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Institute of Applied Geosciences

Engineering Geology Master Program

Master Thesis

DETAILED INTERPRETATION OF GEORADAR DATA AND DRILL CORES ON LANDSLIDE DEPOSITS

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ABSTRACT

The objective of the present document is the detailed interpretation of georadar profiles with information from surface geology and geomorphology and borehole data for a better understanding of the subsurface conditions on the channel of the Schütt Hydropower Plant. The investigations were carried out after a failure in the channel was believed to be caused by cavities in the subsurface. Georadar prospecting was selected because of its capability to detect shallow structures and stratigraphy as well as the possibility to detect cavities.

Parallel and perpendicular georadar lines were surveyed in the critical section of the channel to obtain information on the subsurface stratigraphy and structures. The ground penetrating radar profiles were conducted with a monostatic antenna with frequencies of 200, 400, 900 and 1500 MHz. Several shallow borings were made for ground verification while others were used for piezometer installation. To support the interpretation of the georadar profiles, geological and gomorphological field mapping of the channel length, aerial photograph interpretation, sketching profiles and borehole logging were carried out. The different quality data obtained from the field methods was interpreted and correlated to interpret the geophysical data. The radar profiles were calibrated using the surface geology and drill core layer descriptions. Because of the depth of penetration and different resolution provided by the various measured frequencies of the radar profiles the lower frequency surveys were used for subsurface analysis and the higher frequencies surveys for shallow. From the analysis and interpretation of the low frequency georadar profiles the subsurface stratigraphy was delineated, calibrated with borehole information and several reflection patterns characteristic for voids or cavities were observed.

1. PROBLEM

The Schütt Hydropower Plant is found on the southern slopes of the Dobratsch Range in the valley of the Gail River. The Dobratsch Mountain suffered from massive landslides in pre historic and historic times that have given shape to the actual topography. The Hydropower installations are constructed on landslide deposits, alluvial, and fluvial deposits from the Gail River. Along the channel failures have occurred and are thought to be caused by cavity formation due to fine sediment migration.

Because of the type of chaotic landslide deposit, the natural ground of most of the area where the hydropower constructions lie consists of unconsolidated blocks, gravel, sand, and silt. Alluvial and fluvial materials found in the area have similar characteristics. The unconsolidated state and the grain size distribution allow them to have a high permeability. These properties permit infiltration and therefore water can flow in the subsurface and can also remove and transport fine sediments.

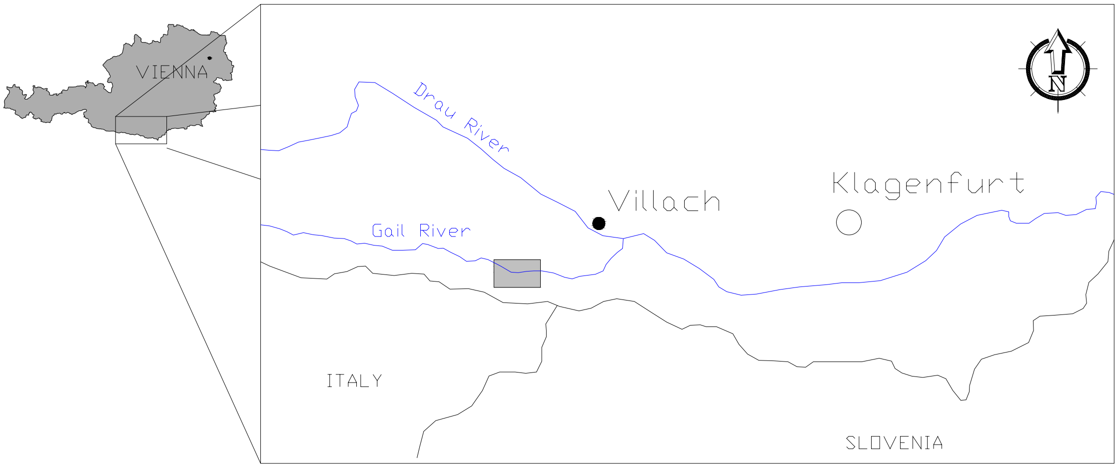
Migration of fine sediments itself can increase permeability of the deposits by the removal of particles. The development of cavities as well as create unstable conditions can cause failure on constructions founded on or located near the areas affected by this process. The oldest part of the Schütt channel possibly failed due to the lack of support perhaps caused by removal of fine sediments and/or cavity formation.

Leakage in the channel originated by concrete fracturing may produce a reduction in flow of water in the channel and in the subsurface. It may also damage the construction, and harm the surroundings as well as create economic loss by affecting the generation of electricity. The detection of cavities along and in the near from the channel of the hydropower is critical for the prevention and mitigation of this hazard.

1.1 Schütt Hydropower Plant Scheme

The Schütt Hydropower is located West of the town Villach in Carinthia, southern region of Austria. It is located on the foothills of the Dobratsch Range. The hydropower has dammed the Gail River whose water is conducted from the dam to the powerhouse in a nearly 3.50 km long V shaped channel. Figure 1 displays the location of the area of investigation shaded in a grey.

Figure 1. Schütt Hydropower location.



Modified from http://www.maps.com/ref_map.aspx?pid=11909.

The hydropower was constructed by the Kärntner ElektrizitätsAktiengesellschaft, KELAG, in two phases. A brief history of the hydropower construction by KELAG (Kraftwerk Schütt der Kärntner ElektrizitätsAktiengesellschaft), describes the two constructive phases of the hydropower. The first phase was conducted from 1911 to 1913 consisting on a dam on the Gail River and a 1750 m channel to the power house. The second phase constructed 50 years later from 1960 to 1961, consisted in extending the channel length 1405 m towards a new power house to increase the energy production.

The Schütt Hydropower installations comprise the dam, channel and powerhouse along the Gail River. The constructions were mainly built on the historic and prehistoric deposits of the Schütt landslides. Recent fluvial and alluvial deposits from the Gail River are also found in the area.

1.2 Failure

A failure of the channel occurred in the old section, at a chainage of approximately 300 to 360 m from the dam. The concrete of the channel failed and caused flooding of the land in the vicinity and the hydropower ceased the production of energy as the channel lost water. The immediate response for the restoration of power generation was the repair of the structure of channel. On the affected surroundings the flood water infiltrated leaving scarce signatures of the event.

Following the failure of the channel of the Schütt Hydropower, investigations were made to determine the possible causes. The collapse of the concrete of the channel led to believe that subsurface cavities were responsible for the failure. A series of investigations followed the event to establish the possible causes as well as to detect other hazards that could cause future damages to the hydropower constructions as well as for the environment.

The investigations included borehole drilling, piezometer installation and georadar prospecting near to where the channel failed. These inspections were followed with this study, which included a campaign of surface geology and detailed interpretation of the previous information and the obtained knowledge of this investigation.

1.3 Tasks

The main tasks of all the investigations carried out in the Schütt Hydropower plant were to understand the geologic conditions of the subsurface as well as evaluate and interpret the actual situation and possible cause of the failure. Stratigraphy, sedimentary structures, presence of blocks and possible cavities are the main objective of the interpretation of this study.

The combination of the investigations carried out with geophysical methods, geology and landscape information plus also drill holes provides an integrated survey to understand the superficial and subsurface conditions. The integration of different quality information by the various methods enables a more reliable interpretation of the gathered data.

Georadar prospecting was performed along the affected areas of the channel to try to establish the best measuring configuration for the detection of cavities. Additionally, the geophysics was used to survey the subsurface conditions and the structure of the deposit and asses places where future failure might be possible.

A borehole campaign also took place in several locations along the oldest and problematic section of the channel. The borings included the drilling of 6 cored boreholes for subsurface investigation as well as additional borings for the installation of piezometers.

In order to fulfill a detailed interpretation of the different quality georadar information the investigation included the elaboration of a geologic and geomorphologic map as well as the information from the boreholes. The field mapping of 100 m on each side of the channel along its entire length, scale 1:1,000, identifying and describing the different units present in the area. Borehole information was then correlated to the surface geology and projected into the georadar profiles for a better interpretation and understanding.

2. GEOLOGICAL SETTING

The Dobratsch Range is part of the Southern Calcareous Alps. The Dobratsch Mountain consists of Middle to Upper Triassic transitional bedded limestones and dolomites. The area is characterized by a number of historic and prehistoric massive landslides potentially triggered by favorable ground conditions and high earthquake hazard.

The geology of the Arnoldstein is (Hauser 1982) in the explaination of the geologic map of the region. He describes that the area is characterized by Triassic limestones and dolomites as well as by reef limestones. Permian conglomerates and Quaternary deposits are also found on the surroundings.

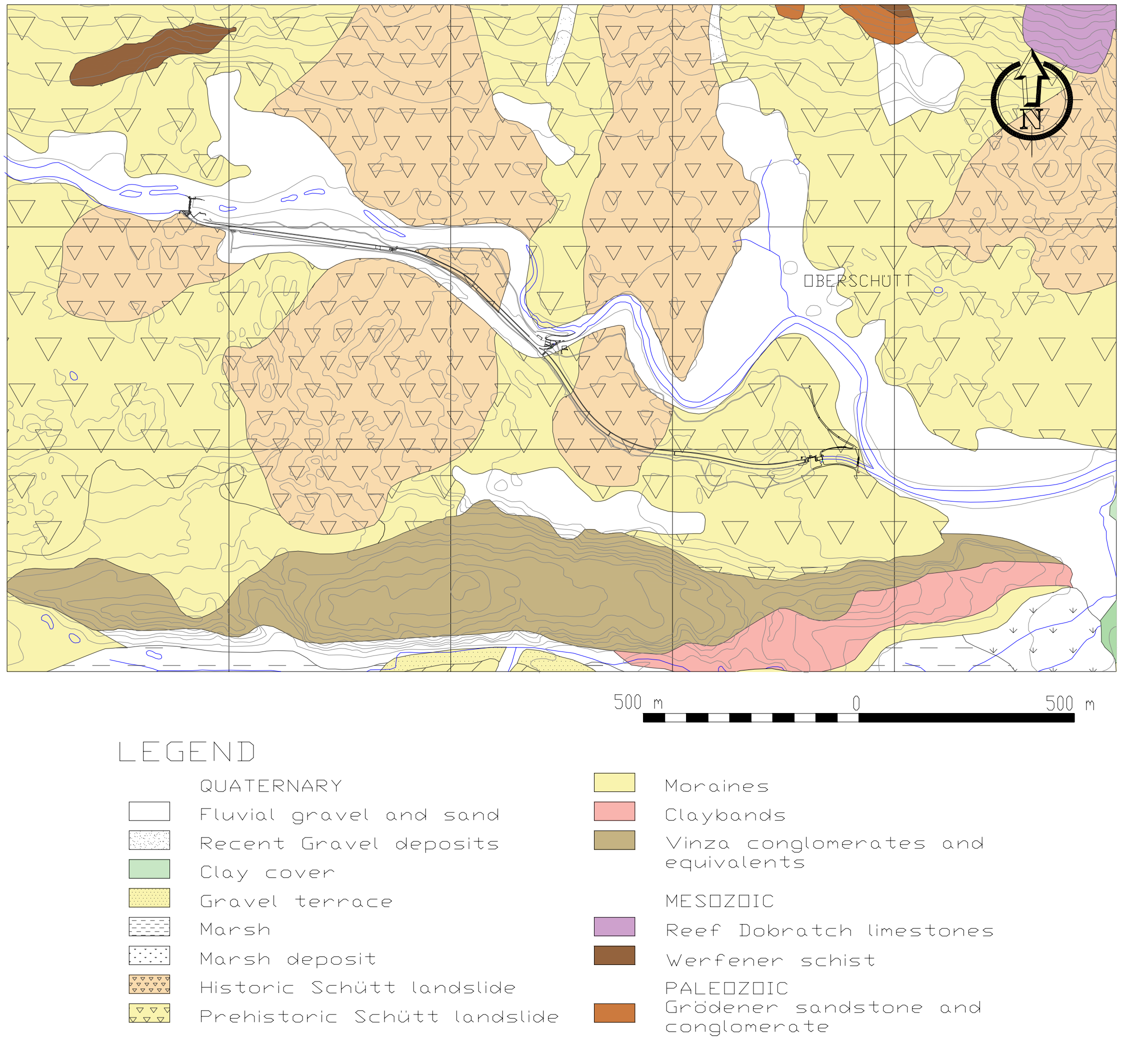
The oldest units (Hauser 1982) are comprised by Triassic weathered limestones and dolomites from the Dobratsch that reach up to 700.0 m in width. They are the main building rock within the Dobratsch complex. In the center the limestones and dolomites contain reef limestones and reef debris that have a thickness of about 1000 m.

