Development of an integral system for dam and landslide monitoring based on distributed fibre optic technology

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SYNOPSIS. A large benefit of distributed fibre optic sensing technology is the opportunity to receive information on temperature (Distributed Fibre Optic Temperature sensing – DFOT) and strain (Distributed Fibre Optic Temperature and Strain sensing – DFOST) along tens of kilometres of a rather simple fibre optic cable in a spatial resolution of roughly one metre.

As part of the development of an integral monitoring setup for dams and landslides, tests carried out on the slope of “Aggenalm Landslide” in the German Alps are described in the paper. Fibre optic strain sensing and TDR cables (Time Domain Reflectometer) were installed vertically parallel to inclinometer casings into the landslide in order to receive information on the location, thickness and movement rate of the sliding plane and at the same time making a direct comparison of the different measurement techniques possible. Horizontally installed fibre optic strain sensing cables can provide information on the development of the primary and secondary cracks on the surface of the landslide.

In the next stage of the project, the installation of strain and temperature sensing cables into an embankment dam is planned. Settlements will be measured using strain sensing cables and seepage can be evaluated by heating up a temperature sensing cable (heat-up method), a method that has successfully been used in canal facings and dykes for leakage detection.

ENSURING RESERVOIR SAFETY

INTEGRAL CONCEPT

The aim of the present work is to develop an integral measurement system for hydraulic structures and their reservoirs with top of the line monitoring and data evaluation techniques.

Distributed temperature sensing in concrete

For more than a decade, fibre optic technology has been used for the monitoring of hydraulic structures. Massive concrete dams have been equipped with fibre optic cables for distributed temperature sensing. The spatial resolution in which the Raman-shift based distributed temperature sensor DTS (or ROTDR for Raman optical time domain Reflectometer) is able to evaluate the temperature along the fibre is roughly 1 m, thus 1,000 measuring points along 1 km of optical fibre can be obtained. The sensing length can today be up to 30 km and more. The large data volume allows the production of detailed temperature cross sections through concrete dams in order to evaluate them for temperature gradients. They mainly occur due to the development of hydration heat of the hardening concrete and such areas are at particular risk of cracks forming within the structure. The comparison of the performance of singe ended temperature and strain sensing devices is summarized in the following table.

Method	model	value	temp. accuracy	strain accuracy
Raman sensor	DTS, ROTDR	temperature only	up to 0.01°C	-
Brillouin sensor	DTSS, BOTDR	temperature, strain	up to 1°C	up to 20με

Distributed seepage and strain monitoring in embankment dams

In soil, a combination of optical fibres and copper wires arranged next to each other in the same cable allows the distributed evaluation of the saturation and under specific circumstances the velocity of water in soil by heating up the copper wire to a certain amount and measuring the heat transfer. This technique has been successfully applied for leakage monitoring in open water canals and research is going on to apply this technology for the monitoring of embankment dams [Perzlmaier et al. 2007]. Recent research is dealing with the application of fibre optic strain sensing in embankment dams [Hoepffner, 2008].

Landslide monitoring

The monitoring of landslides is an important factor in relation to the safety of dams and reservoirs [ICOLD, 2002]. Especially during snow melting, heavy rainfall, first impoundment and quick water level variations, the banks of a reservoir are strongly affected. Depending on the geology, ancient sliding planes can be reactivated and endanger the reservoir and the dam. A combination of different monitoring techniques could help to monitor those movements and evaluate the size, cubature and velocity of the potential landslides. A new method has been developed by the authors to evaluate the shear zone and subsoil movements using inclinometers, TDR cables and optical fibres at the same time to identify large and small shear zones. For the evaluation of surface movements, fibre optic strain sensing cables were installed on the surface of the potential landslide.

The basic idea of monitoring landslides by means of fibre optic cables is not new. Higuchi et al. 2007 proposed a setup with extrinsic sensors to monitor the crack formation in landslides and Facchini (2001) proposed to measure the strain by attaching optical fibres to telephone poles on a landslide. What is new is the installation of the strain sensing cables directly into the ground as well as the vertical shear zone measurements.

TEST SITE AT THE “AGGENALM LANDSLIDE”

The Aggenalm landslide is situated in the Bavarian Alps about 3 kilometres southeast of the town of Bayrischzell. In the north it borders to the “Sudelfeld”, Germany’s largest contiguous skiing resort. One of the main access routes to the skiing resort crosses and is therefore affected by the landslide.

