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THE EFFECTS OF DEEP-SEATED MASS MOVEMENTS ON THE ALPINE ENVIRONMENT

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ABSTRACT

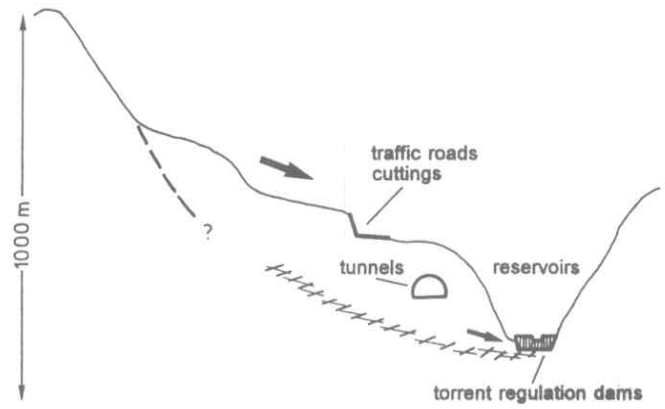
The observation of approximately 60 deep-seated mass movements in form of sagging of mountain slopes ("Talzuschübe"), lateral spreading, mountain splitting areas ("Bergzerreißungsfelder") and earth flows ("Schuttströme") in the Alps have shown that the degree of impairment of the alpine landscape vary. Concerning sagging slopes sometimes the creep rates are so low (some centimeters per year) that displacement pose little or no direct threat to human structure placed on them. But often the gigantic volume of sagging slopes in metamorphic rocks (some hundred Mill. m^3) produces an inexhaustible source of bedrock failures along the toe zone and as a result recurrent debris flow activity.The second geotechnical constellation is characterisized by the disintegration of brittle caprocks into huge blocks resting upon a weak basement is a widespread phenomenon of slope instability. Especially big rock falls on the edge of such spreading of mountain ridges with triggering large-scale earth flows threaten a lot of hamlets, villages and traffic roads in alpine regions.

KEYWORDS: geotechncal aspects of large-scale mass movements, impact on alpine environment

INTRODUCTION AND AREAS STUDIED

Exemplary sagging of mountain slopes reflect very well the impairment to engineering and human structures placed on them (Fig. 1).

Alpine regions controlled by weak sequences (e.g. phyllites, slates, poorly cemented sand- and siltstones, marls) demonstrate sometimes the whole field of impairment from large-scale mass movements (Fig. 2).



torrent regulation dams: incipient displacement of the check dams toward the abutment. Further on then incipient cracks in the discharge section. Finally dam will be strained up to the point of failure caused by lateral pressure.

reservoirs: activation of deep-reaching slope deformation by variations of the reservoir level.

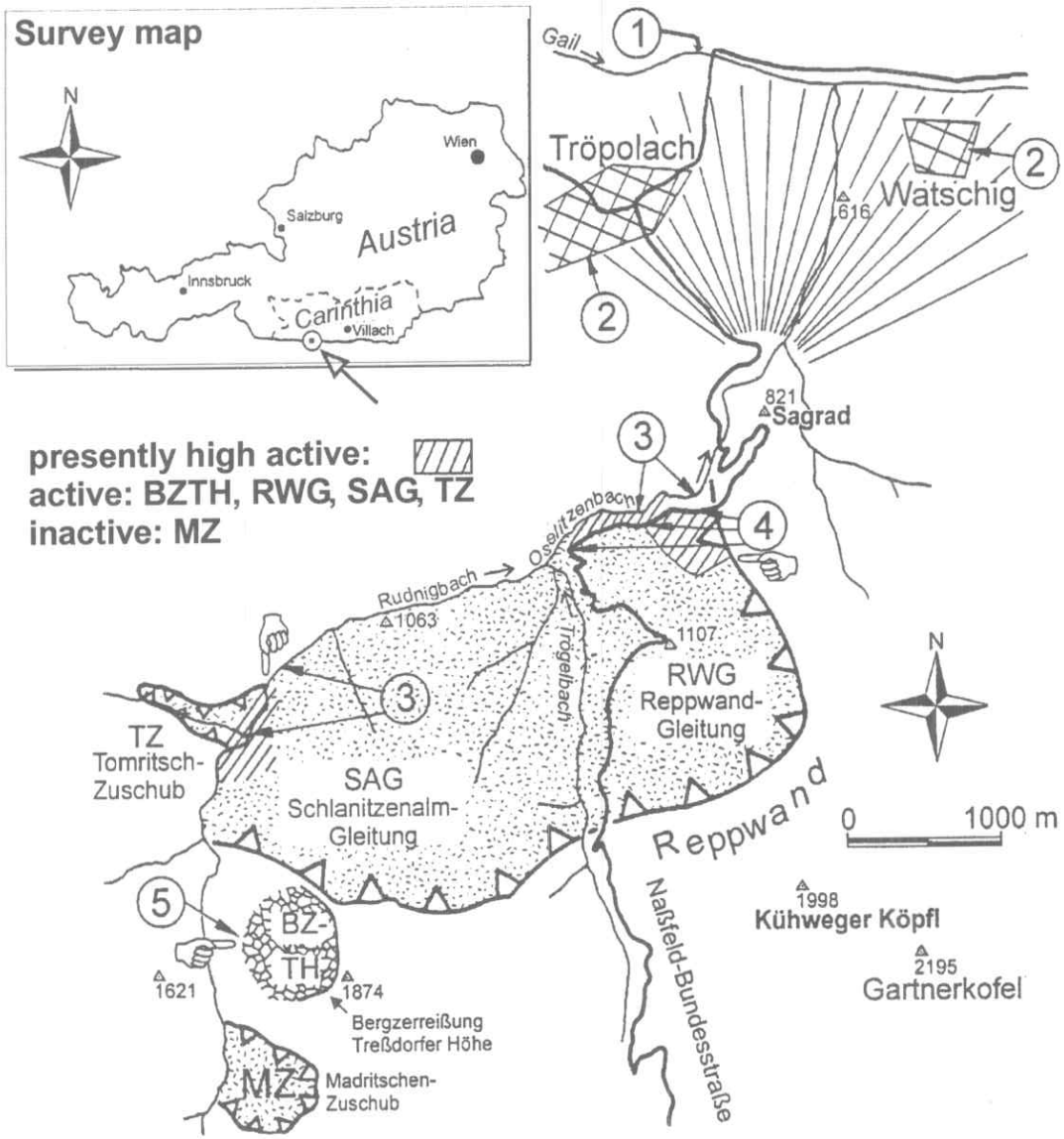
tunnels: important changes in the shapes of cross-sections of tunnels and galleries.

cuttings: desintegration and scattering of rock masses due to slope tectonics; rock slides.

embankment failures on the toe zone: inexhaustible source of debris for recurrent debris flow activity

Fig. 1 Impacts of sagging of mountain slopes on engineering structures.