The explanation (Hauser 1982) of the geology in Quaternary times describes the Drau and Gail glaciers that carved most of the morphology and landscape on the western area of Arnoldstein. Rocks from the Vinza Nagelfluh and Equivalents represent the oldest glacial units. These rocks are predominantly calcareous and range from 100.0 to 150.0 m in thickness.

The morphologic manifestations of the glacial retreat periods from the ice age are found on the Drau and Gail valleys west from Villach (Hauser 1982). These deposits have a thickness of more than 1000 m. The time is represented by ground moraines in the valley areas that can be differenciated from the other units. Kettles and kettle moorlands with rich volumes of clay and silt can be found as morphological features for glacial retreat.

The geologic map of the Arnoldstein region (Geologische Bundesanstalt 1977) represents the different units that are found in the area. The following figure is a portion of the geologic map concerning the Arnoldstein northern region where the hydropower is built (Figure 2).

Figure 2. Geology of the surroundings of the Schutt hydropower.

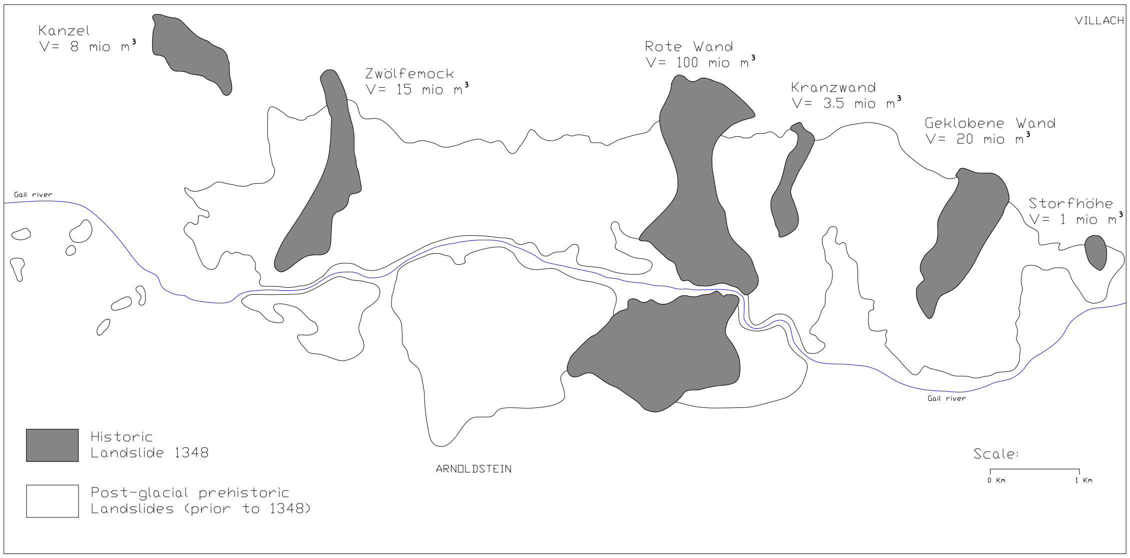


Modified from Geologischce Karte der Republik Österreich. Blatt 200 Arnoldstein. BMN 4716. 1:50,000. Geologishce Bundesanstalt. Wien. 1977.

Slope debris, post ice age fan formations and debris waste deposits can also be found along the southern region of Arnoldstein. One of the biggest landslides occurred in the Austrian territory is that which is found on the south side of the Dobratsch mountain.

The sliding occurred on January 25th, 1348 being caused by 6.5 magnitude earthquake (Hauser 1982). A series of mass movements moved down along the southern slopes of the mountain, figure 3 shows their location. Historical records report the burial of 10 villages, 9 churches and approximately the death of 5000 people. The next figure (Figure 3) shows the location of the different landslides.

Figure 3. Schütt landslide location.



Modified from Lenhardt, W. Earthquake triggered Landslides in Austria-Dobratsch Revisited. Jahrbuch der Geologischen Bundesanstalt. Vienna, Jan. 2007. P. 193-199.

Underlying the slide material from 1348 mass movement, material from larger postglacial, prehistoric landslide deposits are found. The figure above shows the massive prehistoric slide as well as the most recent ones from the 13th century. The Dobratsch Mountain has a southern head scarp corresponding to the slide masses where it is susceptible.

The event caused flooding because the Gail River was dammed by the mass movement (Lenhardt 2007). Commonly the effect of a large landslide along a valley floors is the partial or total damming of the drainage system forming floods, temporal lakes and sediment supply changes. The deposit of the landslide itself is composed by poorly sorted, angular debris, of various grain size distributions that forms hummocky mounds with isolated marsh areas.

The most recent deposits correspond to the fluvial deposits of the Gail River. These are unconsolidated gravels and sands that can be found on the river channel. Soil development is also observed on the units where vegetation and weathering processes have been able to act.

3. METHODS

For the understanding and mitigation of problems of the engineering project the best description possible is needed for the characterization of the underground. Different quality of data of geophysical surveys, drill holes, surface geological and geomorphological mapping as well as an adequate interpretation and correlation can lead to a better understanding of the site conditions.

Boreholes represent only single point information in a lateral dimension of the underground. Geophysical surveys are generally non invasive and give an indirect two dimensional data of the underground conditions. Geotechnical information from detailed mapping provides basic geologic information of the surface conditions. The integration of the methods combined and their appropriate analysis can provide a better comprehension of the subsurface as well as the identification of potential geological hazards.

The field investigations included core drilling, georadar prospecting and also a geologic and geomorphologic mapping of 100.0 m on each side of the Schütt Hydropower channel length. The drilling campaign and geophysical survey was done previous to the field mapping.

Because of the failure occurred in the initial and oldest part of the channel the field investigations were concentrated near the problematic zone. Core drilling was focused on the problem zone at a chainage of 80.0 to 550.0 m. The georadar surveys were done parallel and perpendicular to the channel at 4 different frequencies from a chainage of about 250.0 to 400.0 m. The geological and geomorphological mapping was done at a scale 1:1000 to identify the deposits and survey the channel itself, profiles were done every 100.0 m on the older section of the channel and every approximately 250.0 m on the new section.

The field descriptions are made considering the down flow of the Gail River and channel. The right side corresponds to the southern section of the channel while the left side to the northern side that is alongside the Gail River. The channel chainage begins at the dam and increases towards the two powerhouses, downriver. All of the descriptions follow the same manner.

3.1 Aerial Photographs

Aerial photographs were used for the delineation and characterization of the surface units by means of photo-interpretation. These photographs are from the year 1966 and cover the entire area of the hydropower, from the dam to the new power house. The interpretations were made with the stereopairs and the delineation of these units can be observed in the Annex 1.

Using stereographic interpretation of the aerial photographs, the subdivisions of the units defined in areal photography were made by interpreting the observed patterns, vegetation, landscape features involved in different land forming processes in the area. The units visible in the aerial photographs are also fluvial, alluvial, landslide and anthropogenic.

3.2 Field Mapping

For the comprehension of the conditions of a landscape in a certain region, the geologic and geomorphologic characteristics have to be established. The development that a landscape undergoes depends not only on the geologic characteristics but also on the environmental conditions and the different anthropogenic activities that affect the area. The establishment and understanding of the different processes acting on a certain region gives information on how the system behaves actually and can estimate how it can behave in the future.

Geology involves the investigation of units linked to the landscapes and the processes that affect them. The geologic characteristics include petrography and stratigraphy, as well as the structural geology and other characteristics of the units. Geological units can be lithological and/or deposits.

Using the channel chainage the identification of the landscape and geological units was done. A Leica laser electronic measuring device for measuring distance between two points and a 30.0 m measuring tape were helpful in determining linear distances for the detailed mapping. A base map of the channel with the chainage and a grid every 50 m on each side of the channel was used as a base for the cartography.

A geomorphological and geological map was created for the entire channel length, 100.0 m on each side, with a scale 1:1000. The geological units were identified in the field and represented on the map. Using the legend and principles of the ARGR geomorphological mapping system the information concerning the landscape were also mapped and described. The field work for the cartography was done in 7 days from July 20th to the 28th at the Schutt Kraftwerk in Carinthia. The map created can be seen in Annex 1, the scale of the printed map has been modified to 1:5000 for easier handling.

To be able to visualize the geologic units as well as the stratigraphy of the area cross section profiles were sketched perpendicular to the channel. For the initial 1750 m of the channel that correspond to the older construction the cross sections were sketched every 100.0 m. On the most recently constructed section of the channel the profiles were drawn approximately every 250.0 m. The cross sections can be observed in the Annex 2.

3.3 Geomorphology

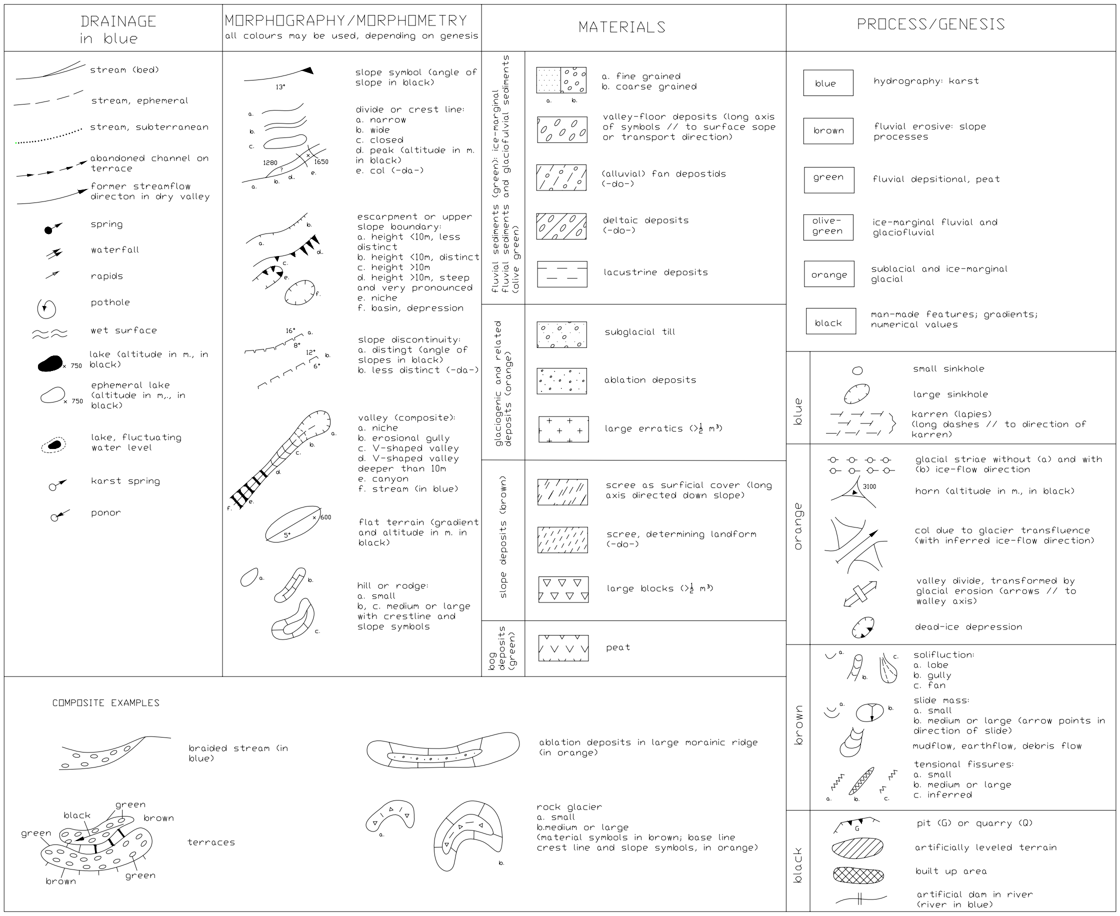
Geomorphology is the science that studies the earth's surface and the processes that create and reshape the surface (Gustavson 2005). It incorporates parts of geophysics, sedimentology, geochemistry, hydrology, pedology, climatology, engineering and other sciences to appreciate how it all affects the environment.

