completely filled, and overflow is near.

To the West of the Schwantelen area proper, a denudational niche excavating from a point upstream of the Schwantelen mouth now makes contact with the Schwantelen mass wasting area, in the near future the intervening area may also collapse.

The Hau flow mass complex (EF 11, 12) forms a difficult problem in the area. In this denudation area, rather organised as an elongated narrow niche confined between two high sandstone spurs, the earthflow material itself is cut up by a rugged microrelief showing many tensional cracks and fissures and long slump masses. At a lower elevation (F 11; ±790 m) water exfiltrates in a diffuse manner, here mudflows originate. This material rapidly flows away after which the depression is developed more deeply and unloading of the walls of sandstone results. The sandstone spurs then disintegrate. At the NW boundary of the Hau niche a form of sheeting is active where large rock slices (5 m long, 5 m high and 1.5 m thick) "topple" and become embedded in the earthflow mass. This process of toppling has been observed in the months of July and August 1985: movement from vertical to 30° from the vertical, creating a crevasse of several metres width took 8 weeks (see Fig.9).

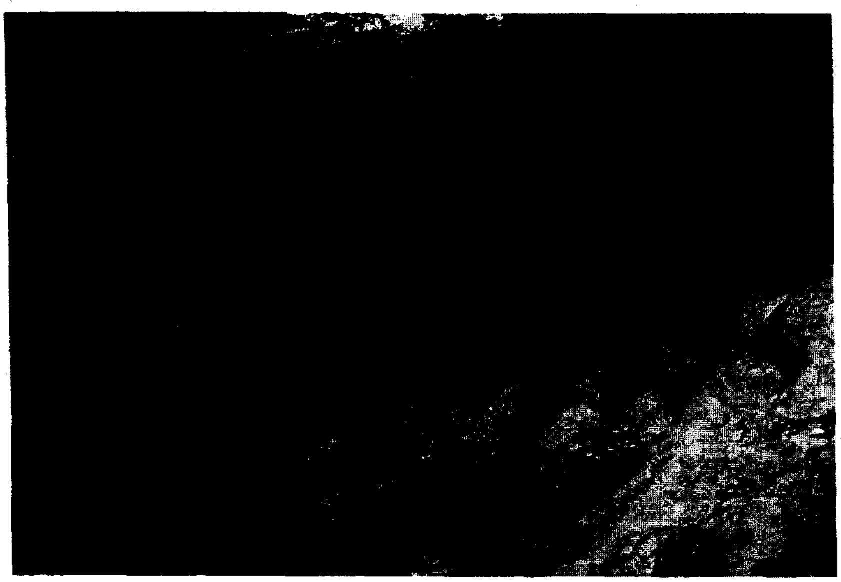


Fig.9. "Micro-ridge" consisting of coarse debris, given off by sandstone and elongated due to movement of earthflow material in Hau flow mass; Map quadr. F 11/12.

At the SE limit of the Hau niche the sandstone desintegrates producing a block-stream at the foot of the vertical sandstone slope, (F 12) containing blocks of 5 cm to 1 m in diameter. This block stream spreads into a fan with a gradient of 18° that can be traced till the Widentobel. The microrelief again is rugged: many smaller (10–50 cm) steps and cracks demonstrate the fast movement and internal deformation going on. The pressure exerted by the Hau flow pushes the Widentobel course to the North, along the eastern margin an outcropping shear plane denotes the boundary between fast moving debris of the Hau unit and the less active surrounding material. Slightly lower (±780 m) the debris flow "overrides" this latter mass to reach a former course of the Widentobel (E 12/13) in the direction Rossfelsen. In due time the mass will be able to reach the present Widentobel course near the 740 m contour (E 13). The area "encircled" by the main Hau and secondary earthflow just mentioned, is in itself showing many signs of instabilty (wet slump masses).

The influence and extension of the large Hau debris flow is not restricted to the southern bank of the present Widentobel course:

Within area DE 13 the contour pattern of the 1979 survey was not fitting the terrain configuration at all. (As the terrain was without higher vegetation during the aerial survey of 1979, we assume that the 1:2000 contour map was correctly prepared).

The large depression in D 13 greatly reduced in size since 1979.

An earthflow mass lobe-like in configuration, extending in the same gradient and direction as the Hau flow mass, is present. This mass "encircles" the high and conspicuous E–W trending relict spur (D 11/D 12) up to its easternmost tip.

Radially arranged drainage patterns in the young lobe of earthflow material make use of fissure systems. These linear depressions can be traced upstream and are extensions of similar fissures in the S flank of the discussed relict spur.

Combining the above summarised geomorphological data, we interpret the lobe-like mass as the NNE-ward extension of the same flowmass across the Widentobel. In this view the Widentobel has not succeeded in keeping its path clear from Hau-delivered mass-wasting material. Instead, through time the Widentobel has been pushed to the N but is also uplifted. The channel is in fact floating on the Hau earthflow, fluviatile erosion is by far insufficient to balance the delivery of material by the Hau "dump".

In combination with the raised Widentobel floating on the Hau flow mass, we find a depression to the NE of the front of this earthflow (D 13); this depression is 15 m deeper than the Widentobel channel. The depression is draining to the Seitenbach. A relatively small flow mass, damming the Widentobel upstream of the Hau flowmass, could raise the channel of the Widentobel by 2 metres or more; the Widentobel would then easily overflow towards the Seitenbach depression making use of the mentioned fissure system around the relict spur (D 11/D 12).

This volume of water could then not be accomodated by the Seitenbach which actually would erode fast, producing large amounts of debris and mudflow material downstream. Moreover, all investments in training the Widentobel down stream of the Hau flow would become worthless. Various small niches "in statu nascendi" can be observed, these are summarised before and will again be discussed in the chapter on geotechnical risks.

The southern valley slope between Hau and Tieftobel. In this area, surveyed during 1986, the same relation between lithology and geomorphology exists as found east of Hau.