In 1935, after being triggered by heavy rainfall, the Aggenalm landslide destroyed three bridges and the road to the Sudelfeld area. Again after extreme precipitation in 1997 a debris flow originated from the landslide area and blocked the road. Since 2001 the landslide has been surveyed periodically twice a year by the Bavarian state office for the environment (Bayerisches Landesamt für Umwelt), showing average movement rates of about two centimetres per year.

Due to the growing economic relevance of the Sudelfeld access road for the tourism of the region, a detailed engineering geological investigation of the Aggenalm landslide was carried out in order to assess the underlying processes. Additionally, in the course of the research funding programme “Geotechnologies” of the German federal ministry of education and research, the Aggenalm landslide was selected as the test site for the installation of an innovative early warning system for alpine instable slopes [Thuro et al. 2007].

Geology

Tectonically the area of the Aggenalm landslide is part of the Lechtal nappe of the Northern Calcareous Alps, which is built up by various sedimentary rocks of mainly Triassic to Cretaceous age. Due to the alpine orogeny, the rock mass is folded into several large synclines and heavily faulted. In the last ice age the area was covered by glaciers, which resulted in typical glacial morphology and the abundance of various glacier deposits.

The Aggenalm slope is mainly built up by the "Kössner Schichten", an alternating sequence of limestone and marl, and the overlying "Oberrhätkalk" – massive limestones and dolomites. The whole sequence dips parallel to the slope with an average angle of 22°.

The marls which underlie most of the slope are sensitive to weathering and with time are decomposed to a clay-rich residual rock. This process coincides with a distinctive reduction of the rock mass strength [Nickmann et al. 2006] and is mainly responsible for the instability of the slope. In the upper part, the Aggenalm landslide can therefore be classified as a rock spread according to Cruden & Varnes (1996). Further downhill, with increasing deformation, the rock mass continuously disintegrates and the mechanism of the landslide changes into a very slow debris flow. As the events of 1935 and 1997 have shown, the Aggenalm landslide is sensitive to heavy precipitation and the accompanying rise in ground water levels.

CONVENTIONAL INSTRUMENTATION

Essential for the hazard assessment of a landslide is detailed information about the distribution, orientation and amount of deformation in four dimensions (on the surface and in the depth alongside boreholes and with high temporal resolution). Additionally the effect of triggering mechanisms (as e.g. precipitation) to the movement and their temporal relation is of great importance.

When selecting measurement techniques for the development of an early warning system, the ability to perform continuous measurements is essential. Time Domain Reflectometry and Distributed Fibre Optic Strain Sensing were chosen for economic reasons to determine subsurface deformation. In order to be able to assess the quality of the measurements, conventional sporadic inclinometer measurements were performed.

Monitoring of the surface deformation can be achieved economically and continuously e.g. by GPS measurements. Additionally the Aggenalm Landslide will be monitored by means of reflectorless tacheometry which will produce deformation data with high spatial resolution [Thuro et. al 2007]. However the main setback of these techniques is that they often cannot be used efficiently in forested areas. Here the measurement of surface movements with Distributed Fibre Optic Strain Sensing is an interesting alternative.

Time Domain Reflectometry (TDR)

Time Domain Reflectometry can be described as "cable-based radar": The TDR cable tester emits electric pulses which are sent through a coaxial cable. When these pulses approach a deformed portion of the coaxial cable a signal is reflected to the cable tester. As with radar, due to the known propagation velocity of the electromagnetic wave, by measuring the time span between emission and reception of the electric pulse, the distance to the deformation can be determined. Furthermore the analysis of the reflected signal (amplitude, width, form etc.) can reveal information about the type and amount of deformation.

For landslide monitoring the coaxial cable is installed into a borehole and connected to the rock mass with grout. When the rock mass starts to move, the coaxial cable is deformed (e.g. altering the distance between inner and outer conductor of the cable). This results in a change of the electric properties (impedance) of the cable, which can be measured with TDR.