Geomorphological processes (Panizza 1996) take place between the contact surface of the lithosphere and the atmosphere or the hydrosphere. It concerns the units of the earth's surface that are genetically linked to the relief that can be observed at the present time. Geomorphology uses schematic procedures to explain the genesis and evolution of a physical landscape.

Good geomophological maps are strong documents of environmental data that describes the configuration of the earth's surface as complete as possible. They illustrate the form of the landscape, the process responsible for shaping and reshaping it, the drainage and the materials present. The surface dynamics through time and the interrelations between the land forms enables the evaluation and reconstruction of the history of the landscapes and in some cases the prediction of future development (Gustavson 2005).

The geomorphological mapping system used in the investigation was developed by the Alpine Geomorphology Research Group (AGRG) in 1987. It is a detailed geomorphological map legend for alpine areas created in the alpine surroundings of Voralberg, Austria. This mapping system (Gustavson 2005) has been successfully applied in areas that have less pronounced relief. The following figure shows an outline of the legend that is used by the ARGR alpine geomorphological mapping system (Figure 4).

Figure 4. AGRG Geomorphological mapping system.



From De Graff et al., 1987.

This system uses the information from morphography/morphometry, materials from unconsolidated deposits, process/genesis and the hydrography as major sources of information. The process/genesis source is mainly interpretative but is an essential tool in applications like land stability and human impact. The morphography and morphometry refers to the actual landscape and topography (Gustavson 2005).

Symbols and colors are combined to describe the landforms as layers on a base map showing topographic contour lines and administrative information. Symbols are also used to indicate the direction of transport as well as the hydrography and artificial drainage if present.

3.4 Drilling

A borehole campaign included the drilling of 6 cored boreholes as well as additional borings for the installation of piezometers in the vicinity of the failures. The core samples were then logged and described for the use of the subsurface interpretation. The logs and borehole description was used for correlating with the surface geology, profile sketches and for the interpretation of the georadar profiles.

Core drilling investigation can be used to determine the types of materials present in the subsoil. Drilling techniques are punctual on the information they provide and tend to destroy the microfabric as well of modify the structures and boundaries between layers of sediments. Core samples are placed on boxes for logging and describing the observed characteristics of the material with the purposes of the investigation.

A drill core layer description is not very detailed and might not indicate clearly the texture and structure of a specific layer. Bore hole descriptions vary considerably and do not provide information on the geometry and dimensions of the subsurface structures. The descriptions of core samples primarily include information on grain size distribution, main constituent, quantity, sorting, color and layer thickness of the entire sampled borehole.

3.5 Geophysics

Geophysical methods can provide necessary data to understand the underground conditions with the combination of outcrop and surface information with the supplemental information of borehole description. The geophysical method selected should meet the requirements for the gathering of a maximum of information. The method selected should be the best approach considering the conditions of the site.

For this case Georadar prospecting was chosen because of the effectiveness of this method in underlining the underground characteristics at a shallow depth as well as the possibility of cavity detection. Seismic reflection and refraction can penetrate to a greater depth but it is not intended for the detection of cavities. Techniques like electric resistivity and spontaneous potential are also not successful in for void detection and therefore GPR was chosen. For a better understanding of the local geologic conditions of the Schütt Hydropower a detailed interpretation for ground penetrating radar profiles was necessary.

Ground Penetrating Radar is a very useful method that can be used in hydrogeological and near surface mapping studies. It is used to study underground contamination, subsurface shallow geologic structures, underground cavities and voids which can all be potential hazards. The sooner these problems can e detected and evaluated the faster a strategic mitigation plan can be established and implemented to minimize further or future damage to structures and the environment (Benson1995). This method has also the capability to determine discontinuities, boulders, sedimentary structures and man made edifices, pipings, drainages, etc.

Georadar is a geophysical method that transmits electromagnetic pulses into the shallow subsurface. A receiver gathers echoes from reflecting boundaries where there are contrasts in the dielectric properties (permittivity). The method is a high resolution technique for the imaging of shallow structures in the subsoil using electromagnetic waves at frequencies that range between 10 to 1000 MHz. The method is most effective when the materials that are characterized have low electrical conductivity such as ice, sand, crude oil, bedrock and fresh water among others (Sharma 1997).

Depending on the electrical properties of the materials composing the subsurface, the radar waves are propagated. The water content, the presence of dissolved minerals, clay content and heavy mineral content are the general controls of the electrical properties a material may have. The penetration capability of the georadar depends on each site of investigations and depends on the source of the signal, the antenna configuration and the electrical conductivity of the subsurface materials. The range of penetration in GPR decreases with increasing electrical conductivity and with higher frequency.

Water content has a primary control over the dielectric properties of materials. Reflections are generated with changes in the porosity, in the amount and type of fluid occupying the pores, grain shape, packing, etc. Groundwater table and discontinuities should all be visible as clear boundaries with the Ground Penetrating Radar method. Water has a value of 81 for a permittivity and most rock forming minerals in between 3 and 6. The following table shows the physical and electromagnetic properties of common geologic materials after Degenhardt (2009).

Table 1. Physical and electromagnetic properties of common geologic materials.

Material	Relative permittivity Є	Electrical conductivity σ (mS m^{-1})	Propagation velocity (m ns^{-1})
Air	1	0	0.3
Fresh water	81	0.5	0.033
Sea water	81	30.000	0.01
Sand (dry)	3-5	0.01	0.15
Sand (wet)	20-30	0.1-1	0.6
Silts	5-30	0.5-2	0.07
Clays	5-40	1-100	0.06
Shales	5-15	1-100	0.09
Limestone	4-8	2-100,000	0.12
Granite	4-6	0.1-1	0.13
Ice	3-4	0.01	0.16

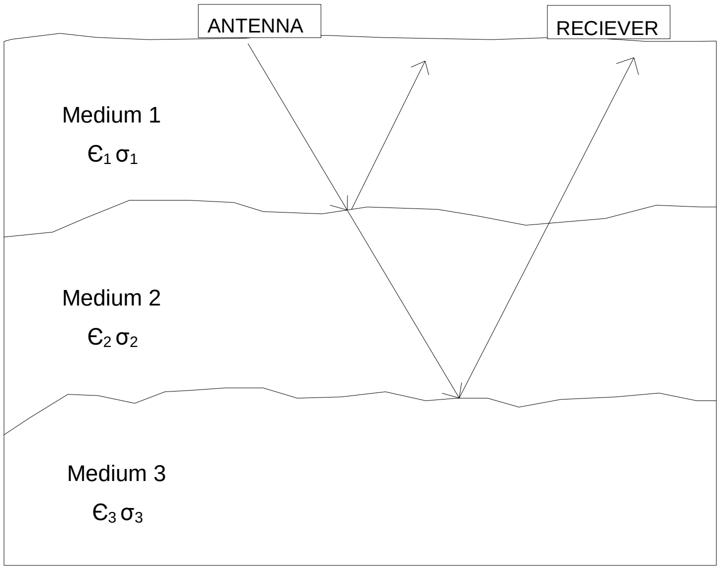
Modified from Degenhardt, J.J. Development of tongue-shaped and multilobate rock glaciers in alpine environments – Interpretations from ground penetrating radar surveys. Geomorphology 109. Pp. 94-107. Elsevier B.V. 2009.

Sharma (1997) explains that radar signal velocities are related to the relative permittivity (ϵ_r) also known as the dielectric constant. The propagation of the radar signal depends on the electrical properties of the ground. The electrical properties of geologic materials are governed principally by their water content, the dissolved minerals, expansive clay content and heavy mineral content. These electrical properties all have a strong influence on the subsurface propagation of the radar pulse. The attenuation of a radar wave and its depth of penetration depend on the dielectric constant and the electrical conductivity (σ) of the medium. The range of penetration decreases with increasing electrical conductivity and with frequency.

Reflections occur when electromagnetic waves meet boundaries between materials with contrasting dielectric constants (Regli, Huggenberger, Rauber 2002). Reflectors may occur at the change of water content within same texture sediments, at the boundary of two distinct sediment types or at different sedimentary structures.

The amplitude of the reflected wave depends on the contrast of the dielectric characteristics of the underground (Morawetz 2009). As the dielectric characteristics of the materials differ the reflected signal is greater. The antenna receives the signal waves into the monitoring unit that are processed afterwards. Because there is a linear connection of the wave velocity and the depths of objects and structures, the depth of a reflector can be determined if the velocity is known. The following figure (Figure 5) is a schematic diagram of the Ground Penetrating Radar measuring method.

Figure 5. Schematic measuring method for GPR.



Modified from Hamzah, U., et al. Geoelectrical resistivity and ground penetrating radar techniques in the study of hydrocarbon contaminated soil. Sains Malaysiana 38. March 2009. Pp. 306.

The data obtained from the georadar surveys is presented in a two dimensional depth profile along the scanned line. The vertical axis of the profile is the two way travel time of the reflected wave measured in nanoseconds. The two way travel time is the period of time that takes the signal to be transmitted from the antenna located at the surface to the reflector and back to the receiver antenna.

If the propagation velocity of the electromagnetic pulse is known the depth of the reflector can be obtained by the next equation (1):

$$z = \frac{vt}{2} \tag{1}$$

where z is the depth to the reflector, t is the two way travel time and v is the velocity through the material in the underground. The velocity is related to the relative dielectric constant (ϵ_r) by the equation:

$$v = \frac{c_0}{\sqrt{\epsilon_r}} \tag{2}$$

where c_0 is the velocity of light in free space or vacuum (30 cm/ns). The relative dielectric constant is the measure of the capacity of a material to store a charge when an electric field is applied to it relative to the same capacity in a vacuum (Benson 1995).

The penetration capability of the georadar is site specific, depending on the source of the signal, the antenna configuration and the electrical properties of the subsurface materials (Neal 2004). For a particular study the radar frequency is selected to provide an acceptable compromise between the penetration desired and adequate resolution. High frequency radar signals produce greater resolutions but are limited in depth of penetration. A lower frequency will be able to detect deeper structures but with a low resolution.

