Sink-hole Collapses in Soft Rocks

Sedimentological and hydrogeological aspects of groundwater induced erosion processes

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Sink-hole collapses in soft rocks are rare events (1, 2) compared to the classic sink-hole collapses in karst. In the Tyrol, however, there have repeatedly been occurrences of sink-hole collapses in the past decades, which have to be seen in connection with lake level fluctuations caused by hydropower plants or erosion processes in ice marginal deposits (3).

The series of sink-hole collapses occurring in the valley fill of the Ötztal in the area of Tumpen/Ried (4) required geological investigations. It also required research into the geomorphological and hydrological development of the valley in post-glacial and historical times, as well as research on its settlement and land use history.

Sink-hole collapses in the area of Tumpen have recently occurred several times since 1980, causing damages to buildings and occasionally reaching considerable dimensions, for instance in the event of December 16, 1992 (Table 1). The sink-hole collapses mostly occurred at the eastern river bank of the Ötztaler Ache. The oldest record of a settlement being abandoned due to a sink-hole collapse in the hamlet of Ried dates from 1755.

While the sink-hole collapses between 1980 and 1993 for the most part can be connected to construction measures in the vicinity of the Ötztaler Ache, this would be unlikely for the older events and can be ruled out for the event of August 1994.

The event of June 1995 was connected to the sinking of a 40 m deep exploration borehole. This sink-hole collapse is significant insofar as it was possible for the first time to document in

Erdfälle in Lockergesteinen – sedimentologische und hydrogeologische Gesichtspunkte zu grundwasserbedingten Erosionsprozessen

In den letzten Jahrzehnten haben sich im Nordtiroler Raum zahlreiche Erdfallereignisse in Lockersedimenten zugetragen. Diese führten teilweise zu nennenswerten Schäden an der Infrastruktur und Bebauung, was in weiterer Folge geologisch-hydrogeologische Untersuchungen zur Abklärung von Ursachen und Schutzmaßnahmen nach sich zog. Erdfälle traten vor allem wiederholt im Bereich der Fraktion Tumpen/Ried der Ötztaler Gemeinde Umhausen auf. Das betroffene Siedlungsgebiet liegt auf ebener Talflur oberstromig von zwei Talstufen, die durch mehrere Bergstürze gebildet werden, wobei für den Aufbau der Talsohle folgende geologische Situationen maßgeblich sind:

- **Feinklastische Stauseesedimente im Hangenden von Bergsturzablagerungen,**
- **Schwebender Grundwasserhorizont mit teilweise labilem Grundwasserstauer.**

Von entscheidender Bedeutung für das Auftreten der Erdfälle in diesem Gebiet ist die vor rund 300 Jahren erfolgte Verlegung des Flußbetts der Ötztaler Ache. Die Ache fließt erst seit Hochwasserereignissen, die sich in den Jahren 1678 und 1679 ereigneten, westlich der Fraktion Ried im heutigen Flußbett und dadurch mit geringem Flurabstand über den Bergsturzablagerungen. Stärkere Infiltrationsraten der Ötztaler Ache beziehungsweise ausgeprägte Schwankungen des Grundwasserspiegels konnten in Verbindung mit dem labilen Stauer im Kontaktbereich zu den Bergsturzmassen eine subrosionartige Abfuhr der Sedimente in die permeablen Bergsturzablagerungen begünstigen und dadurch Erdfälle auslösen. Möglichkeiten der Risikobewertung auf Grundlage einer Bewertungsmatrix für Fragen der örtlichen Raumplanung sowie für bautechnische Maßnahmenkonzepte werden aufgezeigt.