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① blockage of the Gail river

② endangering of the hamlets Watschig and Tröpolach

③ damage of the check dams by the lateral pressure

④ negative impact and destruction of approach road and the main road to the Carnic ski region

⑤ rockfall area threatening ski trail

Fig. 2 Overview of the Nassfeld region/Carinthia with the large-scale slope movements in form of sagging of mountain slopes and mountain splitting areas; especially the sagging slope Reppwand (Fig.3, No. 35) has negative impacts on the environment.

The impact on land management and land use zoning is demonstrated on sagging slopes, mountain splitting areas and earth flows in Austria, Switzerland and in the Bavarian Alps (Fig. 3).

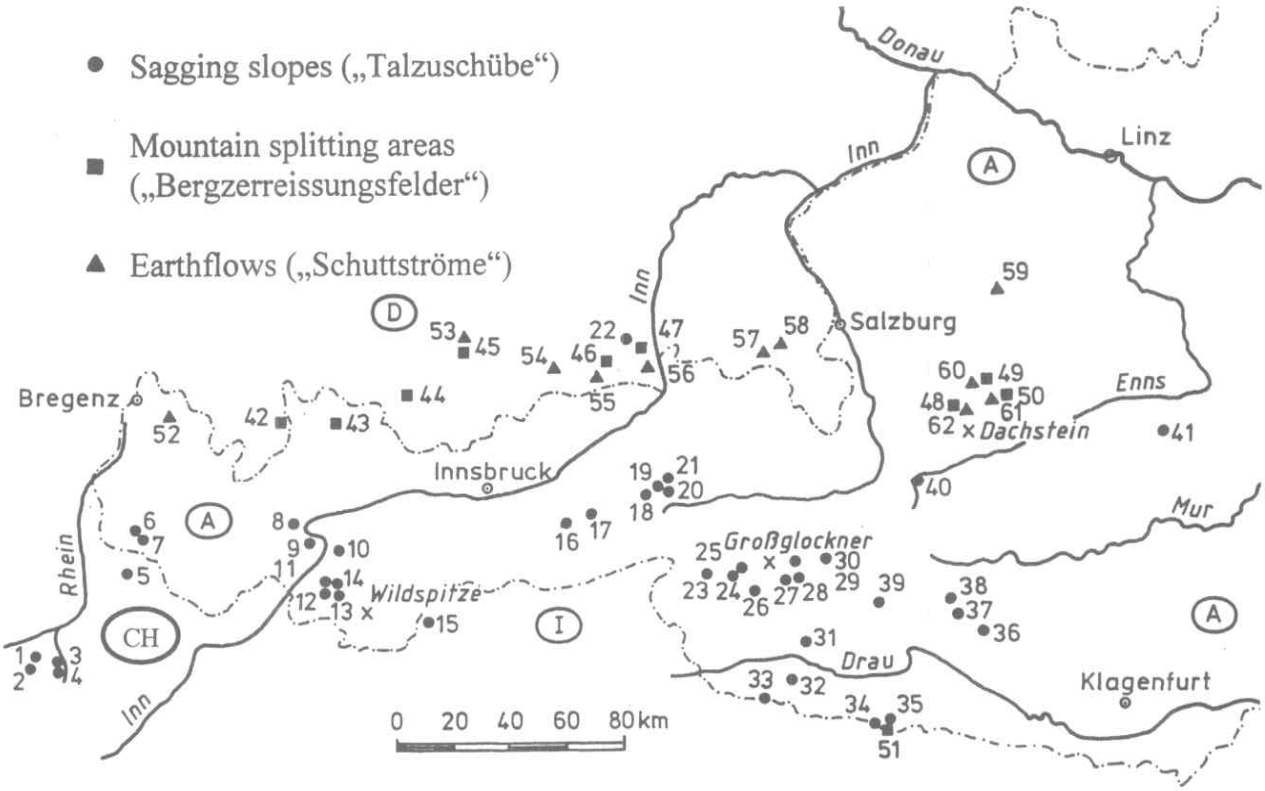


Fig. 3 Location of investigated slopes.

THE CAUSAL CHAIN "TYPE OF SLOPE MOVEMENT - IMPAIRMENTS"

The just mentioned sagging slopes show very well that the causal chain is linked in particular with the areal extent, the thickness and the mechanism and process of movements.

The areal extent:

The areal extent of such slope movements is sometimes on the order of several sq. km and an elevation of more than 1000 m.

The thickness:

With thickness of more than 200 m, slope movements can be very clearly distinguished from "normal soil slips and slumps", which are on the order of meters to tens of meters. The protective works and remedial measures conventionally used against slope movements are ineffective here.

The mechanism and process of movement:

Owing to the mechanism and process of movement, strains of long duration on engineering works and other infrastructures are preprogrammed. Particularly to be noted here is the intensity of the movement, which can amount to several meters/annum. Continuous slope movements bring about a change in the geotechnical features of the discontinuities, resulting in disintegration of the rock masses. This produces heavily crushed rock masses and broken fragments swimming in a silty sandy matrix, thus creating an inexhaustible source of debris in the toe zone (Fig. 4).

And, it should also be remembered that the toes of such slope movements are very often situated in the undercutting zones of V-shaped ravines.

It is obviously that one can discern great differences within **one** sagging slope for **various** years and great differences regarding **various** sagging slopes. This behaviour will influence the kind of monitoring, active remedial measures, the kind of the control works and finally the land use zoning.

Table 1 Velocities of different sagging slopes.

name of sagging slope	velocity [cm/a]			period
	min.	max.	average	
Reppwand (Fig. 3, No. 35)	6	136	33	1983 - 1988
Reppwand (Fig. 3, No. 35)	3	26	11	since 1991
Gradenbach (Fig. 3, No. 27)	6	352	23	1972 - 1990
Millstätter Alpe (Fig. 3, No. 36)	39	83	42	since 1960
Schuders (Fig. 3, No. 5)	0,3	802	111	since 1945
Heinzenberg (Fig. 3, No. 3)	0,4	25	15	since 1887
Lugnez (Fig. 3, No. 1, 2)	0,3	21	5	since 1887

ADVERSE IMPACTS ON HUMAN STRUCTURES

Settlements

Settlements in the alpine area are very often built on debris fans at the mouth of the gorge of torrents where great masses of debris are discharged, because such ground is normally much more suitable for settlements. However, during periods of sustained regional rainfall, bedrock failures and extensive slumps originate in the toe zone from undercutting of the unstable creeping mountainside. Similar to a debris-flood, the resulting debris mass is transported rapidly along the torrent channel and is deposited on the debris cone, often totally destroying buildings and engineering works along the way (Eisbacher & Clague 1984).

Example sagging slope Gradenbach (Fig. 3, No. 27)

During the intense rainstorm of 1966 bursts of debris originating from bedrock failure in the toe zone repeatedly fanned over the cone. By November 6th, some 1.3 x 10^6 m^3 of bouldery material had blanketed the cone, destroying a good part of the hamlet of Putschall. The bedload also choked the channel of the Möll river (Moser & Weidner 1998).