The monitoring of deformations in rock/soil using TDR is therefore an indirect measuring method: the deformation itself is not measured (as e.g. when using inclinometers) but a dependant value: the change in impedance of a coaxial cable due to deformation. A detailed description of the underlying physics and the setup for landslide monitoring is given in O'Connor & Dowding (1999).

Several different TDR devices with different inducted voltage pulses are available. However, so far there is no complete system for deformation monitoring including analysis software available. For the current project a Campbell Scientific TDR100 device and newly developed analysis software was used [Singer et al. 2006].

INSTRUMENTATION FOR DISTRIBUTED FIBER OPTIC STRAIN SENSING

Distributed strain sensing theory

By evaluating the power and frequency shift of the Raman and/or Brillouin peaks in the backscattered frequency spectrum, the temperature and strain along an optical fibre can be evaluated under certain circumstances.

Within the last decade, the backscattered light in the Brillouin frequency band gained interest for distributed sensing as it is sensitive to both temperature and strain along the fibre. Depending on the method for distributed strain sensing, the spatial resolution can be up to several centimetres for a loop configuration using the Brillouin optical time domain analysis (BOTDA) or Brillouin optical correlation domain analysis

(BOCDA) or roughly 1 m for the Brillouin optical time domain reflectometry (BOTDR) which only needs access to one end of the fibre. As temperature compensation is a major task, a Distributed Temperature and Strain Senor (DTSS) which compensates for temperature without additional temperature measurements and cables was introduced by Parker et al. (1997). The latter method, which is based on spontaneous Brillouin scattering, has the great advantage that measurements can also be taken even if the fibre is damaged within the structure as only access to one end is needed at a measuring range of more than 20 km. Field tests showed that the resolution of 1 m is suitable for crack detection in concrete even at crack widths of less than 1 mm [Hoepffner et al. 2007].

A measuring system for distributed fibre optic strain measurements involves basically three parts. A laser sends coherent, monochromatic impulses of light into an optical single mode fibre. As the light propagates down the fibre, it is reflected at any position within the fibre. The photons of the light interact among others with density variations in the fibre core caused by acoustic phonons that propagate along the fibre. The information on both temperature and strain is included in the frequency shifted Brillouin peaks. The third part is the detection and evaluation unit, where the backscattered frequency pattern are detected by a photodetector and processed in a computer. The stimulated Brillouin scattering process additionally involves a continuous wave laser signal which is coupled into the other side of the fibre which is used to stimulate the backscattered signal. Commercially available sensing devices include the laser(s) and the processing unit with software for user friendly data visualization.

Sensing devices

Two methods for distributed strain sensing are most commonly used: BOTDA and BOTDR. As BOTDA involves two counter-propagating light waves in the fibre, the fibre has to be continuous and accessible from two sides. The spatial resolution can be up to a few centimetres. This method is, as far as spatial resolution is concerned, particularly suitable for the subsoil sensing of a shear zone. In harsh environments or in applications where great mechanical impact on the optical fibre cables can not be ruled out, BOTDR is favoured as the measurements are taken single ended which means that the local strain in the fibre can still be evaluated, even if a fibre ruptures. However, due to physical restrictions, the spatial resolution can not be greater than around 1 m. For the monitoring of surface movements and any application inside of a dam structure, BOTDR is most favourable. As the goal should be the integral measurement of the dam and landslides with only one fibre optic strain sensing device, the BOTDR method is favoured.

The strain sensing device being used in the current tests is the Sensornet DTSS which has the unique ability of evaluating simultaneous distributed temperature compensated strain measurements from one single mode fibre.

<u>Cable</u>
The specification for a DFOST sensing cable can easily be summarized by "as tough as necessary, as strain sensitive as possible". Unlike standard telecom cables that are commonly used for distributed temperature sensing, strain sensing cable need a good bond between the very fragile optical fibre in the centre and the outer sheath, as well as to the matrix where the fibre is installed in. The goal is an excellent strain transfer but on the other hand a good protection of the cable against mechanical forces that mainly occur during installation.

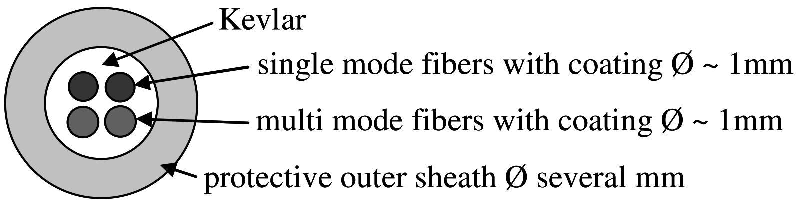

Figure 1: Cross section of a strain sensing cable.