The southern slope of the western part of the Widenbach valley may be subdivided into two zones:

— a lower and steep zone bordering the Widenbach; this zone becomes broader going eastwards;

— a higher and less steep zone covered by till.

The transition between the two terrain types is often quite sharp. The denudational niches accompany small streams draining the upper slope. Flowage of weathered marls from the depressions between the sandstone spurs is the result of exfiltration water from the till mantle. The morphology of the smaller spurs is different from those further east: the flanks are less steep as the influence of subsidence or tensional processes is less.

Due to the larger dimensions of the complex of sandstone members, extended and relatively high raised areas exist. These are split up into a series of relict spurs separated by tensional cracks (G 7 and G 8). The decomposition of these resistant zones is caused by:

— Weakness zones in the material: joint planes, layering excavated by weathering, and intercalation of marls (as exposed in smaller niches);

— expansion, when the marly layers in between the sandstone spurs have been removed by erosion.

In areas of the slope where the activity is intense, development of steep walls takes place. Here sandstone is subjected to weathering in the same way as near Hau. At the foot of these walls consisting of calcareous sandstone, we find bare debris cones.

The strike direction of the rocks parallel to the culmination of the smaller ridges (belonging to the second order, acc. Horton) is WSW–ENE in this area. In many places however, this general direction is erased by active flow masses. These flow masses show, in the higher parts of the slope, a tendency towards a northern direction; in the vicinity of the Widenbach they swerve to the NE. In this way they override the smaller hardly raised sandstone spurs.

This tendency exists definitely in the niche above Hau (E 11) and in the western adjoining niche, where simple drainage ditches lead the atmospheric water away from the Hau niche proper. Here, earlier dams have been constructed but not maintained.

In the large niche 200 m west of Hau (EFG 8, 9) we find the same change in direction in geomorphologically active surroundings. Also further west we see such a conspicuous change in direction.

In the zone west of Hau the following active niches are important, as they may influence the future constructions:

Niche W of Hau, in the higher part of the slope (EH 10, EF 11). This niche is in direct contact with the Hau niche proper. Water flowing over the terrain surface leaves this adjoining niche and flows into the deeper developed Hau area. The drainage system dug to prevent such a flow of surface water into the Hau niche is in bad condition, water infiltrates into it and lubricates the material of the Hau sysem. The niche is wet and active, notwithstanding the drainage ditches and the planting of fir trees. Smaller niches produce active flow masses from water-saturated marly debris (G 6).

A very active large niche borders the Widenbach at one side and extends at the other side in upslope direction up till the partly destroyed forest road. This relatively large niche is fed by a smaller niche situated above this road; the area under denudation reaches upslope to the border of F 10. The flow of material from the lower niche has changed the alignment of the forest road and also threatens three wooden dams in the Widenbach.

It can be observed that the flow mass is pressed through a depression between two sandstone spurs. This means that the flow mass may enter into other depressions, e.g. north of the small water-filled pond (F 9); this would be possible when the incision of the small creek is used.

The risk would be that this active flow mass would follow a shorter route through the niche mentioned, and would reach the Widenbach in this manner. The intervening sandstone spur is already quite low and cut up by tensional fissures (G 9).

4.6.3. The northern valleyside

Here a similar subdivision of major geomorphological units is possible; complicated mass movement niches are separated by high, more resistant relict spurs. The strike of the rock units is still SW–NE, dip amounts are also near-vertical. As the strike direction gives an angle with the main valley direction, mass wasting niches are arranged more according to the weakness zones and lineations in a NNW-SSE direction. Morphologically this leads to a more complicated situation than in the southern valley side.

At two locations denudation activity has reached the railway and road connections between Altstätten (Rhine valley) and Gais (Appenzell), the corresponding niches "eat backward" into a productive and more gentle grassland topography above the steeper valley slope proper. A Nagelfluh conglomerate bank forms the last protection against slumping of sections of the railroad.

From West to East we find:

Stelz niche. This depression is poorly drained by the Schlittertobel. Conspicuous are its wide form containing at the western margin many large slump masses (DE 4/5) and the southern closure by a sandstone spur desintegrating by fissuring. The material in the NE flank is more saturated leading to small-sized slump masses and mudflows. This flank is cut by the Schlittertobel which has a fair discharge. The backwall of the niche is split up into many smaller niches excavated into the conglomerate and linked with solifluction fans at their outlets.

Schlittertobel niche. This very complicated depression has originated in its present form during the years 1930–1945. Quite different types of mass movement geomorphology as compared with 'Stelz" above, are encountered here. The periphery is developed in extremely steep slopes (>40°). At many places in the western side non-weathered rock outcrops are present. The formations are subjected to dilatation expressing itself in various forms of tensional fissures. The relict sandstone spurs are modified in "strike" direction: due to all the gravity-induced fracturing, the morphological expression of the sandstone is deflected southward. We interpret these spurs as rather rootless floating bodies. The structural geological picture cannot explain this deflection. The eastern periphery of the "Schlittertobelniche" has less steep slopes.

In the central part of the niche a number of smaller earthflows originating from the sub-areas between the western sandstone spurs, join. The smaller parent niches show a slow exudation of possibly deep formation throughflow water. In the NE flank of the niche we find a number of smaller (C 8) slumps, poorly drained, though a mesh of fissures is present.

The systems of small earthflows grow together forming a major active flowmass of 60 m across. This mass has overridden a wooden ramp that was erected during the 1940s as a support, a countermeasure, to prevent earthflow material to reach the central valley.

This particular flowmass is the upstream feeder of the composite earthflow that spreads centrally in the valley as described above (section 4.4.1).

At present the composite flowmass is "dammed" by the Hau flowmass (EF 12/13), possibly reactivated since 1979. The composite flowmass (E 10/11) is characterised by low vegetation adjusted to a wet, waterlogged environment (grass, reeds, low bushes (*Alnus, Salix*). The surface gradient along the culmination of the flow topography is gentle (0° to 12°), although this gentle culmination gradient is in places suddenly interrupted by steep slope segments (up to 30°). These latter correspond with the lobes and reactivated sub-units of the composite earthflow. Near the meeting, "collision boundary" with the Hau flowmass (E 11/12) this configuration changes. There we encounter extensive slumping and fissuring. The major composite flowmass is delimited at its southern boundary by a system of sub-parallel elongate relict spurs and fissures directly N of the Widentobel.