The impact on human structures on the creeping mass itself are very often only of a weak nature, and not totally destructive (Huder 1976, Ziegler 1982). Other examples of only slight to moderate adverse impacts are:

- Peiden-Lugnez in Grisons (No. 1)
- Pleiv-Lugnez in Grisons (No. 2)
- Nasserein-Gepatsch reservoir in Tyrol (No. 12)
- Bunzkögele-Bretterwandbach in Eastern Tyrol (No. 24)
- Schlanitzenalm in Carinthia (No. 34)

Owing to its kinematic behaviour, various adverse impacts on the engineering works and mountain settlements can be very well studied on the sagging mountain slopes of Lugnez/Grisons (Fig. 5).

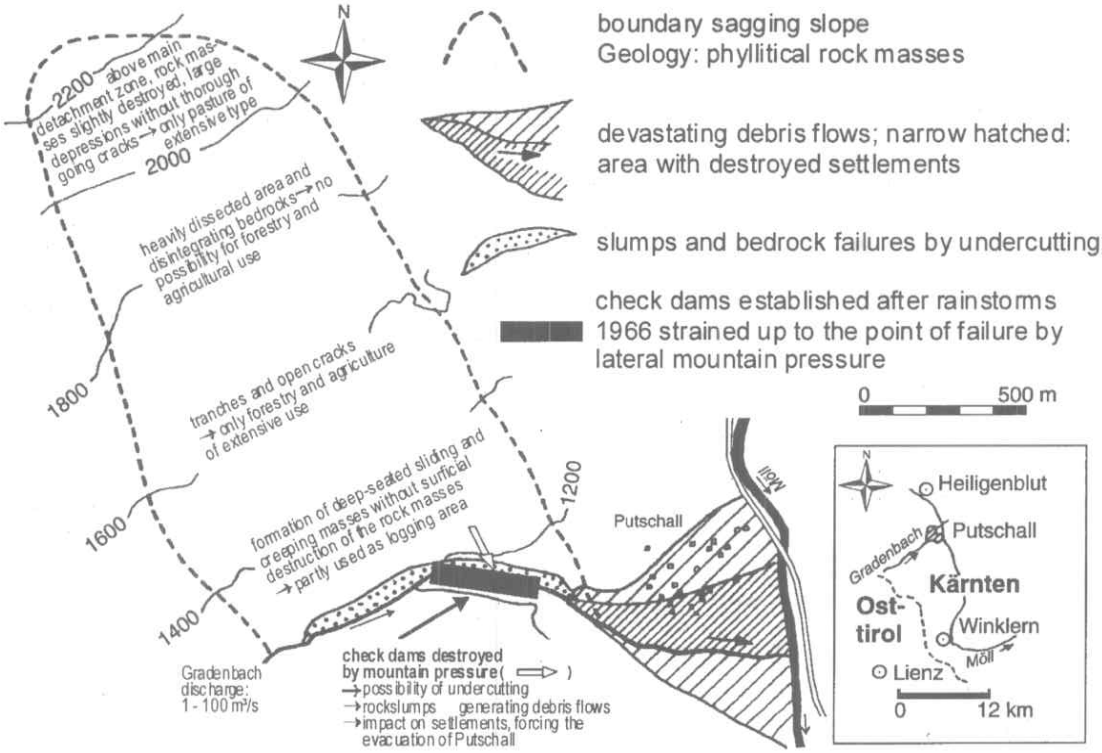
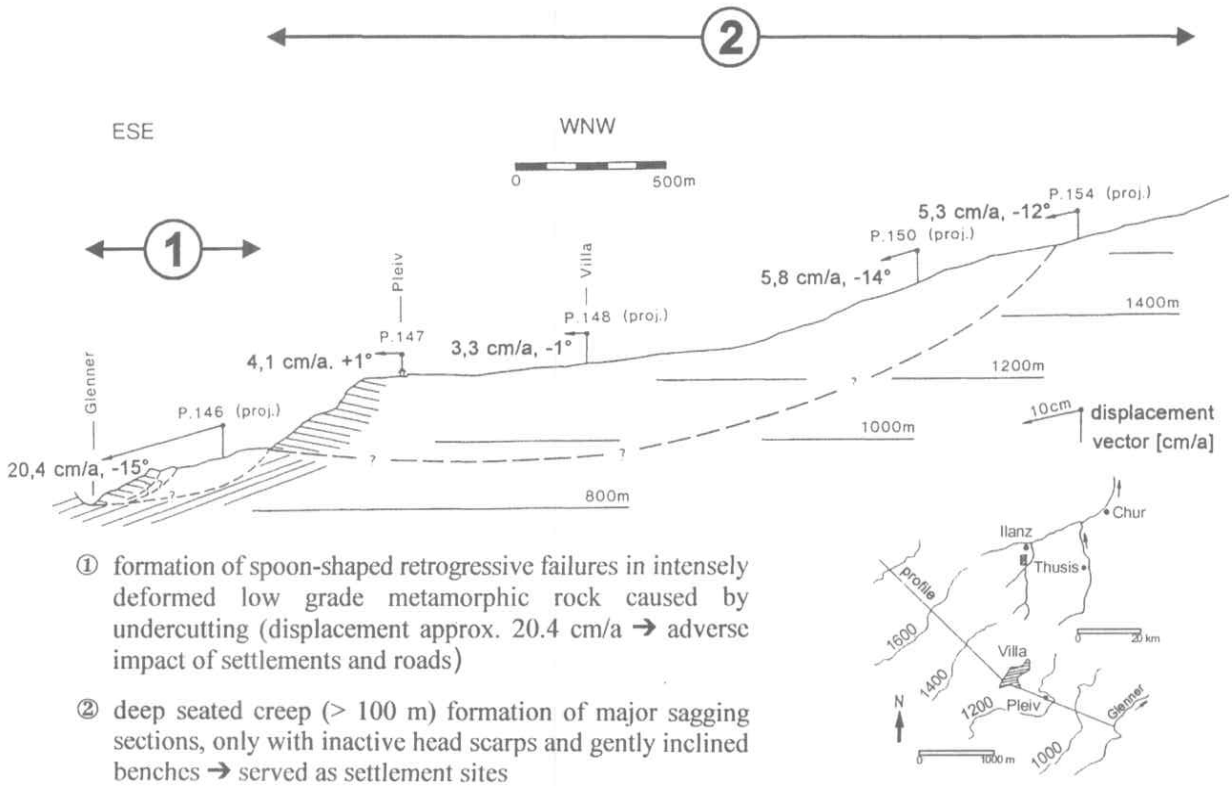


Fig. 4 Restriction of landuse and negative impacts/distructions of infrastuctures and settlements at the Gradenbach sagging of mountain slope (Gradenbach/Carinthia, No. 27).

Another good example for slight impacts is the sagging mountain slope Campo/Rovanna torrent/Ticino, where despite a total movement of ca. 15 m over 70 years, essentially only cracks in buildings have appeared, which are corrected from time to time (Bonzanigo 1988).



① formation of spoon-shaped retrogressive failures in intensely deformed low grade metamorphic rock caused by undercutting (displacement approx. 20.4 cm/a → adverse impact of settlements and roads)

② deep seated creep (> 100 m) formation of major sagging sections, only with inactive head scarps and gently inclined benches → served as settlement sites

Fig. 5 Sagging of mountain Slope Pleiv- Villa – Hitzeggen/Grisons.