The resolution of a measuring system indicates the minimum dimensions for the detection of underground objects. The vertical and horizontal resolutions are both defined by the geometrical characteristics of a wave and its characteristic parameters.

The vertical resolution is given on the radar wave frequency and wavelength applied for the designed surveying system. Because the wavelength depends on the transmitter frequency and the wave velocity, different resolutions are given by different antennae configurations for different materials.

A rule of thumb is applied for the vertical resolution ideally it corresponds to a quarter of the wavelength used in the survey. In reality due to variations and uncertainties it is typically equal to one third to one half of a wavelength, in accordance to Regli (2002). The wavelength is given by the equation that follows (3);

$$\lambda = \frac{v}{f} = \frac{c_0}{f \cdot \sqrt{\varepsilon_r}} \qquad (3)$$

where v is the wave velocity, f the frequency, and C_0 is the speed of light in vacuum.

The horizontal resolution is defined by the Fresnel zone. The Fresnel zone (Neal 2004) uses the case of a spherical wave that depends on the wavelength and depth of a particular reflector. According to this definition the ability to detect an object depends on the lateral expansion of the radius (*r*) of the first Fresnel Zone measure that is defined by the following equation (4);

$$r = \sqrt{\frac{\lambda \cdot z}{2} + \frac{\lambda^2}{16}} \qquad (4)$$

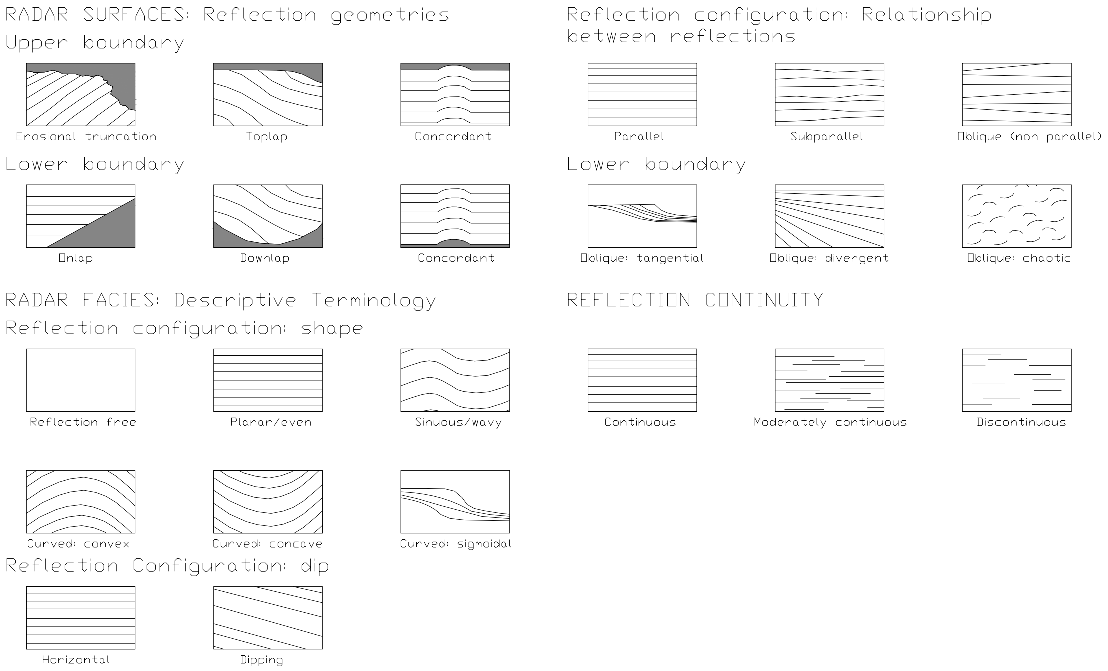
where z is the reflectors depth. From this equation it can be derived that the horizontal resolution is attenuated with increasing wavelength and reflector depth.

Limitations of the radar scanning can be caused by man made pipes and cables lying perpendicular to the survey line as well as sediment grains large in comparison with respect to the radar wavelength, obscuring the subsurface reflections (Neal 2004). Surface reflections can obscure the subsurface reflectors and can be produced by power lines, poles, trees, fences, large blocks and boulders, constructions as well as irregular topography. All of the above have to be considered when processing the radar data.

The Ground Penetrating radar technique is a non destructive method good in determining the structure and range of structures and architectural elements in unconsolidated sediments in the subsurface. Appropriately processed and interpreted data can give a wide variety of information of the stratigraphy and structures allowing the delineation of radar reflectors and radar facies. However, the reflection patterns are only an indication of possible subsurface relationships.

A radar facies is defined (Regli, Huggenberger, Rauber 2002) as a mappable sedimentary structure with a reflection pattern different from those adjacent to it. Their geometry can be delineated by continuous reflections and by the types of reflection patterns within a visible structure. Boundaries delimit the defined facies each with its characteristic properties. Figure 6 shows the terminology used for the description of radar surfaces, packages and facies on the interpretation of the georadar profiles.

Figure 6. Radar reflector terminology.



Modified from Neal, A. Ground Penetrating radar and its use in sedimentology: principles, problems and progress. Scool of applied Sciences. University of Wolverhampton. Elsevier B.V. Jan. 2004. Pp. 311.

The radar facies should be calibrated with the interpreted drill cores located in the vicinity of the radar profiles. This calibration consists of the assignment of sedimentary structure type from the drill core layer descriptions. The terminology used for the facies description is defined by Neal (Neal 2004). Reflection patterns are defined considering their general shape, dip of reflections, the relationship between them, and also their continuity along the profile. Bedding and primary sedimentary structures like depositional within a sequence breaks usually delimit the facies.

Koffman, who worked in the detection of cavities, and says the georadar method has proven to be the most suitable for the detection of cavities in a wide range of soil and rock conditions (Koffman 2006). For the use of GPR for the detection of cavities in the subsurface the waves are reflected from objects and layers within the ground that alter the speed of transmission of the radar signal. Air filled voids and water saturated layers are strong reflectors.

High amplitude reflections in the radar profiles are consistent with the location of voids in surveyed sections and are attributed to the air filled portion of the objects. The main characteristic of cavities is the presence of a strong convex reflector at the top with a low frequency signal below it having a hyperbolic shape of high amplitude (Koffman 2006). It has been suggested that if the wavelength of the antenna and the void diameter are of the same order of magnitude, cavities can be recoded as reverberation patterns.

He also describes that reverberating and oscillating signals are those that have the same time delay between strong reflectors and the surface where signals can bounce back and forth. Strong reflectors can also cause similar georadar signals and should be distinguishable from those signals caused by cavities. Such strong reflectors may be air-water interface, ice-water interface, dry-wet soil interface and water-soil interface as well as the presence of metallic objects. However, the reverberations caused by cavities have a higher period than those caused by strong reflectors.

For a coherent reflection to be obtained, the first Fresnel zone at the frequency of the antenna should be at least the same size as the target. For a cavity to be detected, its geometry should be similar to the Fresnel zone and the resolution of the antenna used for a certain frequency. However, in natural cavities the shape is variable and they are rarely geometric.

4. FIELD INVESTIGATIONS

Geological and geomorphological mapping techniques are useful in understanding the spatial relations of the units present in an area. The characterization of the geological elements found, the processes involved for their formation, the landscape attributes as well as other features are outlined. This information was complemented by the sketching of profiles traverse to the channel and their interpretation towards the subsurface by field observations. The surface relationships of geology were correlated to the drill core information to understand the vertical disposition of the units found, this was performed with the aid of the sketched profiles.

4.1 Field Mapping

Four different geomorphological and geological units were defined in the field. The boundaries between units was made by finding borders between stream depressions, stream accumulations, changes in lithology or deposits, and also changes of slope angle and direction. Aerial Photographs and their interpretation were also useful in the definition of the units within the area.

The first unit consists of landslide deposits that have an origin from the Dobratsch 1348 mass movements as well as the larger prehistoric mass movements. Two units are alluvial deposits from a possible damming of the Gail River forming small basin fills and also terraces that may correspond to flooding of the Gail River. The most recent unit is fluvial and belongs to the deposits along the river channel.

4.1.1 Prehistoric and historic landslides

Schütt in German is defined as rubble. The Schütt are located on the southern slopes of the Dobratsch Mountain. The area around the localities of Schütt, Arnoldstein and Oberschütt is characterized by a hummocky, irregular terrain. The aspect of the landscape is due to the massive landslides that occurred in prehistoric and historic times.

In the field the distinction of the older prehistoric mass movement is difficult but can be made from the most recent one from the 13th century. The surface of the old slide is deep, weathered and has developed a thick layer of humus and dense vegetation. The humus and soil development has created a smoother hill slope surface. Figure 7 displays the prehistoric landslide deposit. Large blocks can be observed as well as soil and hummus accumulation.

Figure 7. Prehistoric landslide deposit.

The prehistoric landslide deposit is composed of large dolomitic and carbonatic limestone blocks of up to 5 m in diameter. The blocks have an angular to subangular shape because of the weathering processes that have acted on the deposit. Because of the age of the landslide and the erosive and weathering processes that have acted on it, soil and humus has managed to develop.

Differing from the underlying most older deposits, the recent landslide material is characterized by poor soil and hummus accumulation and has scarce vegetation. The hill slope found is more irregular where bare blocks can be observed. In the topographically higher areas of the channel the recent slide material is found overlying the prehistoric landslide material.

These historic landslide deposits are also composed of by dolomitic and carbonatic limestone blocks since the source area for both of the slides is the Dobratsch Mountain. The blocks are typically of up to 3 m in diameter, however, smaller rock fragments can also be found and are within the range of a few centimeters. The blocks and rock fragments are moderately weathered and grey in color.

Because of the relatively young age of the landslide event of the 13 hundreds, weathering has not been able to produce vast quantities of soil and humus, and therefore vegetation is not well developed in the deposit. The following photograph (Figure 8) displays the historic landslide deposit where the bare blocks and almost no soil cover is found.

Figure 8. Historic landslide deposit.

In the geomorphologic map (Annex 1) created both prehistoric and historic mass movement material are described as a single undifferenciated unit. Both deposits are described as one unit of unconsolidated deposits composed of large (smaller than 5.0 m^3) limestone and dolomite blocks that are mostly angular to subangular in shape. Smaller blocks and rock fragments compose the smaller fraction.

4.1.2 Alluvial units

These units are consisted by unconsolidated deposits from the Gail River as well as flood terraces from sporadic events. Three major units were identified, two that belong to alluvial processes that differ in textural qualities and one recent corresponding to the actual fluvial deposits of the Gail River. The fluvial recent deposits have been sedimented on the channel of the Gail that the river has carved through older alluvial and landslide deposits.

The older unit is alluvial in nature and is composed by isolated blocks up to 1.0 m^3 in size, rock fragments, subrounded gravel with a silty sand matrix. This unit forms plain that overlie the landslide deposits and was possibly generated by damming of the Gail River by the mass movement. It gives the irregular, hummocky landscape a flatter and smoother aspect.

The plain formed by these deposits is approximately found with a 5 m level difference with the actual Gail River bed. The unit is mainly found at both sides of the channel at a chainage of about 250.0 to 850.0 m and is characteristically a flat terrain with silts and sands.

The surface of the landscape influenced by this unit is relatively flat with protuberances that correspond to large blocks. Because of the low topographic level of the areas where this unit is found, build up material was used to obtain a desirable level for the construction of the initial channel length. Figure 9 shows the topographically smooth and flat terrain of this unit.

Figure 9. Alluvial terraces.