In the past decades several sink-hole collapses occurred in soft rocks in Northern Tyrol. These collapses partially led to significant damages to existing infrastructure and buildings, requiring geological-hydrogeological investigations to clarify the causes and determine protective measures. Sink-hole collapses above all occurred time and again in the area of Tumpen/Ried in the municipality of Umhausen/Tyrol in the Ötztal valley. The affected settlement is located on the valley bottom upstream of two valley steps formed by several post-glacial landslides. The following geological situations were decisive for the structure of the valley fill:

- ***Silty to gravelly sedimentary sequences of lake sediments caused by damming of landslides overlying the boulder deposits***
- ***Perched groundwater system within these sediments with partially unstable basis of aquifer.***

A key factor in the occurrence of sink-hole collapses in this area is the diversion of the river named Ötztaler Ache 300 years ago. The river has only been flowing in its current river bed since the floods of 1678 and 1679, west of the settlement area Ried. This diversion means that the river flows within a section where there is little distance between river bed and boulder deposits of the landslides. Infiltration by the Ötztaler Ache and pronounced fluctuations of the groundwater table favour a subrosive removal of the sediments into the permeable boulder deposits below, causing sink-hole collapses. The possibilities of evaluating the risks on the basis of an evaluation matrix for local planning are shown.

Table 1 Chronology of sink-hole collapses in the area of Ried (Tumpen).
Tabelle 1 *Chronologie der Erdfälle im Bereich Ried/Tumpen.*

Date	Locality, damages	Source	Size of cavity [m³]
1755	Loss of a farmstead in Ried	MTC-TPA	unknown
before 1848	Abandonment of a home in Ried	Oral trad.	Collapse of farmhouse
before 1950	Collapse north of Ried	Oral trad.	>100 (filled in approx.1965)
1980	Sink-hole collapse with damage to building in Ried	RPGT	unknown
13/01/1992	Sink-hole collapse south of Ried	RPGT	> 4 000
16/12/1992	Sink-hole collapse next to the Göbhard house in Ried	RPGT	10 000
13/01/1993	Sink-hole collapse next to the Göbhard house in Ried	RPGT	50
11/02/1993	Collapse of bed in the river	RPGT	Sink-hole collapse prevented
22/04/1993	Collapse south of Ried	RPGT	25
22/08/1994	Collapse north of Ried	ILF	20
21/06/1995	Sink-hole collapse at bore hole KB-T3	ILF	120

RPGT – Records of the Provincial Government of the Tyrol; MTC – Maria Theresian Cadastre; TPA – Tyrolean Provincial Archive; Oral trad. – Oral tradition; ILF – Documentation by ILF Consulting Engineers geologists

Fig. 1 Initial stages of sink-hole development on June 21, 1995.
Bild 1 *Entwicklungsstufen des Erdfalls vom 21. Juni 1995.*

detail the process sequence from the start (Figure 1).

- The instability zone of the borehole was the boundary of the bed at a depth of approximately 32 m between relatively retaining sand-silt of the lake sediments and the subjacent boulder beds of landslides, which were connected to the overlying perched groundwater table by equipping the borehole for groundwater monitoring.
- The collapse occurred almost cylindrically, having an initial diameter of approximately 3.5 m and an initial settlement rate of 40 to 50 cm/h at the cylinder rim and approximately 80 cm/h in the centre of the sink-hole collapse.
- Within 10 h a collapse depth of 4 m was reached.
- Hours after the outset of the sink-hole collapse, the upper 20 m of the PVC water gauge were still passable for monitoring, 10 h after the start of the collapse 9 m of gauge tube were still measurable which implies a largely blocklike settlement of the area.
- During the sink-hole collapse a significant reduction of the measured values of the electrical conductivity in the groundwater column in the gauge tube was seen which could have been caused by an increased inflow of groundwater next to the Ötztaler Ache.

Valley bottom sediments

The area of Tumpen/Ried affected by sink-hole collapses is located on the valley bottom of the Ötztal upstream of two valley steps formed by landslides. The landslides are known in the literature (5, 6).

The different areas of the landslides cropping out as boulder fields can be separated morphologically and petrographically (Figure 2).

- "Piburg" landslide
- "Habichen" landslide
- "Armelen" landslide area
- "Achplatte" (Tumpen/Sandbichl area) landslide
- "Tumpen-Dorf" landslide area
- "Tumpen-Maurach" landslide.