Example: Earthflow Falli-Hölli/Switzerland

On contrary to the just mentioned sagging slopes deep-seated earth flows destroy in their active phase completely engineering and human structures. A famous example is the earth flow Falli Hölli/Prealps canton of Freiburg, causing the total destruction of the village of Falli Hölli (41 houses, 15 million US$ loss, Bonnard et al. 1995).

The landslide mass is composed from deeply weathered sandstones and marls and landslide colluvium. After the reactivation of late spring 1994 the earth flow had a length of 2,3 km and a maximum width of 600 m with a volume of some 40 x 10^6 m^3. In the most active propagation phase the maximum velocity was noticed with 6 to 9 m/day and a total displacement of 200 m was measured (Fig. 6).

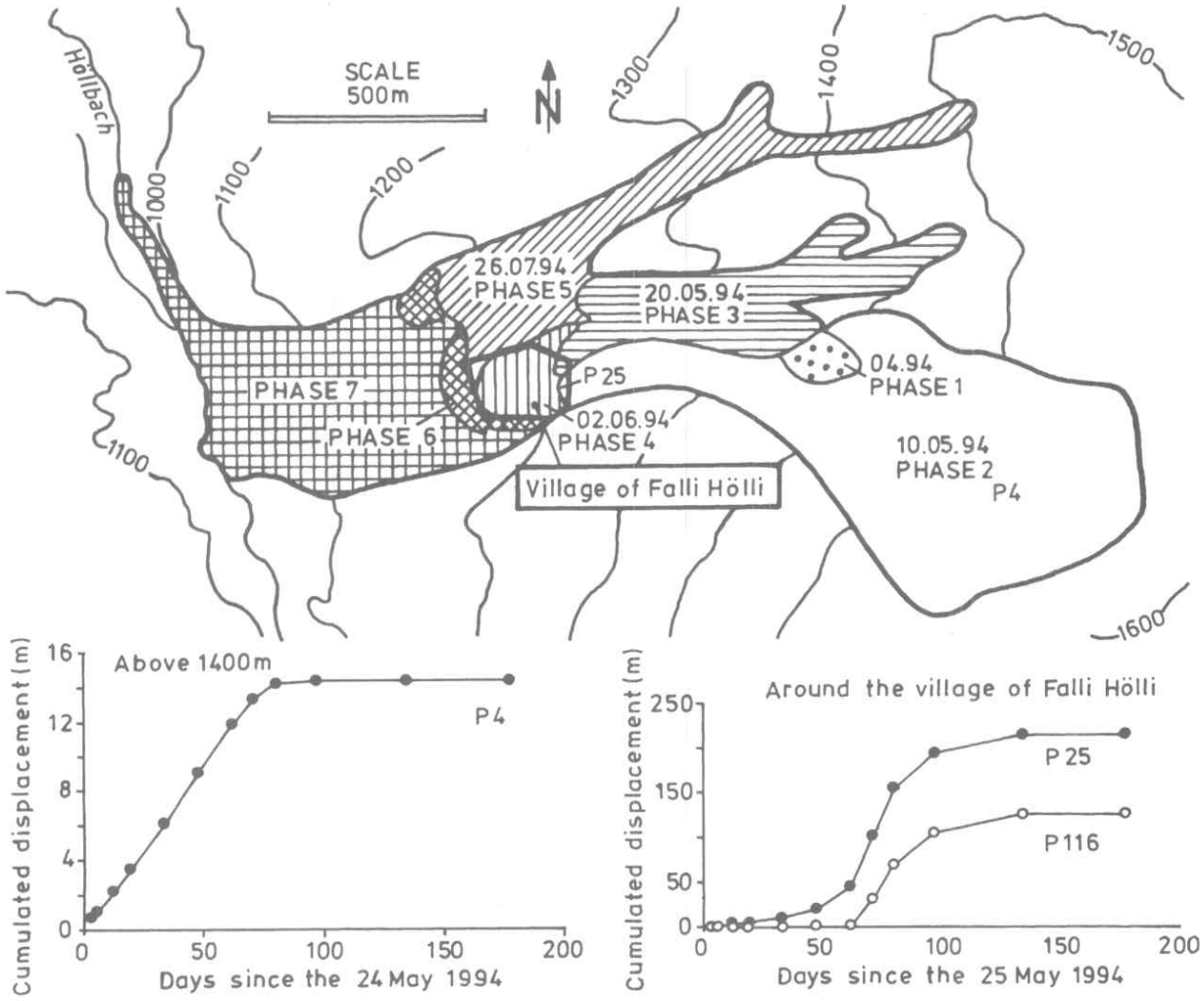


Fig. 6 Simplified map of Falli-Hölli Landslide showing the phases of its development during the crisis of 1994. The dates correspond to the first clearly identified movements. (mod. after Bonnard et al. 1995).

Concerning the impairment of road, settlements and other infrastructures the kinematic processes of mountain ridges must be mentioned. Both examples of spreading of mountain ridges show a characteristic behaviour in the development of mass movements. Initiated by loss of stability in the underlying weak sequences, the brittle slab is disintegrated along a set of discontinuities by troughs and cracks into a "rock labyrinth" (e. g. Stepanek 1992, Simmons & Cruden 1980). In a final stage single pinnacles may be isolated or even a chaotic jumble of blocks and block debris may be observed. Failure

mechanisms at the edge of brittle rock slabs result in toppling and sliding movements of the pinnacles as well as earth flows and debris flows in the weak sequences.

The above described geotechnical situation is the most disastrous landslide risk in the region of Salzkammergut/Upper Austria. In the Hallstatt facies brittle Triassic carbonates overlie weak plastic Permian basement of weathered clay- and siltstone and the evaporites of the Hallstatt salt stock (Lotter et al. 1998).

Example: Rotes Kögele, Steinbergkogel area - Hallstatt/Uppper Austria (Fig. 3, No. 48)

The upper part arround the top of the Steinbergkogel is a competent joint controlled rock formation intersected by cracks and troughs with low or past mountain splitting activity. A steep cliff down to the valley separates this zone from a more active spreading zone with disintegrated rock and huge rock blocks. A detachment zone with block-type slope movements (sliding and toppling) in the eastern margin area of the rock slab is the site of repeated past and potential rock failure activity. A blocky debris plane (block cube up to 2,000 m³) below the composite detachment surface turns into a 250 m long earth flow. Evidence of the dangerous situation gave the great rockfall of the Rotes Kögele in the year 1985 with 40,000 m³ in the vicinity of the prehistoric eastern field.

Owing to a comprehensive monitoring (grid of tape extensometers, tiltmeter measurements, geodetic monitoring system) sites of potential rock failure and displacement date could be identified (Fig. 7). Although the current displacement rates give no significant hint of bigger rock falls and as a result the triggering of earth flows it must be emphasized the widespread and intense recent mass movements of the whole area menacing the region of Hallstatt.