Because of the unconsolidated character of this unit and the presence of blocks, rock fragments, and gravels with a fine sediment matrix, it is highly permeable. The nature of the deposit can permit for the fine sediments to be easily removed and transported by water that percolates in to the underground. The migration of fine sediments allows the formation of cavities that could cause failures at the subsurface that are visible on the surface of the landscape.

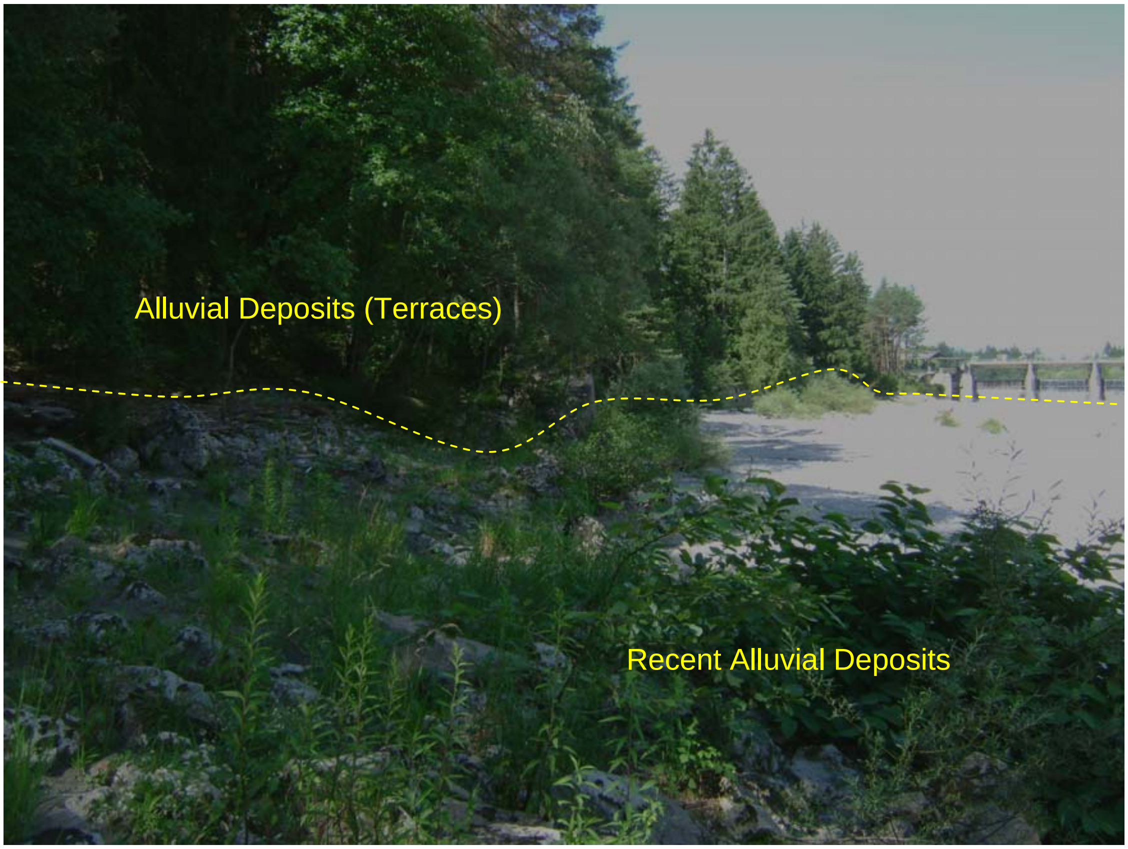
Evidence for such a process of sediment migration is observed in several locations within this deposit. Sinkholes and depressions are found in the initial section of the channel. The failures occurred on the channel could be related to cavities and/or migration of sediments. One of the features identified as a sinkhole can be observed in the previous photograph (Figure 10).

Figure 10. Sinkhole.

The second alluvial unit found is similar to the preceding alluvial unit. It is an unconsolidated deposit composed of large blocks, smaller than 1.0 m^3, subangular to subrounded, with grey gravel and a sandy matrix. This unit also tends to form terraces but in a lower topographic level different from the previous unit.

The location of this deposit is between the first alluvial terraces and the actual Gail fluvial deposit. Because of the topographic level it is relatively younger in age than the landslide and older alluvial units. Erosion and carving of the units by the flow of the river allows the deposition of this unit in a topographically lower elevation. During flooding events terraces can be created by accumulation of material. The following picture displays the recent fluvial deposits as well as the alluvial deposits forming terraces (Figure 11).

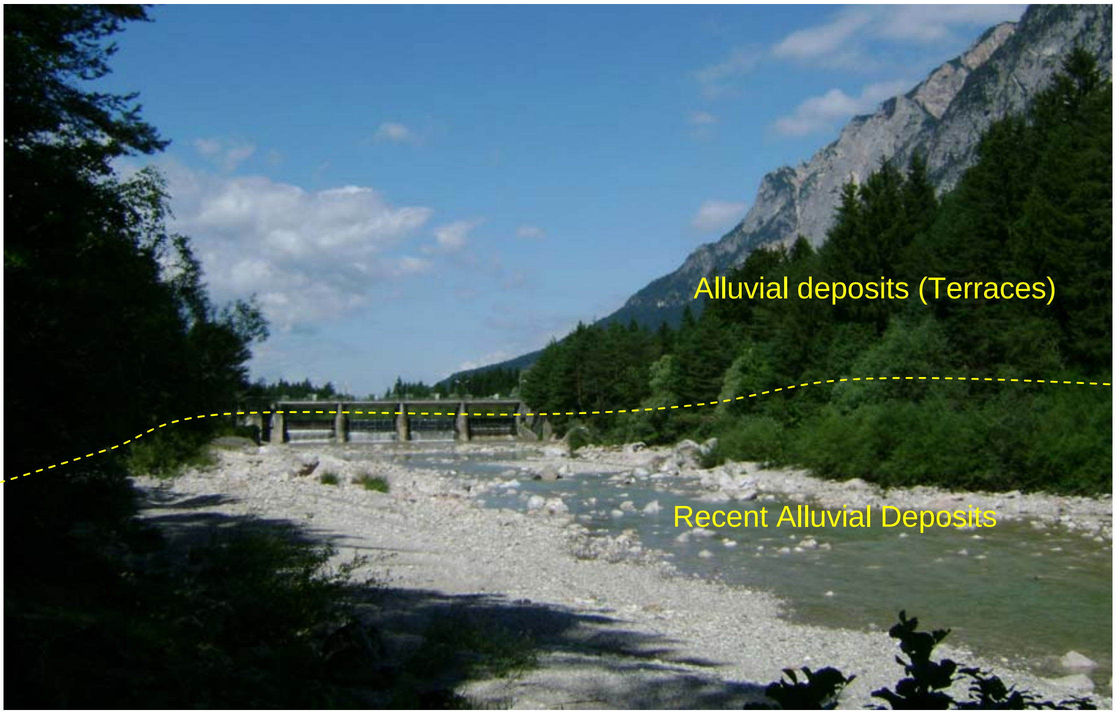
Figure 11. Alluvial terraces.



The third and most recent unit consists of unconsolidated, subrounded pebbles and cobbles, composed mainly by limestone and dolomite but also containing shales and schists within a medium to coarse grained sand matrix. This unit corresponds to the actual Gail River deposits that are continuously carving and eroding the valley.

The erosional processes are diminished and are actually controlled with the damming of the river. However, the process is still active, especially in sporadic events where the river floods causing deposition and/or erosion of the river bed. The Gail has a sinuous watercourse in the surroundings of the Schütt being able to erode and deposit sediments on its meanders. The next photograph shows the recent fluvial deposits of the Gail (Figure 12).

Figure 12. Recent fluvial deposits along the Gail River.



For the building of the hydropower and its installations several locations had to have a modification of the terrain to adjust to the conditions required for construction. In the field mapping the units corresponding to terrain that is artificially built for such purposes was identified and described as anthropogenic units described in the following section.

4.1.3 Anthropogenic units

The anthropogenic units correspond to the artificially leveled and built up areas constructed to acquire the accurate level of terrain for the building of the hydropower installations. These units correspond to infills in topographically low regions where the level of the ground was to be elevated, also leveling in topographic highs to obtain a lower ground surface. This unit also contains the roads used to communicate within the hydropower and villages near by where the natural ground was to be modified to achieve the appropriate conditions for construction.

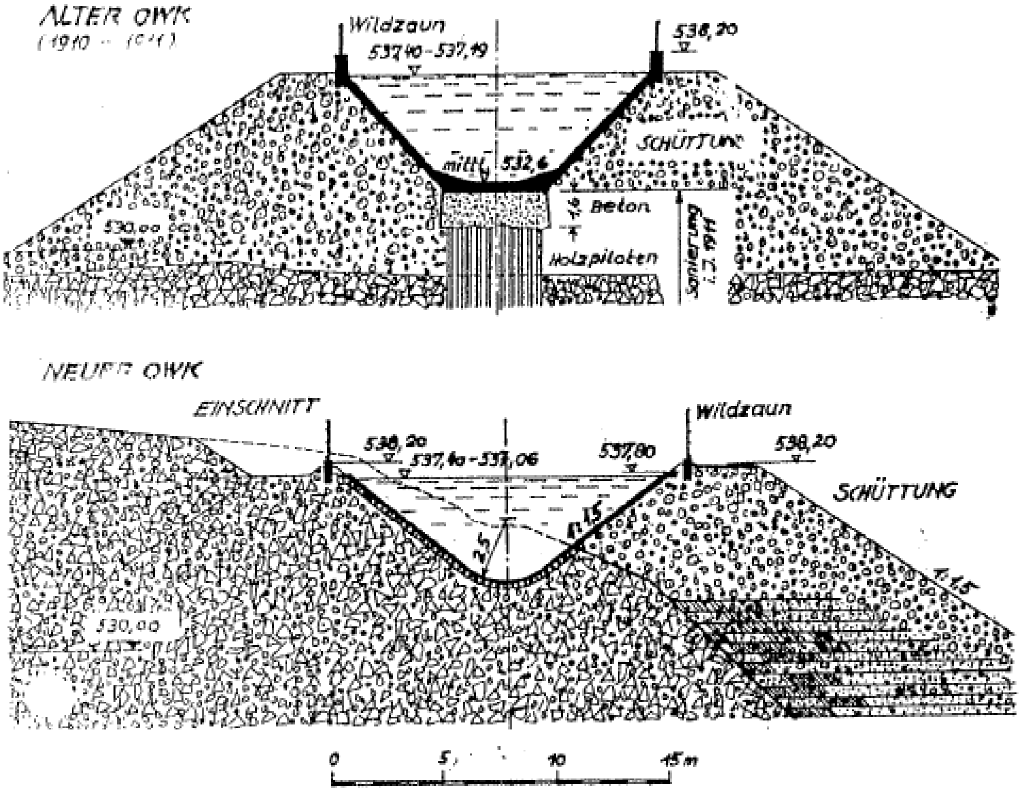
Because of the irregular hummocky terrain several locations had to be leveled and some built up along the channel and the other constructions of the Hydropower.

Artificially leveled terrain was found between the stations 850.0 m to about 1300.0 m and between 3000.0 to 3100.0 m. These leveled areas correspond to topographically high regions of the hummocky terrain formed by the accumulation of landslide material from the most recent mass movement in the 13th century.

Hills are found to have scarce vegetation and soil accumulation that is characteristic for this deposit. Several topographic highs of the hummocky terrain within the area belong to the deposit of the prehistoric mass movement but are different having developed a thick soil and vast vegetation.