The northern and north-eastern margin of the composite flow is formed in part by a valley flank and a relict spur (D 11), that in itself has been stabilized. The contact is masked by a wet grassy surface containing many narrow (few metres wide) relict spurs or rather elongate slices. The intervening fissures are a direct continuation of the Seitenbach system. It is possible that the earthflow from the "Schlitterniche" exerts more pressure here as the Hau flow blocks the composite earthflow in the centre of the valley.

Flowmass Gupf-Zung. This is a complex and large mass movement area where the Seitenbach originates. For the major part the area is rather stable, some parts have shown a renewed activity (D 10 and B, C 10 and 11). The first important reactivated niche is found directly N of the mentioned relict spur (D 11) and stretches itself in elongate fashion parallel to an extensive set of tensional fissures (direction: NW–SE). Within this niche a separate lobe of earthflow material is moving. The northern valley walls desintegrate in two ways: as relict masses cut up by fissuring into blocks and by slow floating movement of complete but rootless masses of rock without desintegration (D 11).

A second active flow area is found further to the east in the seepage zone where the Seitenbach comes to life. The backwall accompanying this actively backwearing process is gradually moving upslope and has endangered the former Stoss road (B 10/11); large volumes of infill material are dumped to keep it in shape. Immediately south of this road the artificially infilled talus is prey to slumping. Construction sheds are also displaced. At several places mudflows are active; they stem from subglacial till material present in a relatively thick mantle here (3–4 metres). The flowing composite mass has not yet reached the valley bottom (C 11).

Any further activity here will lead to a further instability of the backslope. This is one of the high-risk areas considering the state of the morphology, the character of the materials and the high slope angle of the adjoining terrain. The main scar is only at 75 m distance from the railroad. Further E (B 12/13) we meet an older niche almost reaching to Gupf. The morphology is characterized by large elongate slumps (50–200 m long) consisting of subglacial compact till. No measures to prevent reactivation and enlargement of the slide area have been taken.

Flowmass SE of Gupf.

In this area (C/D 15) we have mapped several subunits consisting of concentrically and parallel arranged slump masses in the centre of which a relict sandstone-underlain hill is found. A newly born and active slide mass occurs approx. 175 m SE of the relict hill Gupf (B 14), its sliding plane is lubricated by infiltrating surface water. Along the backwall smaller slumps and slices are found in the central part of the niche. Also an active flowmass denoted by a series of narrow depressions and rises producing micromorphological steps less than 1 m in height is present. This is the expression of internal pressure in the flowmass. Drainage in this area is completely disorganized. Directly above the niche rather flat terrain is cut by a large fissure and many slumps, which will become very active if no countermeasures are taken below.

The northern flanking slopes of the Widentobel, without specific mass movement niches show similar mass movement features as mentioned, only less deeply developed in the form of slumping. Going from West to East we may sum up:

— from W till the Schlittertobel confluence many smaller active niches are endangering the old Stoss-road.

— from there till the Schlittertobel massflow area a peculiar system of parallel arranged slides, accompanied by a system of tensional fissures, opening towards the "Schlittertobel" niche are found. These individual masses are covered with till. Still further eastward (E/D 7/8) the area develops into a morphology of elongate spurs with intervening tensional fissures. The height of these spurs reaches 10 m.

— the next remnant of the valley flank we find between the "Schlittertobel" niche and the Gupf–Zung niche (D 8/CD 9/C 10). Here several sandstone layers, dipping steeply (C 10/11) control the local relief producing debris fans. The surface morphology is still mainly developed as slumps.
— still further E (E of 10/11) we find either active large niches or "fossil" forms.

The upper zone of the flanking slope till Stoss-passhöhe. Less steep gradients are found here (0° to 15°) increasing eastwards; at Stoss no appreciable slope angle is present. The gentle Stoss morphology is suddenly interrupted by the described large niches of Stelz, Schlitten etc. In the Stoss zone, large till-underlain surfaces with minor solifluction gullies and vague lineaments, possibly expression of fissures below the grass cover, can be seen (photo-interpretation). Further E (AB 11/12) the terrain slopes increase and large slump masses, developed in till, are seen. Near Gupf a 15–20 m high and approx. 150 m long relict hill, consisting of till and representing the original postglacial local surface, is situated. The terrain NE and N of this relict hill is considered relatively stable (reaching to Hotel Harmonie (out of map, NW of A 13).

5. GEOELECTRIC SOUNDINGS

5.1. Introduction

Important questions raised during the planning and design phases of the construction works are:
— What is the thickness of the unconsolidated flow mass in the direct surroundings of the planned dams? Can we indicate particular sites where dams may be anchored in unweathered rock?
— What will be the composition of the flow mass in depth? What is the influence of infiltrating water on the mobility of the material?
— Is it necessary to drill exploratory boreholes to obtain further data on the dynamic behaviour of the moving masses? Where should such exploratory drill holes be located?

To answer these questions we executed a series of geo-electric soundings as a supplementary source of information next to the geomorphological and materials surveys. The following geo-electric profiles were investigated and interpreted:
— a longitudinal profile along the crown line of the complex main flow mass in the central Widenbach valley;
— short profiles along or at right angles to the crown lines of the smaller adjoining "feeder" flow masses "Schlittern", "Hau" and "Schwantelen";
— profiles for calibration purposes, in particular terrain parts, where the nature of the materials in the subsurface is known, to derive specific values of the electrical resistivity for the more important types of material that occur in the Widenbach valley.