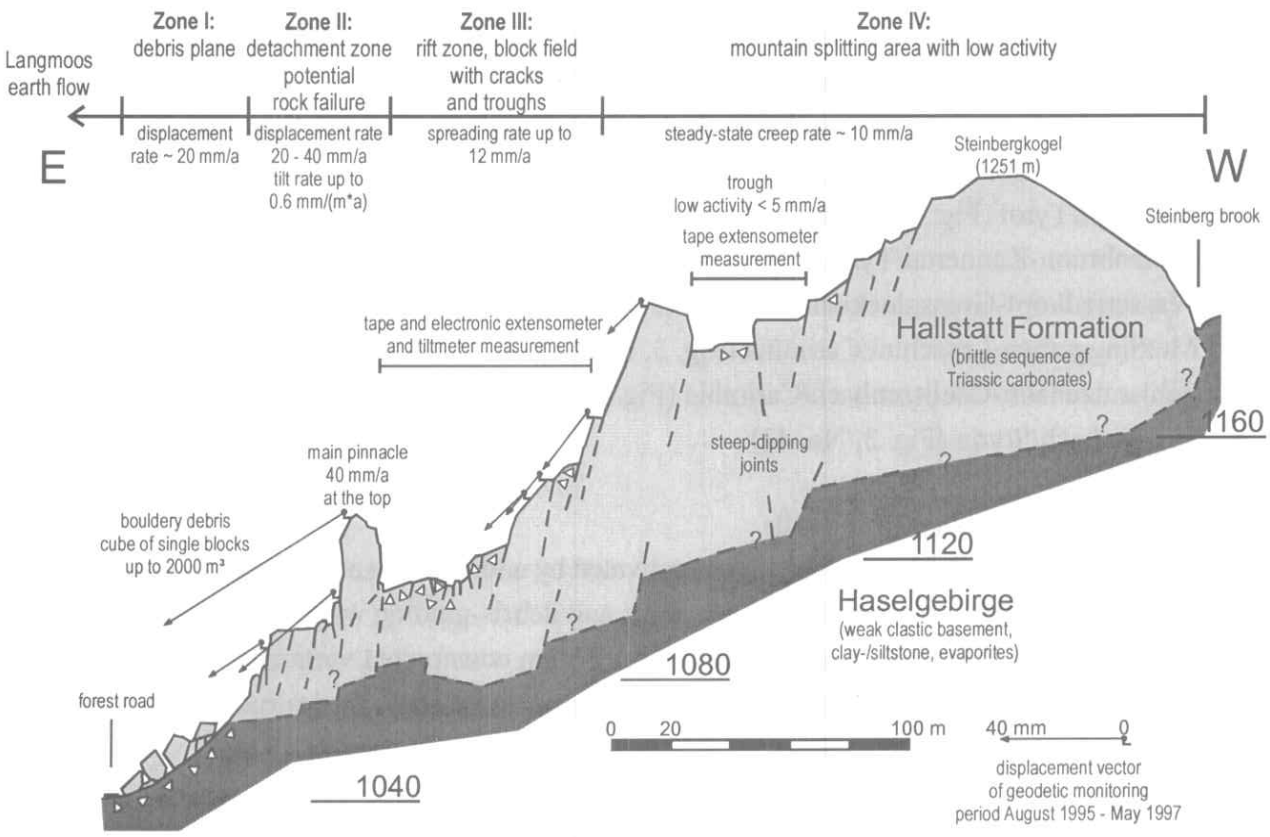


Fig. 7 Geotechnical cross section of the Steinbergkogel area including kinematic characteristics.

A further famous example are the big repeated rock falls on the Zwerchwand/Upper Austria (Fig. 3, No. 50) also in the Hallstatt facies including the same geotechnical situation. In this case, due to the rockfalls a big earth flow (Stambach, Fig. 3, No. 61) was triggered with the developing a debris flow at the front which threatened the town of Bad Goisern (Rohn 1991).

Roads and Highways

The difficulty of building a main road near the active toe zone of an unstable mountainside and maintaining its functioning, is demonstrated particularly well by the example of sagging slope of the Reppwand/Carinthia (Fig. 3, No. 35). Owing to an extremely intense rainstorm in August 1983, about 300 m of the old street was destroyed through undercutting. As a result of political pressure and short-sighted economic considerations the new road was rebuilt a little bit higher, but still within the area of the highly unstable toe zone. After repeated flooding events (particularly in 1987) further undercutting and retrogressive, deep-seated rotational failures created large-scale vertical displacements on the order of meters. In 1988 the decision was made to start a comprehensive control program at the mouth of the gorge of Oselitzenbach torrent, for the following reasons:

- to maintain the Nassfeld main road and the tourist facilities within the Carnian ski areas
- to secure the villages of Tröpolach and Watschig
- to avoid the occurrence of potential masses of debris-flood near the channel of the torrent and their transport into the receiving stream Gail.

The project consisted of shifting the stream from the toe of the sagging slope to a ca. 400 m long channel lying in a competent bed, hence creating an almost 100 m high embankment on the left flank of the slope. The material removed from the channel and the newly created embankment (ca. 200,000 m^3) were used as a toe load on the unstable flank of the slope (Fig. 8). The costs of these remedial measures amounted to 15 million Austrian shillings (Moser & Weidner 1998).

Further examples for endangering and even destroying of roads in the area of sagging slopes are

- Schuders/Switzerland (Fig. 3, No. 5)
- Zintlkopf/Tyrol (Fig. 3, No. 8)
- Kaltenbrunn-Kaunertal/Tyrol (Fig. 3, No. 10)
- Wasserradkopf-Grossglockner/Carinthia (Fig. 3, No. 29)
- Mattlinggraben-Lesachtal/Carinthia (Fig. 3, No. 31)
- Schlanitzenalm-Oselitzenbach/Carinthia (Fig. 3, No. 34)
- Triebenbach/Styria (Fig. 3, No. 42)

Check dams and debris-guiding walls

Very often the whole unstable mountainside is activated by undercutting at the toe of the sagging slope near the torrent channel. To avoid this, check dams and debris-guiding walls are set up in the torrent channel. Particularly the check dams, which are very often constructed vertically to the direction of movement, are strained to the point of failure, leading in most cases to destruction of these time-consuming and costly protective works.