The rest of the channel lies on artificially built up terrain in order to provide a homogeneous and topographically flat terrain for the construction. For the initial section of the channel built in the 1910's few records mention the constructive method and types of materials used for the fill.

Figure 13. Artificial buid up terrain for the channel construction.



Modified from Laufkraftwerk and der Gail – Im Bergsturzgebiet des Dobratsch bei Arnoldstein. Kraftwerk Schütt der Kärntner ElektrizitätsAktiengesellschaft.

Figure 13 displays a channel cross section sketch where the fills, cuts and general channel construction can be seen. Most of the old channel is built on a land fill and has a concrete footing of approximately 1.6 m thick in the bottommost part as the sketch displays. The channel's footing is supported with timber piles that transfer the load to a firm soil stratus being the natural ground.

The natural ground for the topographic lows in the initial and oldest section of the channel consists of an alluvial deposit that composes a vast plain. This deposit underlies the fill constructed for the channel. Because of the nature of the alluvial deposit and its high permeability, water can infiltrate and can affect the deposit by removing and transporting fine sediments. By this removal the permeability increases and can also form cavities as well as possible collapse structures.

In the most part of the new channel locations, fills had to be constructed, in fewer locations where the ground level was lowered by slope cutting to achieve the design criteria. For the topographically high areas in the new channel, figure 13 shows a sketch of a slope cut on one of the sides of the channel as well as a land fill on the opposite side. This section of the construction does not have piles to transfer the load of the channel to lower more stiff layers in the subsurface because most of the new channel lies over the landslide deposits.

Where the channel lies on artificially built up areas large to approach the adequate height, the material was accumulated in talus and benches. Some of these fills are comprised by several steps of benches when the change in elevation was significant, while some do not have benches when the amount of change in level desired was not as large.

The cross section profiles found in Annex 2 are sketches that indicate whether the channel lies on infilled or leveled terrains. A rough representation of the fills and cuts can be observed in such sketches at the different locations where they were observed along the channel. The following photograph (Figure 14) displays one of the highest fills along the channel.

Figure 14. Artificially built up terrain.

The previous photograph (Figure 12) is from a built up area at the station of 2900.0 approximately on the right side of the channel. The level was built up approximately 25.0 m with several benches and slopes on both sides of the channel where the natural ground has a topographic low.

For the interpretation and establishment of the underground conditions, several boreholes were drilled along the problematic section of the channel. The borings were useful in the understanding of the stratigraphy for the investigated sections that was later correlated with the field mapping and with the radar profiles.

4.2 Drilling

A borehole drilling campaign took place from February 19th to the 20th, 2009. Cored boreholes were drilled to investigate the subsoil and determine the types of material present below and near the channel. The borings were made with a hammer boring machine with a diameter of 151 mm from the surface to a depth of 6 and 8 m. Piezometers were also installed to investigate the hydrological conditions along the channel. The location of such boreholes and piezometers can be observed in the geomorphological map on Annex 1.

Six cored drills were made for subsoil investigation, identified as KB-1 Wehr, KB-1 Damm, KB-2, KB-3, KB-5 and KB-7. The boreholes were located near the problematic zone of the channel to investigate the critical parts. Core samples were placed in 1.0 m timber boxes, labeled, photographed, described and logged.

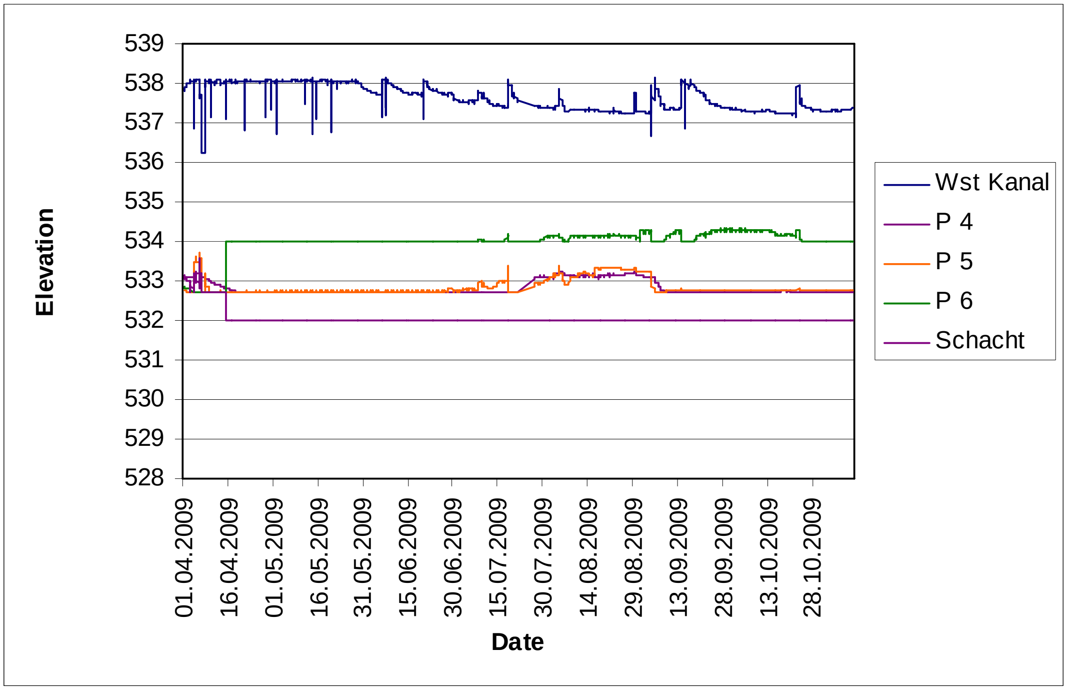
The borings were located near the problematic area. KB-1 Wehr is found before the failure zone near the dam where the channel begins. KB-7 was also made away from the zone and is found almost at a chainage of 550 m. The other boreholes were located to characterize the subsoil very close to the failure (KB-3, KB-2, KB-1 Damm and KB-5).

The core description was used for the interpretation of the subsurface stratigraphy as well as for the correlation with the surface geology and the geophysical surveys. The borehole logs can be observed in Annex 3 and the photographs can be found in Annex 4. A profile was created using the core logs and can be observed in Annex 5, this was later correlated to the georadar surveys for a better understanding.

Five additional borings were drilled to depths of 8 and 6 meters for piezometer installation. The wells were fixed with PVC piping and with digital measuring systems. The data gathered from the wells is registered by KELAG. A register of hourly measurements of 5 piezometers was obtained by KELAG to observe the hydrologic behavior of the area close to the problem zone.

The record of the wells begins from April 1st, 2009 to November 10th, 2009 but continues to be measured. Each of the piezometers is referenced to a mean sea elevation. The information was plotted in a graph with the elevations of the piezometers in the period of measurement, and can be observed in the following figure (Figure 15).

Figure 15. Hourly piezometric measurements.



From KELAG.

In the previous graphic it can be observed that the level of P-4 and 5 behave similarly and increase in level during the months of July and August. Piezometer P-6 also has an increased level starting from July and continues until October. On the Wst Kanal the water level decreased from May until November and on the Schacht (pit) the water level remains constant after increasing 2 m in height in the first 15 days of April.

4.3 Ground Penetrating Radar

The performance of a geophysical method depends on the fundamental geophysical constraints (penetration, resolution, signal-noise ratio, etc). The information derived from the surveys is obtained by a suitable combination of the geophysical method applied and their interpretation.

The field surveys were performed on March 10th and 11th, 2009 by Joanneum Research along a 130.0 m section of the channel where the failures occurred. The corresponding chainage of the channel to the surveys is from 246.2 to 376.2 m. On the channel chainage the GPR profiles begin at 246.2 being 0 m the initial measuring point of the geophysical profiles. The geophysical surveys end with a total length of 130 m at a corresponding chainage of 376.2 of the. The longitudinal radar profile with the 1500 MHz antenna has a total length of 115 m, beginning at the same point and ending at 361.2 of the channel chainage.

The equipment used for the data acquisition consisted of a SIR-3000 from GSSI/USA with a monostatic antenna. The tool is able to measure frequencies of 200, 400, 900 and 1500 MHz. Two antennas were used one for the lower frequencies and one for the 1500 MHz survey (Figure 16). The instruments were pulled manually in sections perpendicular and parallel to the channel. Different frequency profiles were measured according to the most critical points in the channel. The distribution of the lines is presented in the following table (Table 1), the orientation and location of them can be observed in the Annex 6.

Table 2. Distribution of georadar profiles.

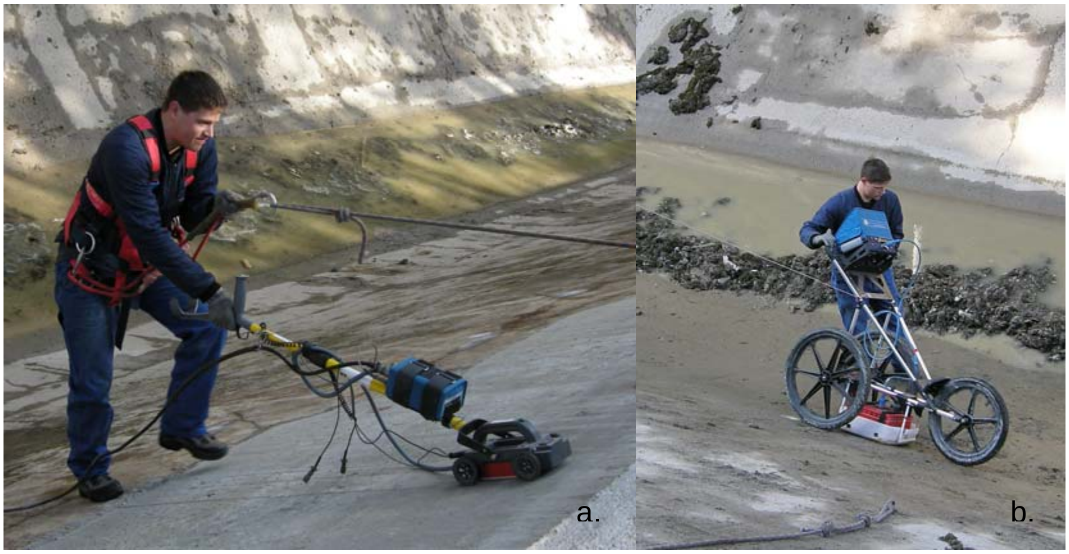
Frequency (MHz)	Profile	Quantity	Length (m)
200	Parallel	2	130
400	Parallel	5	130
	Perpendicular (right)	92	6.9
900	Parallel	2	130
	Perpendicular (left)	115	6.9
	Perpendicular (right)	135	6.9
1500	Parallel	3	115
	Perpendicular (right)	131	6.9

Parallel profiles were carried out with a frequency of 200, 400, 900 and 1500 MHz antennas, most are of 130 m in length except for the higher frequency of just 115 m. Each of the perpendicular profiles is of approximately 6.9 m in length and they were also measured with the 400, 900 and 1500 MHz antennas. For the different frequencies surveys test were done to optimize the measurements. For all of the profiles the time is registered in nanoseconds and is indicated as well as the interpreted depth and their length (Annex 7).

The measurements with the 200 MHz antenna had the goal to investigate the section of the channel that failed. Two profiles were done parallel, each with 130 m in length. The purpose of these measurements along the channel was to survey the geologic character and nature of the subsurface.

The 400 and 900 MHz antenna measurements were done parallel and perpendicular to the channel. For the traverse profiles the cart was pulled downward starting at the edge of the channel moving towards the deeper center part. The scans were calibrated with an odometer installed on a cart where the antennas were mounted on.