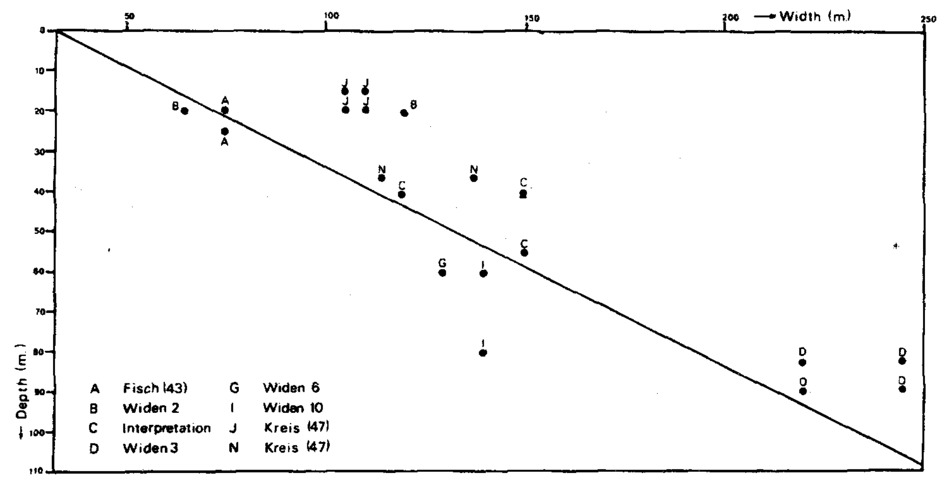


Fig.10. Width–depth relation of the Widentobel earthflow mass in several cross-sections.

The micro-relief at the terrain surface of the main flow mass provided, next to the geo-electric data, valuable supporting material on which we could construct the longitudinal profile. Moreover, the comparison of the micro-relief mentioned, occurring in the NE continuation of the sandstone spurs exposed in the southern valley flank, shows a pronounced correlation between this micromorphology of the flow mass and the projected continuation of the resistant lithology below. We must conclude that the sandstone spurs of the southern valley slope are continuous under the central flow mass and have a blocking effect on the basal part of the central earth flow.

Further, we were able to calculate the width/depth ratio of the main flow mass system for several cross sections. When plotted, these data show a linear curve (Fig.10). This enabled us on the one hand to check the depth values interpreted on the basis of the geo-electric soundings and, on the other hand, we could extrapolate the depth values of certain cross-sections selected between geo-electrically based cross-sections.

5.2. Results

The results of the geo-electric investigations have been depicted in a series of profiles along and at right angles to the main flow mass (Fig.11). The following interpreted results may be presented:

— The thickness of the main flow mass reaches values of 60–90 m in between "Hau" and "Schwantelen";

— In several cross-sections the main flow mass may be subdivided into two superimposed flow systems: a relatively water saturated and mobile upper mass, which flows on a relatively dry and slower basal mass;

— The contact between flow mass and the hard rock is pronouncedly asymmetric (the deepest incision occurring south of the crown line of the main flow system);

— The buried hard rock is reflected in the micro-relief of the mass movement terrain surface: relatively resistant sandstone spurs in the hard rock controlled subsurface cause a system of shear- and sliding planes in the mass flow system, and are observed at the surface as a series of terrain steps which run across the earthflow.
— Having lost contact with the southern valley slope the Widenbach flows upstream of profile F (Fig.11) completely on mobile unconsolidated material, whereas farther eastward it follows the southern margin of the flow mass;
— Because of the great thickness of the flowing mass and the steeply sloping contact between the flow mass and the hard rock of the southern margin, it will be impossible to anchor the foundations of future dams on both sides in hard rock.
— Exploratory drilling will most probably not lead to different conlusions and, considering the lack of funds, is advised against as the probability to find hard rock within 20 m depth, being the maximum anchoring depth, at both sids of the Widenbach is quite small.
— The glacial scouring of the 3 km long Widenbach valley has produced a postglacial relief in which extremely thick mass-movement deposits could be stored; these take a long time before being "flushed" to the Rhine valley floor.