By means of core drillings a facially correlatable sequence of two lake phases with the pertinent silting-up sequences in the valley fill was explored upstream of and laterally to the landslides. The southernmost drilling (KB T-1 in Figure 2) with a final depth of 60 m did not reach the base of the older lacustrine sediments (Figure 3). In those drillings which are closer to the landslides crossing the valley (landslide of Tumpen/Sandbichl, see Figure 2), however, the basal sandy-silty lake sediments transgress coarsely clastic boulder beds of the landslides already in depths of 12 to 32 m.

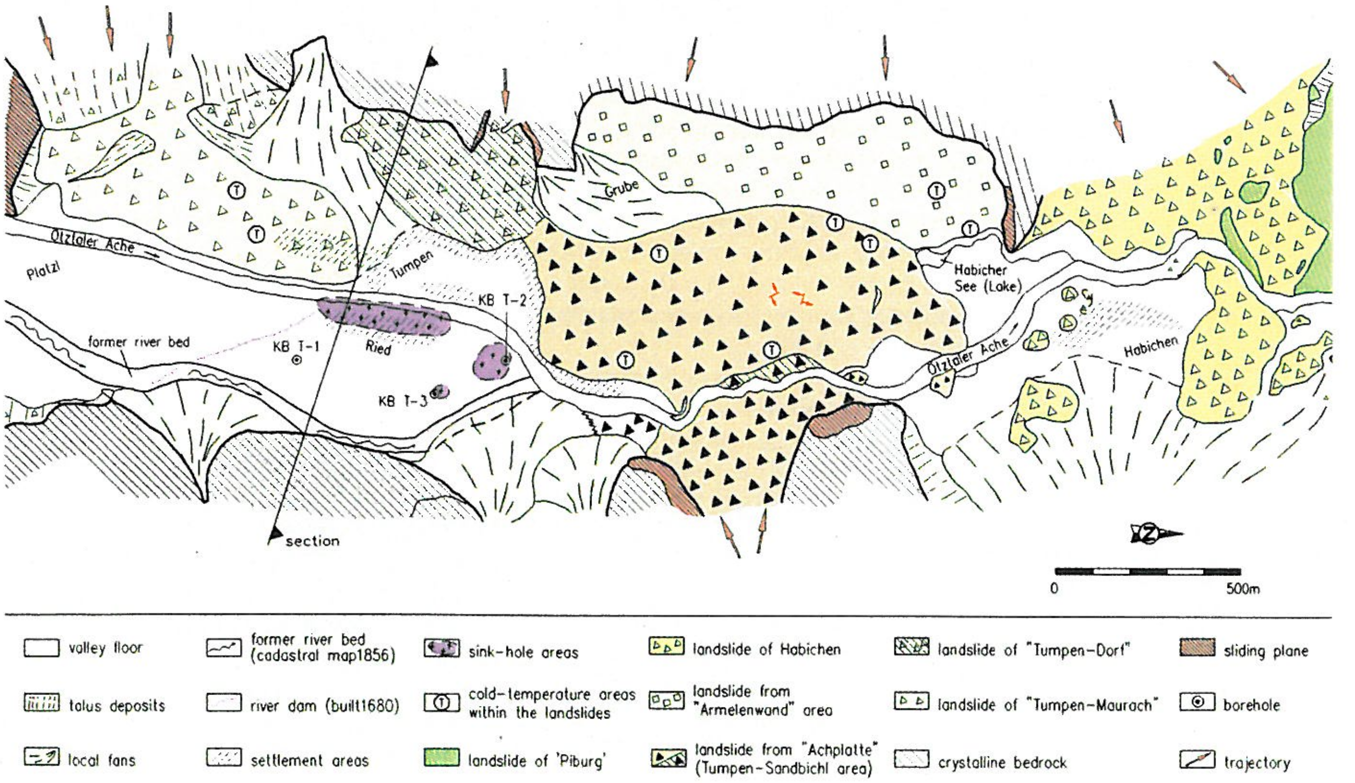
Geophysical measurements were performed by means of combined refraction-reflection seismics on three transverse valley profiles and two longitudinal valley profiles and complemented by geoelectrical measurements. The overdeepening of the Ötztal valley determined by reflection seismics is 200 to 250 m in the area of Tumpen (see Figure 3).