Figure 16. Antennae for georadar surveys



Modified from Morawetz, R. Bodenradaruntersuchung Testmesung Kanal von Kraftwerk Schütt. Institut für Wasser Ressourcen Management. Leoben. Jul. 2009. a.1.5GHz antenna b. 400 MHz antenna

For the 1500 MHz antenna measurements a similar procedure was carried out as with the 400 and 900 MHz. The antenna is provided with its own cart and odometer. The traverse profiles were measured upward, starting from the deeper section moving towards the upper edge of the channel. The reason for this different measuring scheme was the equipment manipulation.

5. RESULTS

An engineering construction changes the natural environment in its proximity and also the natural processes affecting the area. It also changes the slopes, the soil conditions and hydrographic conditions among others. Introduction of anthropic soils and constructions can modify the natural evolution of the surroundings. Hydraulic structures like dams produce alterations in the environment and natural processes reducing transport of debris, changing the development of the river.

The constructions can also have a positive effect as flood control, the improvement of the flow of watercourses, stabilization of slopes. To reduce the negative effects a construction can cause on its surroundings it is necessary to investigate scientifically all the possible consequences on the environmental system. Negative results may pose as hazards which may affect the environment and also the population.

Surface geology, geomorphology, drill core and georadar interpretation leads to a better understanding of the conditions of an area. The detection of underground structures and cavities is more easily made if a variety of data from the zone of interest is obtained. Different quality data gives different quality information when interpreting and evaluating, but the combination of methods provides a more precise perception of the underground.

The interpretation of this investigation involves the analysis and interpretation of georadar profiles, surface geology and borehole data to establish the underground conditions of the channel of the Schütt Hydropower. Each of the data has its own indication to the subsurface but with a different character and quality. All have a special degree of uncertainty but are all useful for the underground characterization. The underground conditions object of the analysis and interpretation are the understanding of the underground conditions as well as presence of structures.

The investigation is focused on the understanding of the underground conditions where the channel is constructed. Failures along the channel have led to the suspicion that cavities formed by fine sediment migration are found on the subsurface of the channel. With the investigation also the stratigraphic relations were established based on the interpretation of surface geology and geomorphology, drill core and ground penetrating radar. The analysis defined and located possible reflectors that may be beds and layers as well as the boundaries and structures that exist on the ground.

Throughout the analysis of geology, geomorphology and drill cores an understanding of the processes that acted on the deposition was obtained. The geomorphologic characteristics, the sedimentary textures as well as the bounding surfaces that the different units pose are important in their distinction. The characteristics for the units include color, grain size distribution, sorting, texture and possible structures. All of these characteristics are unique for each of the defined units.

The occurrence of each of the units is directly associated to the mechanics involved in the sedimentation processes. The landslide deposit is characterized by large angular blocks, rock fragments and coarse sands. The silty and clayey sands with gravels and rock fragments compose to the fluvial and alluvial deposits that correspond to the Gail fluvial system.

With the field investigations, a better perception of the geology and the geomorphology within the area of interest was achieved. Determining the type of deposits present as well as the land forming processes that have acted on the area to develop the relief was essential for comprehending the spatial relations of the defined units. With the aid of aerial photographs, the definition of the units found in the field was improved. The profile sketches prepared in the field traverse to the channel length were used to understand the vertical relations of the units defined in the mapping.

5.1 Field Mapping

From the field mapping and profile sketches, the stratigraphy of the units found in the area was interpreted. It is simple and comprises landslide, alluvial and recent fluvial deposits. The landslide deposits lie as a base that is overlain by alluvial deposits. The fluvial deposits have carved and eroded the landslide and alluvial deposits creating the channel for the Gail River. All of these deposits are unconsolidated and have a high permeability allowing infiltration as well as the flow of groundwater.

Landslide units are considered in this investigation as an association of deposits resulting from gravitational processes. Within the area of investigation several landslide deposits are found, these are due to different events and age of occurrence. However, in this study, the units corresponding to both events historic and prehistoric landslides are represented as one unit. The unit is described as undifferentiated landslide deposits, making the cartography and the interpretation more understandable.

The area is characterized by unconsolidated landslide, alluvial and fluvial deposits. The nature of the units found suggests they have a high permeability and allow the infiltration of water. As water infiltrates and subsurface flow occurs, the deposits can be affected by the removal of fine sediments. This removal of sediments can increase the permeability and can also form cavities in the subsurface that may lead to the generation of collapse structures in the surface.

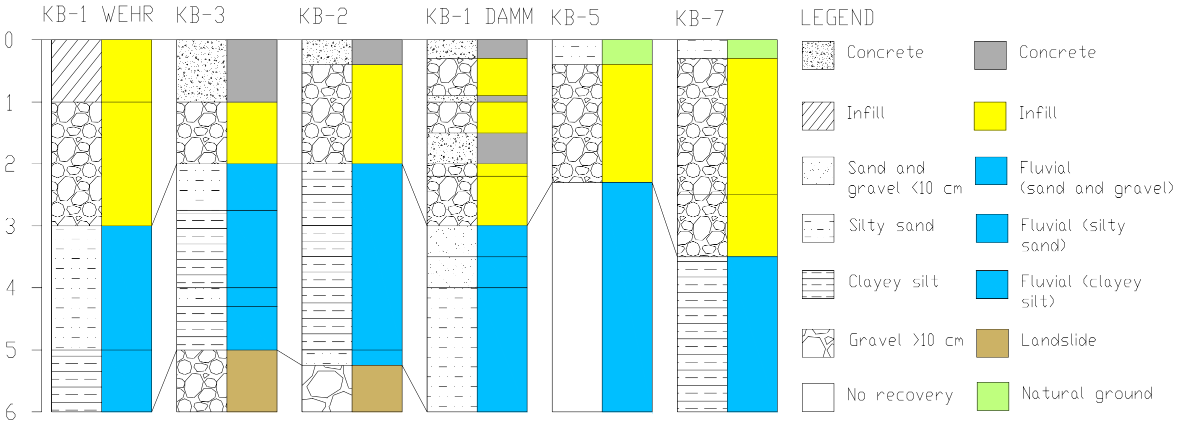
Subsurface flow occurs when the water percolates into the soil. Water can remove and transport fine particles. With the influence of gravity the particles will follow paths and are removed through networks of underground passages that can lead to outlets in the surface. The diameter of the water paths depends on the soil porosity, swelling and shrinking properties of soils, precipitation and the vegetation cover.

5.2 Boreholes

A schematic cross section interpreted with the borehole data was created with the information of four of the boreholes located near the failure (Annex 5). The boreholes used for this cross section were KB-3 located at a chainage of 291 m approximately, KB-2 at 310 m, KB-1 Damm at 329 m and KB-5 at 331 m. The profile is oriented parallel to the channel and the landslide deposits lie on the bottommost part, these are overlain by the alluvial deposits. Then a fill material is found that was constructed for the increment of level necessary for the building of the channel. Because these boreholes are located on the area where the geophysical surveys took place they were used to correlate with the georadar information.

Using the description and interpretation of the six cored boreholes a profile sketch was created (Figure 17). In this sketch the units described consist of: a natural ground recently developed on top of the infill of the channel; concrete; below infill material principally composed by gravel and rock fragments; underlying fluvial gravels, silty sands and clayey sands; underlain by landslide gravels and rock fragments.

Figure 17. Sketch profile with borehole information.



Similarly on the sketched profiles (Annex 2) traverse to the channel length, this stratigraphy can be observed. The landslide deposits at the bottom, overlain by alluvial deposits that are carved and eroded and have deposited alluvial terraces. The recent fluvial deposits are laid on the Gail river bed and have eroded through the alluvial terraces as well.

To observe the hydraulic behavior of the channels' 5 wells were located before, on and after the failure zone and the level record was analyzed. The variations of the water levels on P-4, 5 and 6 (located around the problematic area) tend to increase during the summer months. The P-1 corresponds to the piezometer before the problem zone and the P-7 to the well located after the failure. The level of P-7 is constant throughout the time period while on P-1 variations are recorded throughout the summer.

5.3 Ground penetrating radar

For the appropriate investigation of a site a compromise between frequency, depth of penetration and vertical and horizontal resolution is to be made. Depending on the desired resolution for the purpose of the study, an accurate frequency is to be used. For this purpose the geophysical surveys concerning this research, 4 frequencies were used.

The data processing was done with the software Reflex-Win Version 4.5 from Sandmeier Software. The quality of the raw data was usually good with exception of the locations where fresh concrete was applied for the channel repairs. The processing for all of the surveys included the reading, conversion and control of the raw data, zero point regulation, band pass filtering, energy decay and analysis of diffraction hyperbolas.

From the analysis of the diffraction hyperbolas the speed was determined for the two way travel times into depth values (Morawetz 2009). From the radargrams speeds of 0.06 m/ns to 0.1 m/ns were determined. A mean propagation speed of 0.1 m/ns was assumed for the depth conversions, which means the depth of the visible structures is shallow. This velocity corresponds to a relative permittivity of 9 characteristic for wet sediments

The horizontal and vertical resolution was calculated using 0.1 m/ns for the wave velocity for each of the different frequencies used in the geophysical surveys. This velocity corresponds for wet sediments. The following table presents the calculated values for wavelength, depth of reflectors, the vertical resolutions, approximate horizontal resolution and the corrected horizontal resolution (Table 2).

Table 3. Calculated resolution for different frequencies.

Velocity (m/ns)	Frequency (GHz)	Wavelength (m)	Vertical resolution (λ/4)	Vertical resolution (λ/2)	Depth (m)	Approximate horizontal resolution (m)	Horizontal Resolution (m)
0.1	0.2	0.500	0.125	0.250	1	0.5000	0.5154
0.1	0.4	0.250	0.063	0.125	1	0.3536	0.3590
0.1	0.9	0.111	0.028	0.056	1	0.2357	0.2373
0.1	1.5	0.067	0.017	0.033	1	0.1826	0.1833

Derived from the equations for the resolution (equations 3 and 4) it can be established that for the 1500 MHz antenna using a value of 1.0 for the relative permittivity of air, the vertical resolution for an air filled cavity is of 0.05 m. For the other frequencies used the values corresponding to vertical and horizontal resolutions can be observed in the previous table.

The representation of the radar profiles was done in two patterns, one with several colors and another in shades of grey to enhance details that are not easily recognizable. Cavities of the order of decimeters were searched but are not easily distinguished. The diffraction of an object depends on the mean wave velocity of the surrounding material and on the objects depth and slope.

The description of the radar profiles was made according to the section starting at a channel chainage of 246.2 m. The initial chainage of the georadar profiles is the reference 0 m corresponding to the 246.2 m of the channel chainage and continues downstream of the channel until 150 m where the corresponding channel chainage is 372.4. The prospected section can be observed in Annex 1. Since the radar profiles are represented in the surveyed distances, the observations are indicated with this scale because of simplicity issues.

For the profiles traverse to the channel, the measuring scheme with this antenna was opposite from the other perpendicular profiles. With this antenna only profiles on the right side of the channel were carried out. However, as the depth of penetration is too shallow, the information obtained with the survey is useful only for the evaluation of the concrete of the channel. The same can be said of the longitudinal profiles.

5. INTERPRETATION

In areas where large landslides have occurred, usually the mass that has been displaced causes partial or total damming of the drainage system. This damming causes temporal lakes and marshlands as the water accumulates in a reservoir behind the dam. The backwater causes aggradation and the deposition of sediments in these temporal lakes and marshes. These dams tend to be breached as the water continues to accumulate. The level of the backwater is lowered as drainage carves its way trough the displaced mass.