6. GEOMORPHOLOGICAL–GEOTECHNICAL RISK ANALYSIS

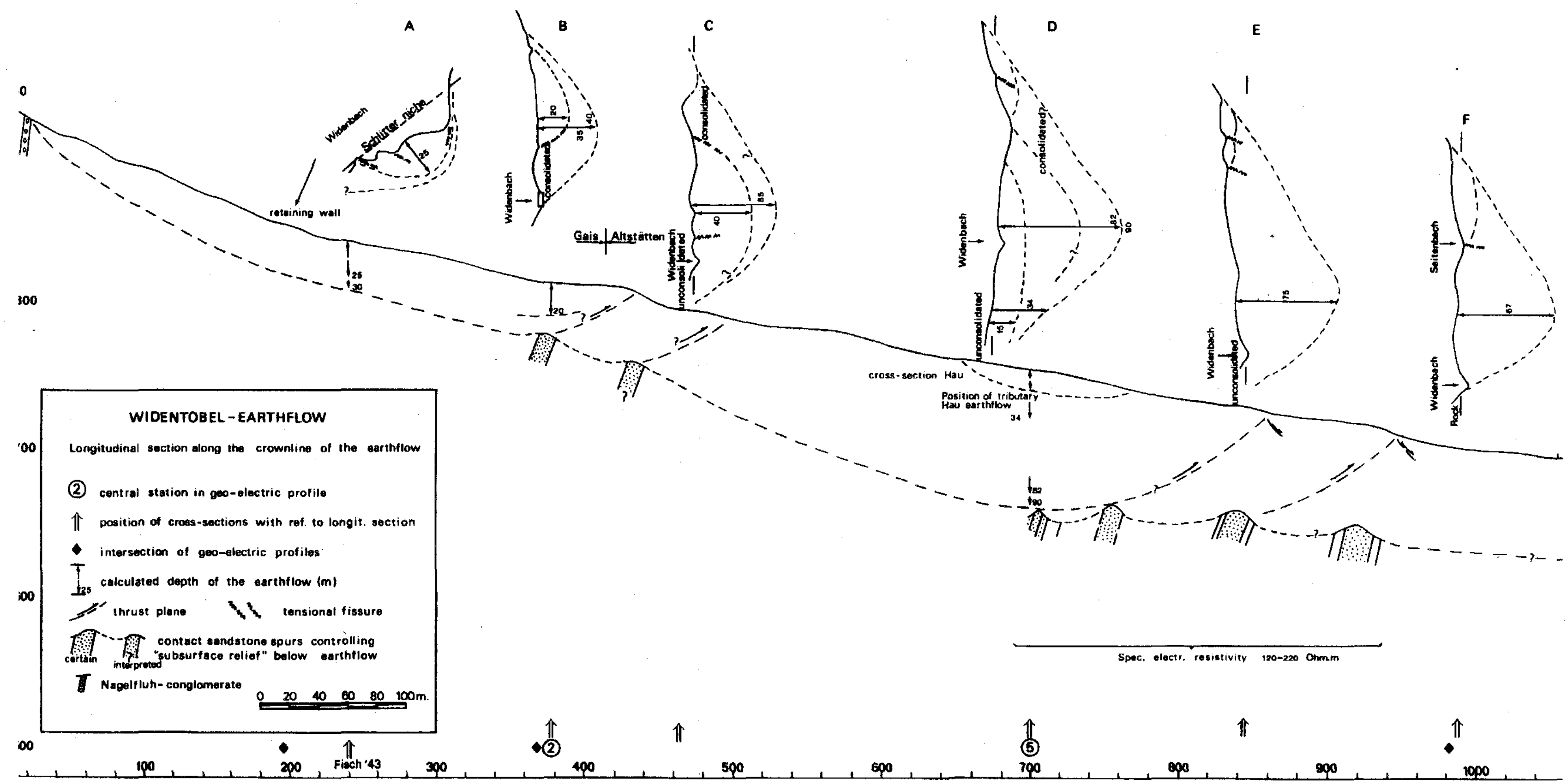
6.1. Introduction

The geotechnical appraisal and risk classification as given below and expressed in map (see Annex) are based mainly on:
— detailed geomorphological survey 1:2000 (see Annex)
— qualitative classification of the materials
— appraisal of the hydrology of the area
The first two subjects have been discussed in detail (see above), the third is briefly summarized in section 3.

We discern five classes of mobility in the stability map (Annex.):
S.A.: very active
A.: active
M.A.: moderately active
W.A.: little activity
S.: stable
High risk areas are summed up below and concentrate in the following sectors EF 11, E 12, E 13, E 14, E 15, F 16, F 17, F 18, F 19 and 20.

6.2. High risk areas, slide masses along the Widenbach

In the southern valley flank: SA (very active) complex sliding masses near Hau, possibly leading to a shifting of the Widentobel channel with the risk that the main drainage channel will develop a new course (see Fig.13). In EF 11, E 12, E 13 the slide/flow mass from Hau (F 11, G 10, G 11) already has forced the Widentobel into a more northward course, at the same time heaving



WIDENTOBEL - EARTHFLOW
Longitudinal section along the crownline of the earthflow
central station in geo-electric profile
position of cross-sections with ref. to longit. section
intersection of geo-electric profiles
calculated depth of the earthflow (m)
thrust plane
tensional fissure
certain
interpreted
contact sandstone spurs controlling "subsurface relief" below earthflow
Nagelfluh-conglomerate
0 20 40 60 80 100m.
A
B
C
D
E
F
Widenbach
Schlutter niche
retaining wall
consolidated
unconsolidated
Gais
Altstätten
cross-section Hau
Position of tributary Hau earthflow
Seitenbach
Rock
Spec. electr. resistivity 120-220 Ohm.m
Fisch '43
100
200
300
400
500
600
700
800
900
1000