The cables used in the present tests is a tight buffered especially designed strain sensing cable with two single mode fibres for redundant strain sensing and two multi mode fibres for independent temperature measurements, inside (Fig. 1). A standard cable with gel embedded fibres and thus no load transmission was used as extension for the surface strain sensing cable as the actual measurements were taken in an area difficult to access with the sensing device.

CABLE INSTALLATION AT THE LANDSLIDE
For the first test run, three cables were installed in fall 2008, 44 m optical strain sensing cable in the upper part of the landslide and 46 m optical stain sensing cable in a loop configuration in a 23 m deep borehole next to a 23 m long TDR cable, both attached on the outside of an inclinometer casing.

<u>Measurement of surface movements</u>
An appropriate section where considerable surface movements can be expected was visually identified, supported by geological movement indicators. The cable was installed into an excavated trench with a depth of at least 15 cm where possible, following the slope line. The cable in the trench was protected from people and animals that might pass the test area. The transmission of soil movements into the cable without applying further means could not be expected. Thus in order to guarantee a good transmission of movements to the cable, special anchors of up to 50 cm

length were designed and hammered into the ground. The top of the anchors is designed in a way that the optical cable can easily be attached without applying excessive mechanical forces on them. As depicted in Fig. 3, the cable was attached in total to 30 anchors of different length and varying spacing.

Fig. 2 shows the installation work which was carried out during strong snowfall. The cable was a little pre-strained in order to be able to locate and measure even very small movements. The readily installed cable passes a secondary rotational sliding plane and an area of probable rapid surface movements. It is planned to measure strain in the rift at the beginning of the secondary slide plane, and contraction in the lower part of the stretch. Additional strain zones can be expected in the steep part of the cable layout, where surface movements up to a depth of some hundreds of millimetres are expected.

Measurement of subsoil movements and shear zones

Shear zones are vital parameters in order to obtain information on the thickness of a landslide and thus its cubature. It is generally not possible to evaluate the depth of a shear zone from boring profiles only. For more than a decade, the TDR measuring technique proved to be a very appropriate method for the detection of localized shear planes. However the deformation detection reaches its limit, resulting in a gradual bending of the coaxial cable with no significant change of the cable cross section geometry (see Fig. 3).

On the other hand, optical fibres have a maximum elongation of around 3 % and are sensitive to buckling. Very distinct shear zones would lead to a break of the fibre after only little movement, where movements within a thick shear zone would be measured as strain within the moving zone. Therefore the combination of the two systems could provide very valuable information on the situation and the movements at the shear plane. In our tests, the cables were attached onto the outside of an inclinometer casing. The inclinometer data can later be used to validate the measurements.

TDR

A single semi-rigid aluminium coaxial cable with a diameter of about 12 mm was attached to the outside of the inclinometer casing with duct tape. In order to prevent ingress of moisture into the cable, its end was sealed with heat shrink tubing and a cap. When installed below the groundwater table the aluminium cable should be protected against corrosion either by using a jacketed cable or by applying a corrosion inhibiting paint.