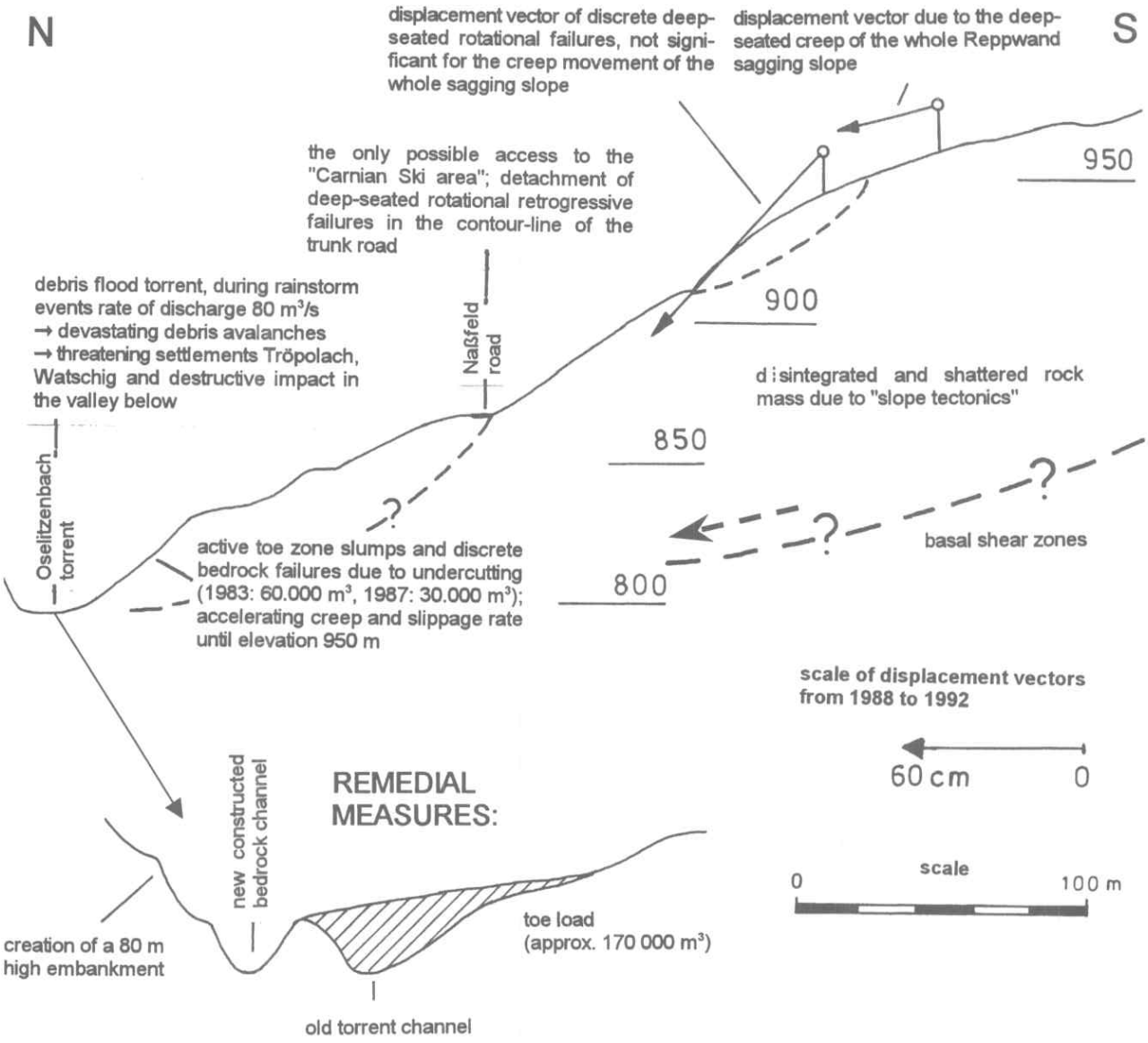


Fig. 8 Negative impact on roads and resultant remedial works at the toe of the sagging mass of the Reppwand-Gleitung/Carinthia (Fig. 3, No. 35).

Example: Toe of sagging slope in Gradenbach (Fig. 1, No. 27)

After the flood disaster of 1966 attempts were made to reconstruct the toe zone area of the sagging slope, at a cost of 40 million Austrian shillings.

The extreme lateral pressure exerted by the slope (cf. movement rates of 88 cm in 1972 and 352 cm in 1975; Fig. 9) resulted in:

- a displacement of reinforced check dams as well as an uplift on the order of meters
- incipient displacement of the check dams toward the abutment and
- further cracks in the discharge area and finally total destruction (Fig. 9).

Since the end of the 1970s all the check dams have essentially been destroyed and the protective works are an ineffectual defense against undercutting at the lower end of the toe zone of the sagging slope. However, this means that once again the threat of debris flow deposition still looms over the village of Putschall and other infrastructures.

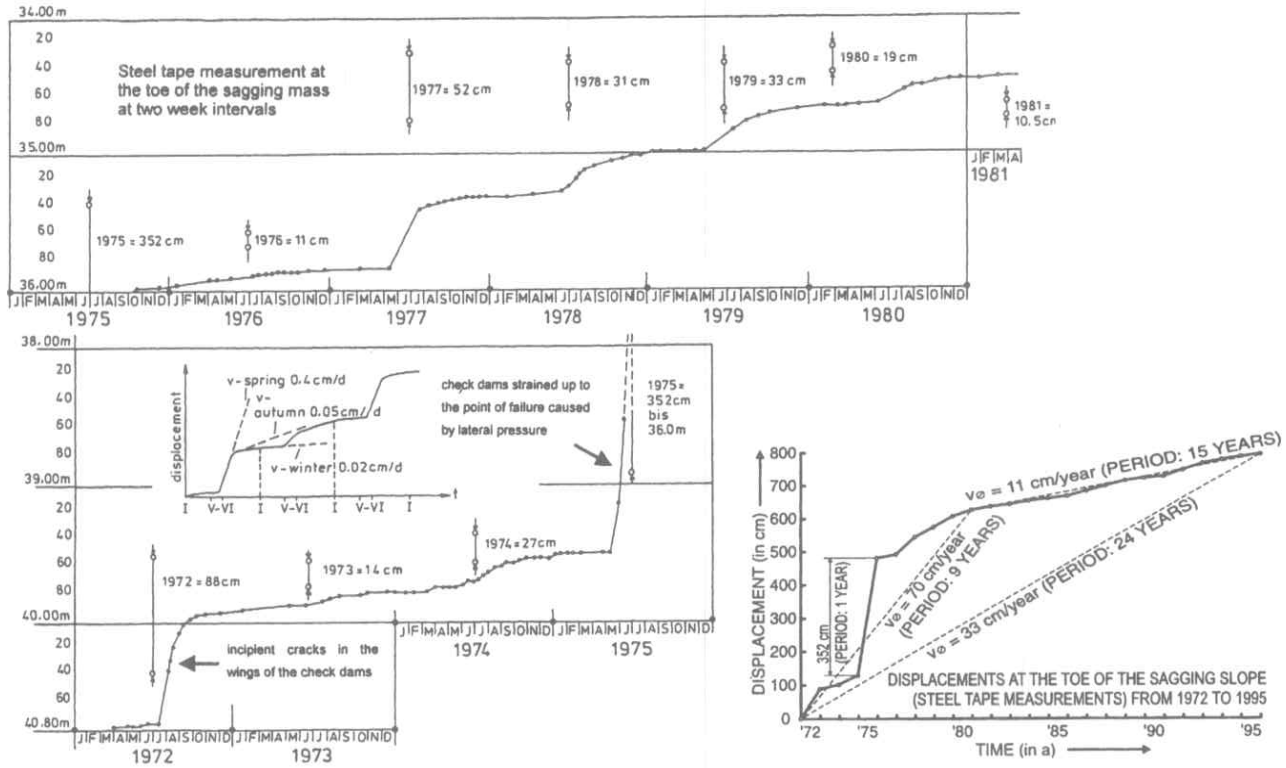


Fig. 9 Displacement-time curve of the steel tape measurements between 1972 and 1980, showing the distinct regressive cyclic behaviour of the mass movement. – The measurements took place at interval of 2 to 3 weeks.