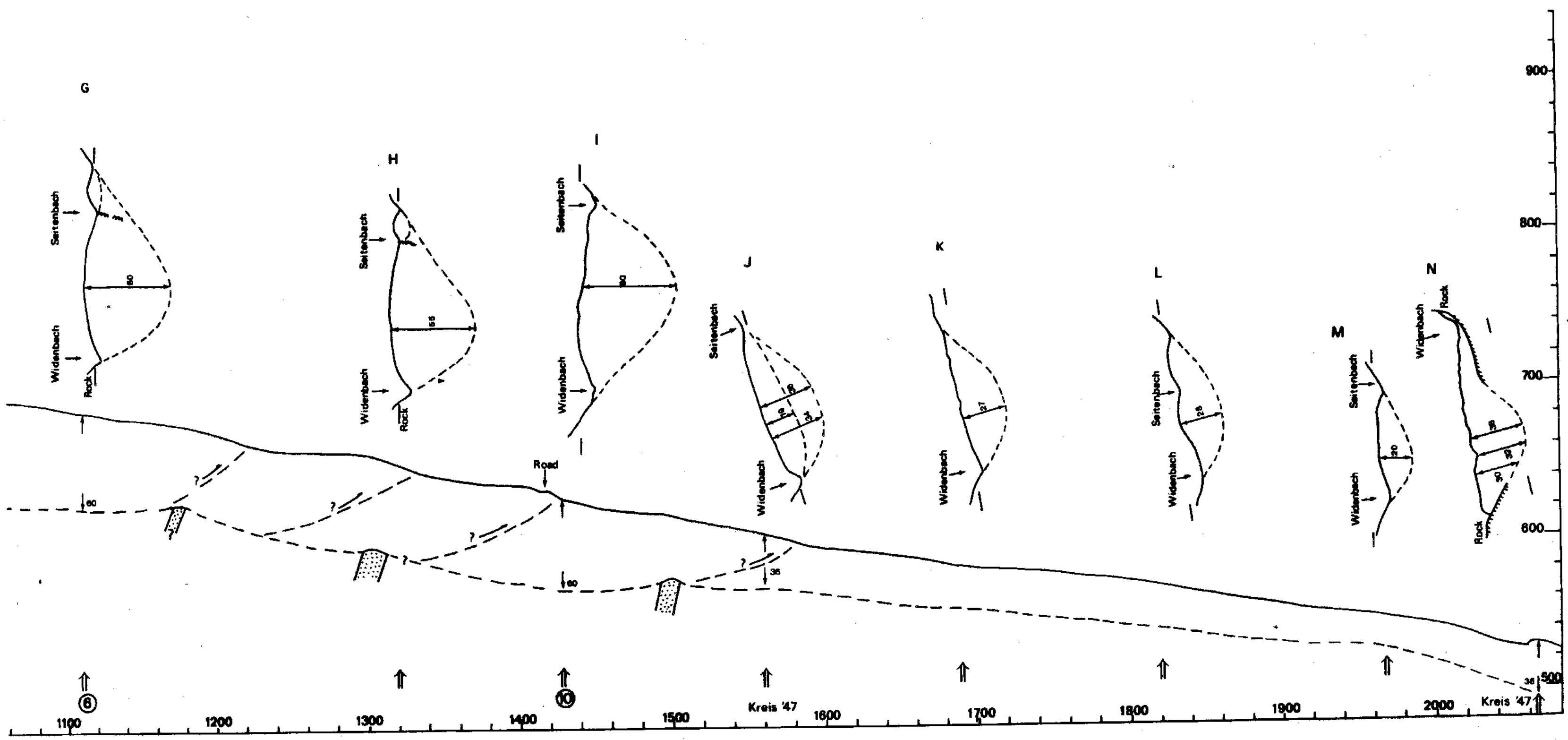


Fig.11. Longitudinal and cross sections of the Widentobel earthflow including geo-electrical results.

Fig.12. Typical development of the vegetation on a saturated mobile sliding mass belonging to the main Widentobel earthflow; Map quadr. F 17.

Fig.13. Bank erosion in earthflow material at the knickpoint in the longitudinal gradient of the Widentobel opposite Hau; Map quadr. E 13.

the channel upward. The earthflow-mass has made connection with a very active lobe of material reaching into D 13, E 13. The Widentobel could react to a relatively minor blockage of its channel, upstream of E 12, by developing a new channel in the direction of the swampy infiltration area (D 13, D 14), using existing fissures. The difference in elevation between E 12 and D 13,. D 14, being more than 10 metres, would facilitate this breaking out of the Widentobel. The result of this would be a short-circuiting of a series of newly constructed dams and lead to an increase in sliding activity of the slopes north of the Seitenbach. Besides, new mass movements at the northern side of the river would be initiated.

Further SA slide-masses are encountered in F 13, F 14. These could easily extend their activities in upslope direction (as is happening near Hau (F 11, G 10, G 11). This pertains to F 13, southern half, and G 12.

The slide area (F 15, F 16, G 15, G 16) is very active. This activity will "eat backwards" upslope in the near future. The marls and clays will easily be carried away; the sandstone outcrops will be left as positive relief, in due time these will desintegrate due to rockfall. In this zone it is obvious that diffuse exfiltration of water is the main underlying cause, in contrast with the next terrain east in FG 16 where concentrated runoff results in a rather stable situation.

The complex area F 16, F 17, G 17 is classified as SA (very active). We must expect a near future connection with the main Schwantelen area if no measures are taken.

Schwantelen earthflow area: the normal pressure is already so high in the existing flow mass that a restabilisation in the next years cannot be expected. Drainage of the upper slope will retard the sliding process.

In the northern valley side we may indicate the following:

Area F 16 till F 19 is very active (SA); earthflow- and slide masses containing block streams are found. In contrast to the southern flank, all material found here is part of earlier slide masses that have become less active. However, due to two processes this material of the northern river embankment is reactivated:

— fluviatile undercutting, bank erosion by the Widentobel water
— throughflow of water infiltrating into the reach of the Seitenbach and from the area (CD 12, D 13 (springs), D 14, D 15, E 15) lowers the shear strength of the material.

The area (SA) D 14, D 13, F 13, F 14 is difficult to interpret. Although not close to the channel of the Widentobel, we expect high activity of movement to occur in the near future as a reaction to changes up- or downslope. This area belongs to an older slide-mass and an increase in pressure in this flow system is to be expected as more slide material is loaded onto it in the upslope region.

In the southwestern part the following active subareas have been recognised:

The area in F 10, SW of Hau; parallel to the elongated Hau niche a flat denudational niche extends itself. Active tensional fissuring and rockfall from

Fig.14. Looking eastwards from front of Schwantelen blocky earthflow system. Situation September 1986; Map quadr. E/F 20.

the sandstone do increase the transporting process from this niche. The danger of breaking through to the slide area is great.

A zone N/S through EF 9; an active muddy flow mass has breached the old road. Without remedial works this process will quickly affect the upper slopes. Freely flowing non-concentrated water can be observed on this active mass.

Areas FG 6, 7 and FG 5, 6. Similar conditions as in FG 9 are found here. Small niches produce flowing material that in its turn overflows several slump masses. When such masses reach the Widenbach, the risk of blocking the stream is high.

Three areas along the Widenbach: F 4, 5. Some small niches have developed at the southern bank of the Widenbach in clayey material. The dam construction program (Wildbachverbauung) has reached up till this area. Future constructions will have to be erected next to "worse slopes" with a larger production of slope debris.

6.3. Infiltration zones, throughflow through the material

Infiltration areas, swampy areas, must be regarded as the root cause of future mass movement, hence they need treatment. The so-called Seitenbach has no normal channel, i.e. caused by fluviatile erosion. We must regard the Seitenbach as a complex of linearly arranged tensional fissures. The "discharge" reaching this Seitenbach system from the adjoining northern slopes is to a large degree caught, but infiltration at many places (D 13, D 14, D 15, F 16) lubricates the earthflow mixture south of it.

Subsiding earthflow masses accompanied by open fissure systems are under constant lubrication by atmospheric water.

6.4. High risk areas outside the Widenbach channel zone

Within the northern valley slopes three high risk areas (hatched in activity map) occur:

Schlittertobel: if the conglomerate, Nagelfluh, banks next to the railroad remain unprotected, the result will be that the slope, being less supported, will desintegrate, including the area underlying the railroad (BC 7, BC 8). This situation has already attracted much attention in the past, the area is still relatively dry at the surface itself. The conglomerate member on which the railroad is built is the last natural support in place.