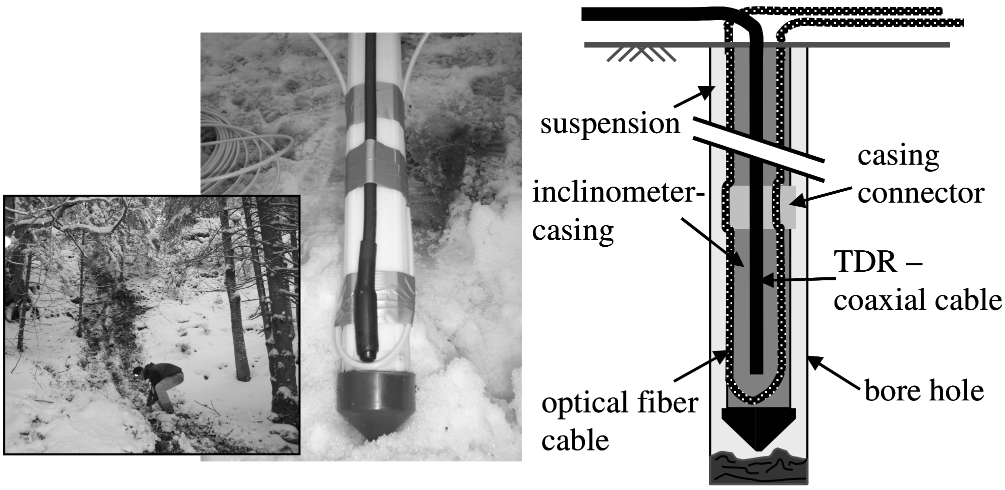

Figure 2: Equipment in the vertical borehole: TDR cable, optical cable and inclinometer and near-to-surface cable installation during snow fall (left)

Fibre optic cable

The fibre optic cable was also attached onto the outside of the inclinometer casing with duct tape. On the low point of the casing, the cable was looped back up, to be able to measure the cable from two sides which could also be essential in case of a damaged fibre. To have the theoretical opportunity to measure the direction of the subsoil movement, the two parts of the cable were attached on the casing with 90° spacing thus at 12 and 3 o'clock (see fig. 2).

FIRST DATA EVALUATION

TDR

Until the installation of the continuous measurement system is completed in the spring of 2008, only sporadic TDR measurements were carried out. In the three measurements since December 2007 so far no deformation could be detected. This is not surprising since the installation of a coaxial cable parallel to an inclinometer casing prohibits an effective transmission of the rock mass deformation to the cable and results in a rather gradual deformation of the coaxial cable, which can not be measured. Only after a considerable amount of deformation (several centimetres) the measurement will start to change the cable geometry and therefore produce results. At this time the inclinometer will almost certainly be near the end of its lifetime, so that the TDR measurements can considerably prolong the lifetime of a subsurface deformation measurement site. This could, for example, enable identification of additional shear planes below a main shear zone [Singer et al. 2006].

In principle, the installation of a coaxial cable parallel to an inclinometer casing into the same borehole is not advisable for the above reasons. It is better to install the coaxial cable into a borehole of its own and to connect the cable to the rock mass with a rather stiff grout, thereby making the transmission of the rock mass deformation to the coaxial cable possible.

In 2008 the installation of several boreholes solely instrumented with coaxial cables for TDR deformation measurements are planned. Some of these are placed near to inclinometer measurement sites, so that a direct comparison of the collected data will be possible.

Optical cable

Right after installation, OTDR measurements were taken from the installed cables in order to assure the fibres are continuous, not excessively bent, damaged or broken. As the DTSS device was not available since the time the installation was made, the measurements were postponed and are estimated to be carried out in spring or early summer 2008 after snow melt.

INTEGRAL DAM AND LANDSLIDE MONITORING SETUP

An integral monitoring system based on optical fibres for several safety concerns of a hydraulic structure and its reservoir bears many advantages. The sensors are cheap while collecting a huge amount of data due to a spatial resolution of up to 1 m. Optical fibres are not affected by electrical interference, weather conditions or vegetation. The data collection and processing can be automated and remote controlled via modem. A permanently installed temperature and strain sensing device could provide information on the state of the dam and at the same time monitor landslides that might affect the reservoir, even if located many kilometres away.