Geological and hydrological development of the valley

The age of the individual landslides in the area of Tumpen/Ried is unknown. The prognosis of the subsoil conditions shown in Figure 3 suggests

Fig. 2 Geological sketch map of the Tumpen area, Ötz valley/Tyrol.

Bild 2 *Geologische Übersicht für die Umgebung von Tumpen im Ötztal/Tirol.*



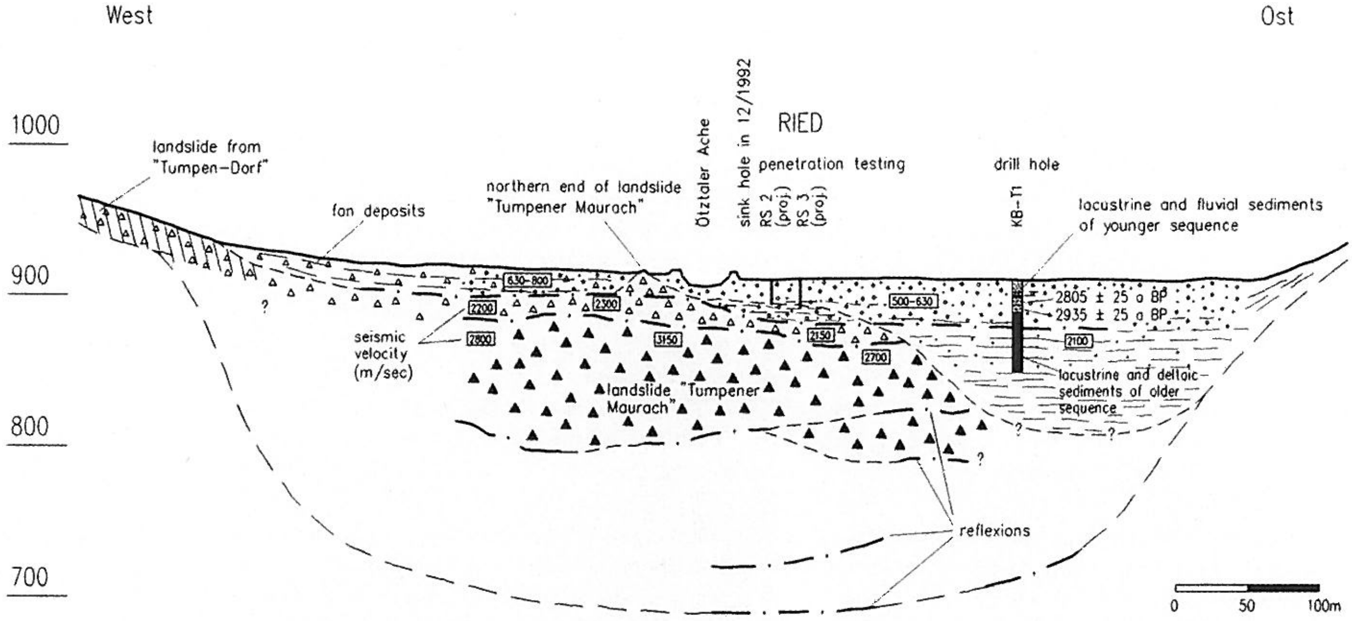


Fig. 3 Prognosis of the geological conditions in the Ried/Tumpen area (Profile A in Figure 2).

Bild 3 *Prognose der geologischen Bedingungen im Bereich Ried/Tumpen (Schnitt A in Bild 2).*

that the landslide of "Tumpener Maurach", which originates from the western valley flank, should be classified as relatively older than the landslides of the "Achplatte" (Tumpen/ Sandbichl landslide). The reason for this is that the lake sediments of the older lake phase transgress the landslide deposits of the "Tumpener Maurach". This lake was in all probability dammed by the landslides of the "Achplatte" at the northern end of the valley bottom. The ^{14}C datings of organic matter from sediments of the older lake phase from the southernmost drilling KB T-1 furnish clues as to the minimum age of the landslides of the "Achplatte" (Tumpen/Sandbichl area) causing the damming up. These clues indicate a post-glacial age taking into account the sedimentation rates mentioned below (Table 2).