The area A 10, A 11, B 10, B 11 has attracted less attention, but poses a higher risk than the above mentioned area.

Large volumes of surface flow and spring water are passing here. This leads to correspondingly instable flow masses and subsidence areas. In A 10, A 11, B 10 we observe the old road in fast downward movement. This zone extends already upslope till the rail track and receives no remedial attention. The material consists of subglacial till up to 2.5 m thick.

In the area C 14, C 15, D 14, D 15, D 16 we observe very active mass movement "eating" backwards, only pasture land is involved. In the lower part of E 16 a risk of damming the Seitenbach by earthflow material derived from upslope exists; this would lead to further forced infiltration and consequent lowering of shear strength of the main earthflow system. It is noted that the little brook in area CD 14/15 loses its discharge in the subsiding area below.

7. CONCLUSIONS

Erosional processes and the transport of material in and through the Widenbach is only part of the difficult complex of mass movement activities. In all remedial designs the two following main risk factors must be kept in mind:

(a) bank erosion;

(b) infiltrating water increasing the pore pressure and decreasing the shear strength and the internal friction of the material.

The strategy followed up till now of erecting controlling dams in the downstream sector of the Widenbach (Sector A, Fig.7) can be regarded as fitting the situation there and has been quite successful. In sector B and C we must adopt different methods to bring the natural hazards under control.

We should make relatively cheap investigations before selecting further construction schemes:

— Detailed surface analysis by geomorphological means and by geophysical methods. This applies especially to high risk areas or to checking the effectivity of earlier erected works.

— Installing a network of continuous observations by triangulation and photogrammetry of the mass movement and erosion processes.

The subdivision of the erosion and denudation areas into several activity zones should be monitored during a long period by means of a triangulation network in "quadrants" measuring the 100 × 100 metres.

Development of an integrated (i.e. relevant for the complete range of remedial methods) masterplan based on geological, geomorphological and geodynamic understanding of the total catchment.

— Execution of complementary works in the periphery of the catchment in order to decrease the instability of the area, e.g. drainage of selected slopes, catching in small streams, reafforestation etc.

In the following high risk subareas controlling works must be given high priority:

(1) The described forcing away of the Widenbach channel by the Hau slide mass in the direction of the Seitenbach deserves immediate attention. The bank erosion between Schwantelen and Hau could be partially brought under control using methods as used in sector A (disregarding the foundation problems in that stretch), but the second risk factor (water infiltration, pore water pressure) would not be influenced favourably. The water saturation and the mobility of the flow mass would rather be increased through the effect of raising the local groundwater level in the vicinity of future dams.

In the light of the geo-electrical soundings and the geomorphological survey data, we know that building heavy dams in this sector of the Widenbach would be a technically difficult and very costly operation. We may remind here: the Widenbach is, as it were, "floating" on the margin of the thick main flow mass and a foundation by anchoring at both sides would not be practicable.

Moreover, we must take into account that any dam constructed here would probably be covered by debris produced by the complementary flow systems in the adjoining terrain. Any future works should be based on further detailed field investigations at preferably 1:500 scale (see Fig.15).

A different strategy could be thought of: the Widenbach could be caught upstream of Hau (i.e. in the lower part of sector C) and via an artificially lined channel be brought in a detour around the active "Hau" flow mass before

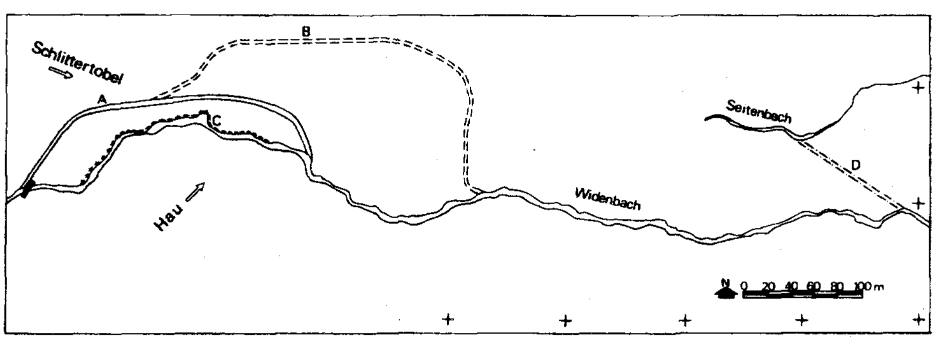


Fig.15. Proposed rerouting of the Widenbach (A, B, C) and of the Seitenbach (D).