Example: Sagging slope Reppwand/Carinthia (Fig. 3, No. 35; Fig. 2)

A similar situation can be seen in the sagging slope Reppwand. As a result of downslope creep (8 - 12 cm/a) and despite sliding elements, cracks have occurred, which will also lead to the destruction of the check dam in the near future (Fig. 10, 11).

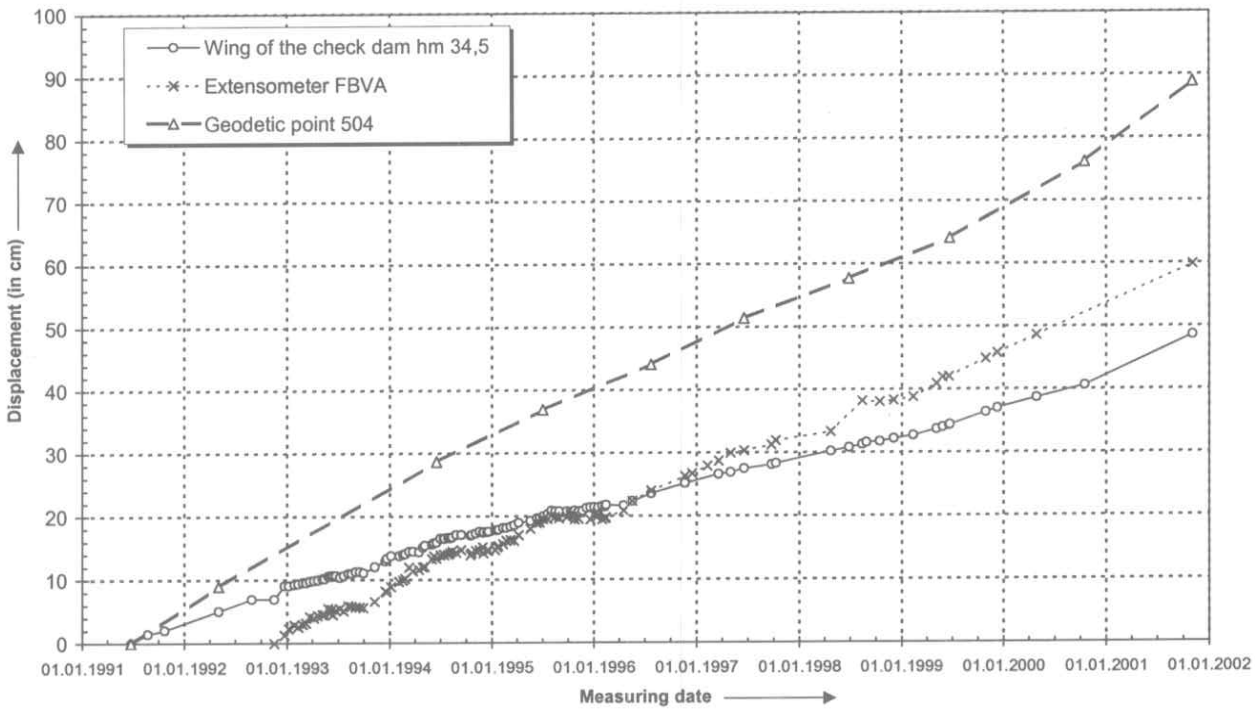


Fig. 10 Displacement at the toe of the sagging mass Reppwand / Carinthia.

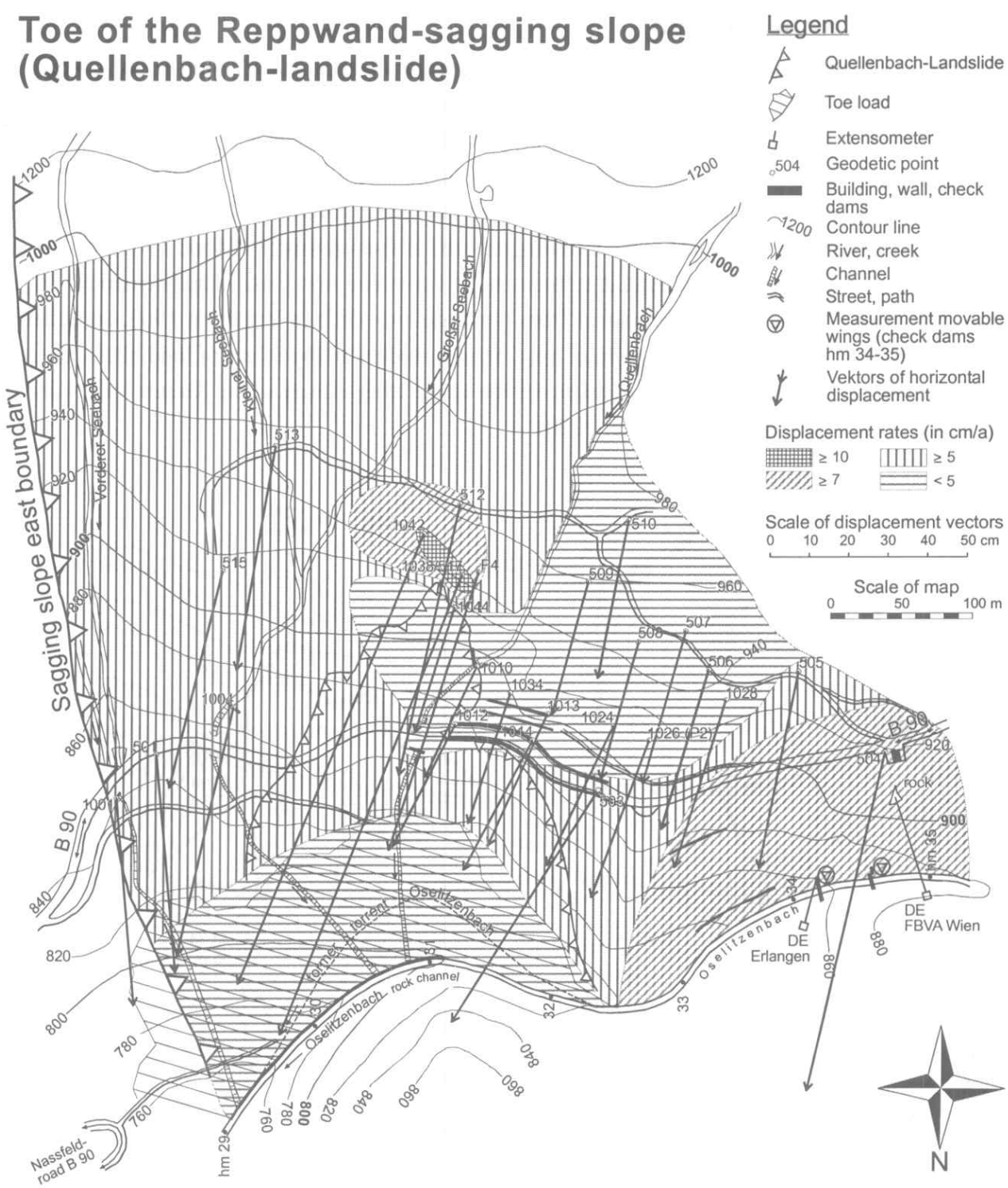


Fig. 11 Displacement at the toe of the sagging mass Reppwand/Carinthia with different kinds of measurements.