Assuming a mean sedimentation rate of at least 2 cm / year – as is deduced from the datings – a silting-up of the older lake around 500 B.C. is probable. This means that the sedimentation of the lake sediments decisive for the perched aquifer occurred around 2 500 to 2 000 years ago. This places the silting up of the younger lake in the AD period, which correlates with the settlement development of Tumpen/Ried documented from the 13th century onwards.

Of primary importance for the occurrence of sink-hole collapses is the diversion of the river of the Ötztaler Ache about 300 years ago from the eastern side of the valley to the west. The old river bed can be mapped due to small differences in the valley bottom, borders in land use and the road network (see Figure 2).

The Ötztaler Ache has only been flowing west of the settlement of Ried since 1691 when it was diverted to the current river bed after the catastrophic floods which happened as a result of the outburst of a glacier lake in the Rofental valley in 1678 and 1679. The outbursts of the glacier lake which occurred several times during advancing phases of the "Vernagtferner" during the "Little Ice Age" are well documented as regards their occurrence and their effects (7, 8). Proof of this diversion of the river bed is furnished through historical cadastre documents.

Table 2 Results of ^{14}C datings in years before present (BP).

Tabelle 2 *Ergebnisse der ^{14}C-Altersbestimmung in Jahren.*

Drilling	Depth (m)	^{14}C age	Lab. number
KB T-1	16.2 - 16.6	2805 ± 25	GRN - 21547
KB T-1	19.0 - 19.3	2935 ± 25	GRN - 21546
KB T-1	29.6	3380 ± 80	VERA - 0089

Conclusion

The preconditions for sink-hole collapses are to be found in the sedimentological behaviour of the valley fill, in the existence of a perched groundwater table with partially unstable basis of the aquifer and the possibility of infiltration of the Ötztaler Ache.

In the overlying sediments there is a perched groundwater table, the level of which lies below the bottom of the Ötztaler Ache. Infiltrations of the Ötztaler Ache were demonstrated and recorded during flood periods before the sealing of the river bed in the stretch Tumpen/Ried. The comparisons of the runoff measurements of the Ötztaler Ache indicate that the large sink-hole collapses in 1992 also involved infiltrations of the river.

Infiltration and strong fluctuation of the groundwater table in connection with the unstable basis of the aquifer in the contact area with the boulder beds of the landslides can lead to a subrosion-like erosion of sediments and their removal into the landslides within the valley fill and thus cause sink-hole collapses. In the largest event to date in 1992 there was a subrosive transfer of approximately 10 000 m³ of material probably into deeper landslide deposits in the valley fill.

Determining the conditions which significantly further the occurrence of sink-hole collapses and/or initiate them was the object of the investigations. For the evaluation of the sink-hole collapse risk a matrix was elaborated which makes use of the parameters closeness to the river bed, thickness of the finely clastic lake sediments above the boulder beds and the depth of this sedimentary inhomogeneity, as well as of the frequency of sink-hole collapses nearby (Figure 4).

This evaluation can be used for risk categories which are implemented in a risk map which takes into consideration zones where settlement should be prohibited and in zones with special requirements for construction measures (9). A decisive risk reduction was achieved through the sealing of the stream bed of the Ötztaler Ache in the vicinity of existing settlement areas. Since 1995 no further sink-hole collapses have been registered.

(1) Distance between boulder-bed surface and ground surface (m)

(2) Distance (m) to registrated sink-holes (m)

	boulder beds absent	> 40	< 40	< 40	< 40
> 200	GK1				
> 200		GK2			
> 100		GK3			
< 100			GK4		
< 50			GK5	GK6	
0					GK7
	/	/	< 2 sink-hole collapses < 50m	> 2 sink-hole collapses < 50m *)	well known sink-hole area

(1) Criteria: vertical distance <> 40m:
Known occurrences of sink-hole collapses during earthworks registered up to <20 m ground surface distance (safety factor 2);

(2) Criteria: horizontal distance < 50m:
Known subsequent sink-hole collapses following major events within a radius of 50 m

Fig. 4 Risk categories due to sink-hole collapses.

Bild 4 *Risikoklassen aufgrund von Erdfallereignissen.*

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