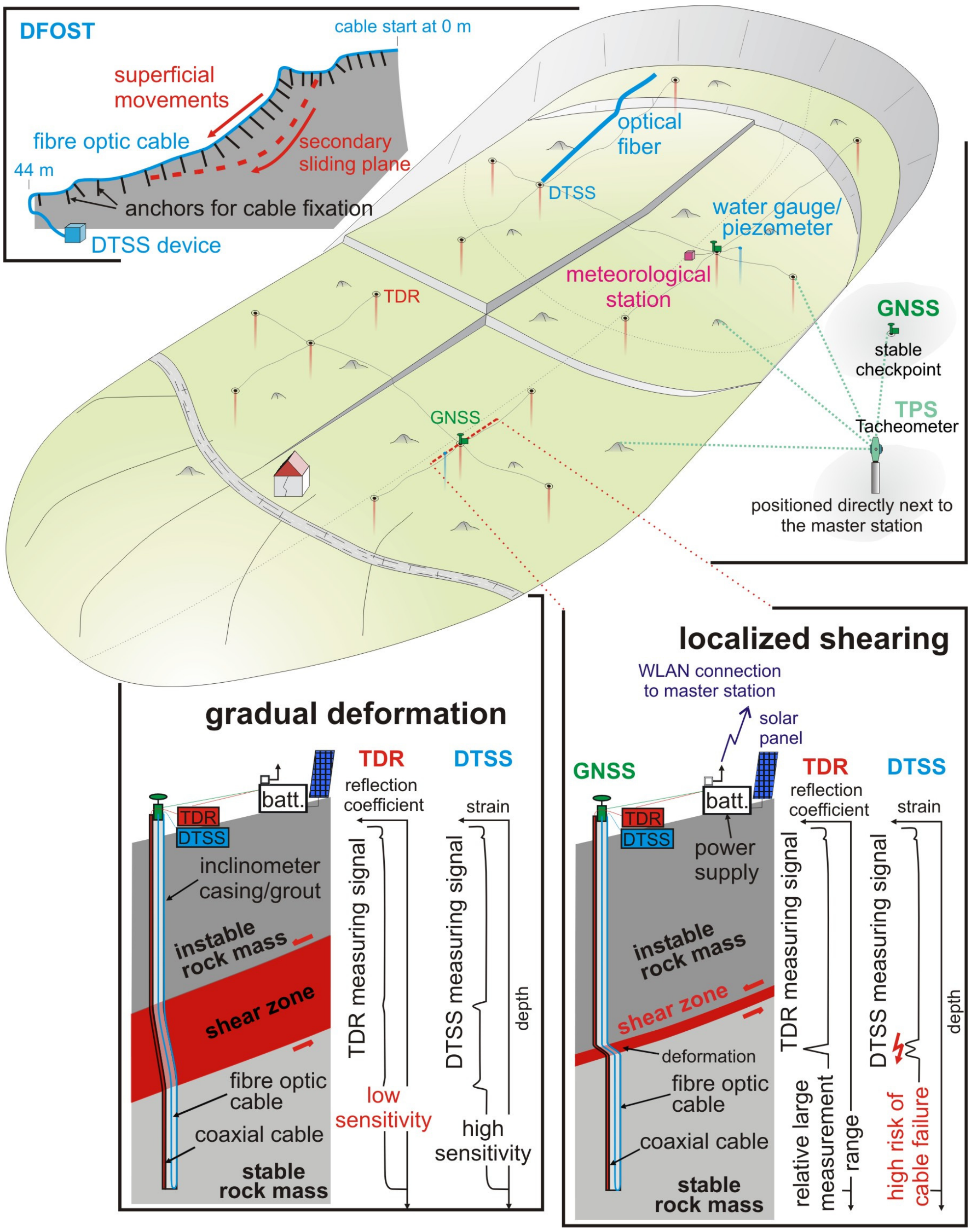

Figure 3: Measuring setup and expected measurement data at the Aggenalm Landslide.

Despite all its advantages, a combination with other measurement systems is absolutely essential. For the monitoring of landslides, TDR seems to be the ideal match for the evaluation of shear zones (see fig. 3).

OUTLOOK

The versatility of optical fibres and the sensing technology leads to the concept of an integral measuring system based on fibre optics. Dam monitoring with optical fibres in connection with monitoring of the slopes of the reservoir are ideal in connection with conventional methods. The TDR measurements presented in this paper have been used in multiple landslides but research is going on towards the optimization of the software and evaluation methods in order to receive not only information on the location but also the amount of movement in distinct shear zones. A combination of those two techniques allows the monitoring of the entire structure including the shore area of the reservoir remotely even in remote and wooded areas. As the optical sensors are rather cheap, the advantages can easily overcome the high price of the sensing device. For TDR, the coaxial cables as well as the sensor are relatively cheap, but as the range of a single measuring device is limited to cable lengths of about 300 m, for large project areas several TDR devices are needed.

Further research is being carried out into the performance of distributed fibre optic strain sensing devices, use-orientated cable designs and new installation, layout and monitoring techniques for optimal data evaluation in landslides, concrete and embankment dams. The first strain measurements at the Aggenalm Landslide are scheduled for 2008.

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