Similar damage and partial destruction of the check dams by lateral mountain pressure can be found, for example, in Nolla in Grisons (No. 3), Dürnbach in the Austrian province of Salzburg (No. 20), Jenbach in Upper Bavaria (No. 22), Bretterwand in Eastern Tyrol (No. 25), Wasserradkopf in Carinthia (No. 29), Mödritschgraben in Carinthia (No. 31), Mattlinggraben in Carinthia (No. 32), Triebenbach in Styria (No. 42).

DAMS AND RESERVOIRS

The impact of deep-seated creep on reservoirs will only be touched on here. A good example which has been well-studied since it went into operation in 1964 is the Gepatsch reservoir/Tyrol (No. 11). Four major unstable mountainsides in a schist zone of the Ötz valley bedrock can be found in this reservoir. The upper detachment zone of the somewhat inactive head scarps lies between 2,000 and 2,300 meters. Of the four unstable mountainsides, the slope movement of the "Hochmaiss" 20 x 10^6 m^3) exhibited particularly large movement during the first filling as well as the refilling (1964 and 1965), which after refilling in 1965 amounted to vertical displacement of 7,5 m and horizontal displacement of 10,8 m (Fig. 12). Based on the experience gained from the large rock slide in Vajont in 1963, an extensive geotechnical research program was ordered (e.g. Model studies on the effect of land-slide generated water waves) and preventive measures taken for the lower lying village of the Kauner valley and the upper Inn valley (Neuhauser & Schober 1970).

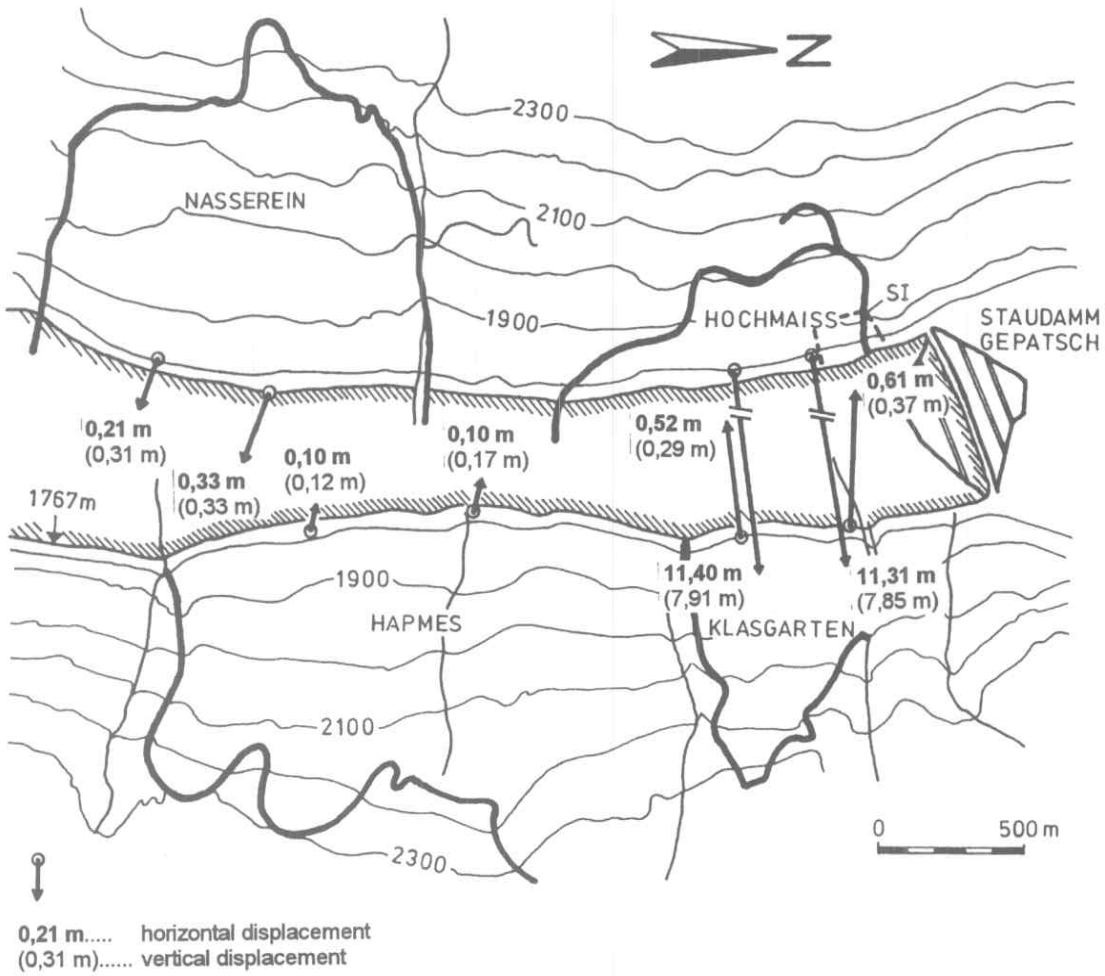


Fig. 12 Sketch map of the Gepatsch reservoir/Tyrol containing the four large-scale slope movements. Especially the slope movement "Hochmaiss" shows great horizontal and vertical displacement rates (1964 – 1985).

SUMMARY

The oberservation of approximately 60 deep-seated slope movements in the Alps have shown, that the degree of impairment of engineering structures and of the alpine landscape vary. If the creeping mass concerning sagging slopes moves slow (< 5 - 10 cm/year) on deep-seated shear surfaces and without the formation of active slumps the impairments deliver only slight restrictions. Examples are Mt.

Heinzenberg and large regions of the Middle Lugnez/Canton Grisons/Switzerland, particularly on gently inclined benches where settlements have remained for a few hundred years. In contrast to the above mentioned conditions, higher displacement rates (> 10 cm/year) cause damage to the check dams in the torrent channel and lead to the complete destruction of engineering structures over the course of time.

On contrary deep-seated earth flows destroy in their active phase completely engineering and human structures with total down ward displacement up to some hundred meters in few months. Especially the last mentioned large mass movements have shown that periods of high rainfall only in combination with certain preparatory conditions trigger these catastrophic events.

In order to minimize the loss of homes and engineering structures, and to plan remedial measures, extensive geotechnical research projects are imparative. In particular, an appraisal of the stage of activity in the individual zones of the slope movements must be conducted. This requires various types of monitoring activities over long periods of time.

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