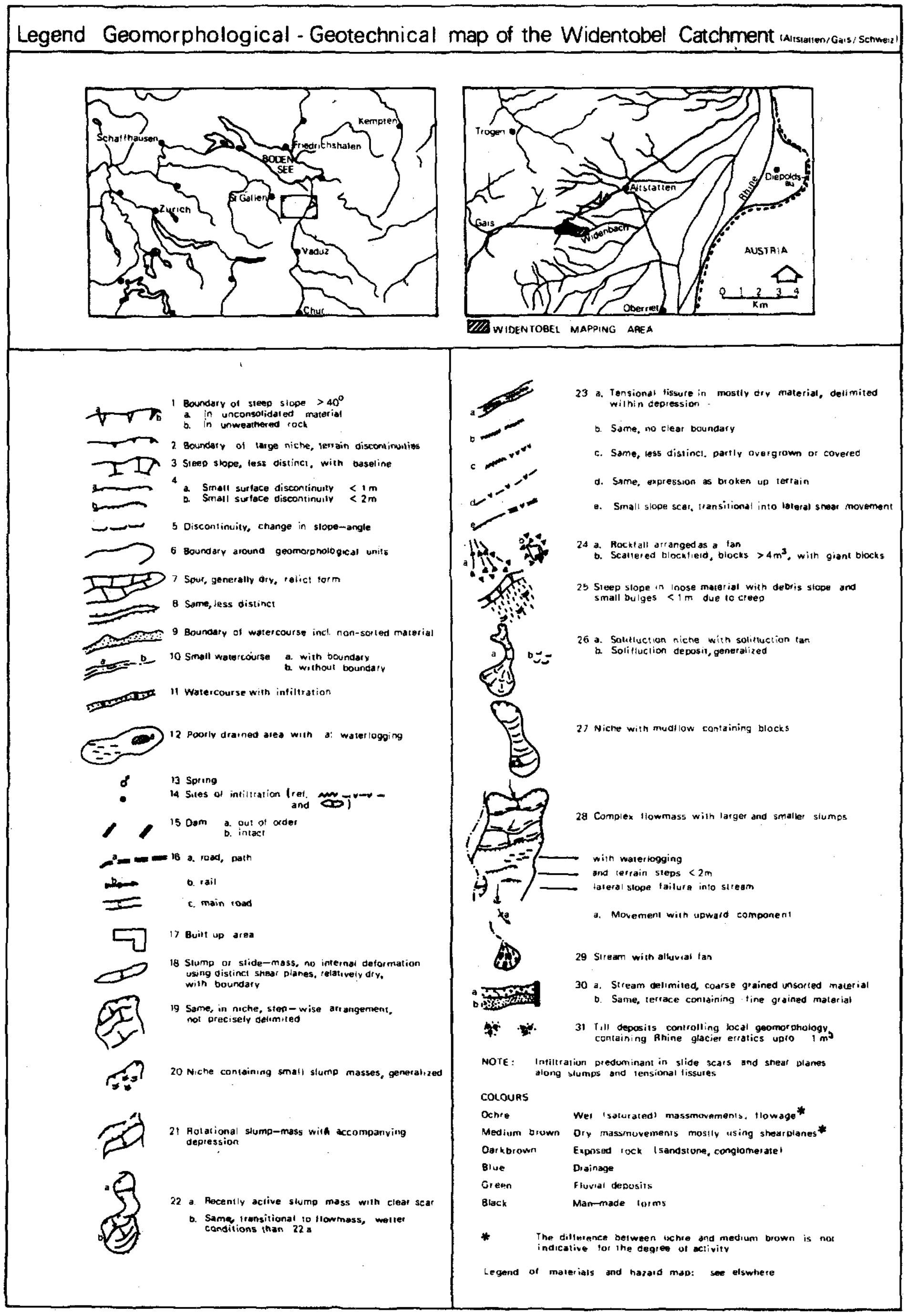


Fig.16. Geomorphological–geotechnical legend.

A. Primary materials
1 Nagelfluh, tertiary conglomerates
2 Sandstone
3 Marls, yellow
4 Marls, red/grey
5 Subglacial till (Grundmoräne)

B. Secondary materials
6 Weathered marls in earthflow
7 Mixture of blocky sandstone fragments in earthflow
8 Sandstone blocks prevailing in earthflow
9 Sandstone debris
10 Transported weathered marl, homogenised in earthflow
11 Transported weathered till, homogenized in earthflow
12 Earthflow with important till component
13 Fluviatile transported material
14 Solifluction material

C. Intermediate deposit (no clear boundary between A and B)
15 Sandstone and marl, partly weathered, partly disintegrated, in places covered with till. Combination of figures can be indicated, e.g. 15/2: desintegrated sandstone

D. Other signatures

Fault in solid(?) rock

Water stagnation and infiltration

Fig.17. Legend to classification of materials.

S	Stabil	stable
WA	Wenig aktiv	low activity
MA	Mässig aktiv	medium activity
A	Aktiv	active
SA	Sehr aktiv	high activity

Schraffiertes Gebiet: Direkt von Massenbewegung bedrohtes gelände.
Hatched area: directly by mass-movement threatened terrain.

Abgrenzung der Einheiten
Boundary of units

do., weniger ausgeprägt.
Less clear boundary.

Widenbach.

The risk classification map is based on the following considerations:
a) Signs of recent bank erosion
b) Infiltration of surficial water
c) Morphogenetic and morphodynamic elements as: presence of various mass-movement units; presence of recent tensional fissures and cracks; presence of 'bare' backwalls of niches visible active mudflow and earthflow deposition; damaged artificial objects as dams or roads; changes in contourlines in comparison with different base-maps; type and quality of the vegetation cover.

Fig.18. Legend to classification of geotechnical risks.

bringing its water back into the natural channel (Fig.15). It would be important to catch the Seitenbach water also in this new channel as a considerable volume of Seitenbach water infiltrates into a tensional fissure system representing surface outcrops of an equal number of shearplanes activating the main flow mass. The peak flow would still be using the natural channel, but saturation by the base flow is the main hazard. By these works the two main hazards — the bank erosion and infiltration of river water into the flow mass — could be brought under control to a high degree. The result would be a decrease in the activity of the main flow mass or parts thereof. At the same time smaller amounts of earthflow material from the adjoining mass movement systems in the southern valley flank would reach the Widenbach.

Even without detailed cost calculations we may assume on the basis of the present state of knowledge that the measures proposed will in the long run cost less in total, and that the positive effect on the stabilisation of the Widenbach system will be larger and more durable than a programme of only dam construction in sector B.

As an alternative we may catch the continuous base flow in such a detour channel and allow higher discharges to make use of the existing natural channel. This would also create drier conditions in the critical area.

(2) A thin, 1–2 m, almost vertical, in parts already "overturned" conglomerate layer prevents the Altstätten-Gais railroad to slide onto the Schlittern slide mass. Without remedial measures that will be only a matter of time, as the supporting conglomerates are continuously undercut by mass movement. Not to have to resort to costly reconstruction works in the future, it is necessary to collect all surface- and ground-water and to guide it away from the critical area.

The investigations show that not only the occupants of the lower parts of the catchment, as the forest owners and the farming community, but also the authorities responsible for railroad and road connection, would benefit from a total restoration masterplan.

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