The alluvial and lacustrine deposits that are formed in these temporal marshlands and lakes caused by river damming or depressions are formed along the hummocky terrain of the landslide body mass. The alluvial plains found along the Gail River lie on top of the landslide units and were possibly accumulated as a result of a damming phase of the course of the river by the mass accumulation.

As the water from the dam of the landslide carved a river channel it changed the depositional environment into a fluvial system subject to the processes that it involves. Terraces are found along the Gail River channel, possibly sedimented in subsequent flooding events. The terraces are found at a topographically lower level than the alluvial plains suggesting these are more recent in age.

As the Gail carved its way, it has accumulated sediments leaving terraces as evidence. Today the sedimentation and erodability of the Gail has decreased due to the construction of the Schütt Hydropower Plant. However, the river continues to transport and deposit sediments in its meanders.

Erosional processes are responsible of the transport and deposition of sediments. These processes depend on the fluid carrying the particles as well as the properties that the particles may possess. According on the quantity of water in a specific period of time or intensity a soil can be affected depending on its nature. Grain size distribution, porosity, packing, arrangement, permeability and other properties are some of the determining properties that control the erosional processes that may affect a material.

Correlations were made with the use of information obtained from a geological and geomorphological surface mapping and from drill core samples. The different methods used provide a different quality of data that leads to different uncertainty when correlating one method with another. Geological and geomorphological mapping were created to describe the surface around and along the channel length. Drill cores were used as punctual sources of information to understand the subsurface and the stratigraphy of the initial portion of the older section of the channel. The boreholes were located before, after and on the problematic zone where failures occurred. Geophysical surveys were performed to survey the subsurface below the failure zone.

The most useful radar profiles for the understanding of the subsurface conditions, stratigraphy, presence of structures and also the definition of radar facies were those of lower frequencies. The 200 and 400 MHz frequency surveys have a greater depth of penetration and reach the natural ground lying below the infill of the channel. The subsurface conditions, stratigraphy and structure can be analyzed, interpreted and evaluated. Nevertheless these surveys have a lower resolution and reflectors of a smaller size cannot be distinguished.

For the interpretation of the radar reflection profiles the configuration of radar facies were described. The primary facies pattern observed on the radar profiles referring to shape are reflection free, planar or even, sinuous or wavy, curved concave and curved convex. The dip of most of them is horizontal while the convex and concave have an apparent dip parallel to the length of the channel. Most of the reflectors have a subparallel and oblique relationship, being most moderately continuous.

A better display of the structures is more easily observed with the multi color display georadar profiles. Drill core information was correlated and projected with the radar information to understand the spatial and vertical relations of the geology in the underground. The borehole projection has also the purpose of the detection and correlation of structures, stratigraphic conditions and if possible cavities. The georadar profiles corresponding to the 200 and 400 MHz antennas with the projected boreholes and interpretation can be observed in Annex 7.

A summary of the general characteristics and detected structures of the Georadar measurements can be observed in figure 18. In this diagram an explanation of the depth of penetration, the vertical resolution as well as the observed structures is presented for the different frequency profiles.

Figure 18. General characteristics and structures of GPR measurements.

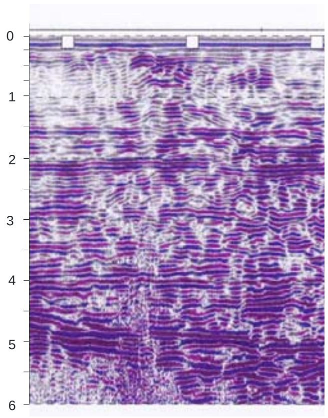
Frequency	200 MHz	400 MHz	900 MHz	1500 MHz
Depth of penetration	~ 5 - 6m	< 4m	~ 2.5m	< 1m
Vertical resolution	0.25m	0.13m	0.05m	0.03m
Characteristic structures  	~ 0.5m concrete boundary ~ 2m infill boundary Visible and confirmed structures with boreholes. Failure zone (54-76m). ~ 5m basin structure boundary Limit of penetration	~ 0.2m steel reinforcement ~ 0.5m concrete boundary ~ 2m infill boundary Visible and confirmed structures with boreholes. Failure zone (54-76m). Visible internal parallel reflections. ~ 5.2m basin structure boundary	~ 0.6m concrete boundary Limit of penetration	Internal concrete reflections. Limit of penetration

Image from Morawetz, R. Bodenradaruntersuchung Testmesung Kanal von Kraftwerk Schütt. Institut für Wasser Ressourcen Management. Leoben. Jul. 2009.

With the 200 MHz antenna the depth of penetration is 6 m approximately. Parallel to the channel, between the sections from 54 to 76 m a basin like structure with horizontal layering is easily recognized. This basin structure has a maximum depth of approximately 5 m. A smaller basin is also observed on the parallel profile from 104 to 109 m, this one is found at a shallower depth of about 1 m.

The strong reflectors corresponding to the large basin like structure with a maximum depth of approximately 5 m display a horizontal layering and parallel facies. Borehole KB-2 was drilled at 65 m of the geophysical survey where clayey silt was found from a depth of 2 to 5.25 m. The projection of the borehole corresponds to the limit of the basin. On the same borehole from 5.25 to 6 m the landslide deposit was drilled, suggesting the basin is delimited by these deposits. In the radar profile the lower part of the basin is characterized by curved concave facies. The smaller basin observed from 104 to 109 may correspond to similar materials but is found at a shallow depth that should correspond to the channel infill.

With the 400 MHz antenna on the longitudinal parallel sections of the channel the same structures as in the 200 MHz antenna were visible. Because for this frequency the resolution is higher the structures are more easily identified. The large basin structure is found at the same section and at the same depth. The smaller basin is found 98 to 110 m at a depth of about 1 m.

The large basin which can be correlated to the clayey materials is visible at the same distances and at the same depth to the lower frequency survey. The facies observed within the basin are more subparallel and the basin is defined also by a concave shape. The smaller basin on the other hand is observed from 98 to 110 m, much larger and with a better definition than with the lower frequency configuration. The features displayed by this frequency as well as the interpretation of the radar structures, facies and geologic information from the section of about 52 to 80 m of the georadar profiles can be observed in figure 19.

Figure 19. Interpretation for 400 MHz Georadar profile.

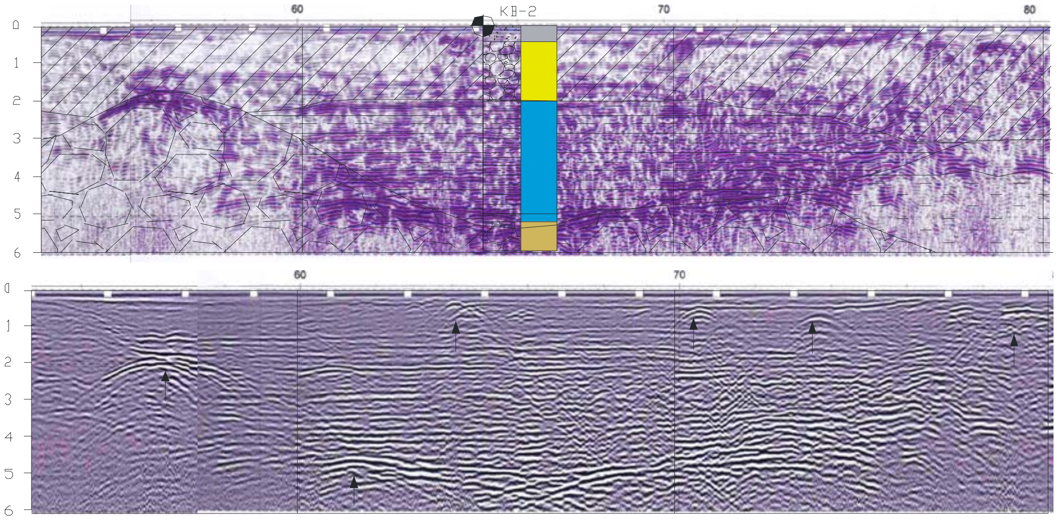


Image from Morawetz, R. Bodenradaruntersuchung Testmesung Kanal von Kraftwerk Schütt. Institut für Wasser Ressourcen Management. Leoben. Jul. 2009.

The basin like structure outlined in the previous diagram (Figure 19) is identified at the same distance where the failure zone lies (from 54 to 76 m). A few days prior to the geophysical surveys the failure zone had been repaired with concrete. The basin structure reflections may also correspond to the fresh concrete from the repairs as well as for the fine grained fluvial sediments.

Over the entire range of the profile a strong reflection can be observed at a depth of about 0.2 m, this might correspond to the steel reinforcement of the channel. Another reflector is found at a depth of about 0.4 to 0.5 m and can be interpreted as the lower boundary of the concrete of the channel. Perpendicular profiles were executed on the right side of the channel but show similar observations as the 0.2 m depth reflector that corresponds to the steel reinforcement of the channel.

With the 900 MHz antenna the resolution is higher but depth of penetration is smaller, reaching up to 2.5 m in depth. Because of the shallow depth of penetration these profiles are useful to evaluate the condition of the concrete lining and infill below of the channel. Nonetheless these profiles show few strong reflectors where structures can be observed and correlated with borehole information.

On these longitudinal profiles few strong reflections can be recognized. A reflector can be observed at a depth of about 0.5 to 0.6 m at the section from 64 to 66 m, this reflection might correspond to the concrete boundary of the channel. Perpendicular profiles were carried out with this frequency on the left and right sides of the channel. On the perpendicular profiles few reflectors are visible with the exception of the sections from 70 to 90 m.

The measurements with the 1500 MHz antenna for the parallel profiles were done in 9 sections to fulfill a single profile from 0 to 115 m. The depth of penetration is limited because and the resolution is the highest. For these profiles the depth of penetration is 1 m and few reflectors are detected. From the sections from 40 to 60 m strong reflections can be seen at a depth between 0.4 and 0.6 m and are probably caused by the concrete boundary.

The profiles obtained with the 1500 MHz antenna, similar to the 900 MHz, are useful for the evaluation of the internal structure of the concrete of the channel. With this survey the depth of penetration is too small to be able to observe reflectors of the infill. On these profiles the steel reinforcement of the concrete are clearly visible.

Further reflectors are scarce indicating that the condition of the channel concrete lining is similar in the entire surveyed section.

Either natural or artificial cavities, georadar prospecting has been often successful in detecting them. Early detection of such structures may avoid problems and hazards posed by them and also result in savings in cost and timing. The detection is then useful when planning and developing remedial measures to potential hazards. In the case of the Schütt Hydropower the finding of cavities and the measures taken to remediate their hazard may prevent the occurrence of failures.

For the detection of cavities and voids, characteristic convex reflectors with low frequency signals below were searched for on the profiles. Cavity detection requires good resolution and good depth of penetration. The profiles that were more adequate for the desired penetration depth and resolution for the recognition of cavities in the subsurface are the ones from the 200 and 400 MHz frequencies. The higher frequencies have a better resolution but the depth of penetration reduces the investigation to the concrete and infill material of the channel.

The 200 and 400 MHz georadar surveys that were more suitable in the identification of were the longitudinal profiles presented in grayscale. With this representation convex reflectors are more easily distinguished. On the lower frequency reflectors typical for cavities can be observed at 57 m at a depth of 2 m and also at 61 m at a depth of 4.5 m. The structures can be observed in the profiles found in Annex 7.

Because of the higher resolution of the 400 MHz frequency antenna, the reflectors in these profiles are observed clearly. Possible cavities are seen 18 m and 25 m with an estimated depth of 0.2 m. Similar reflections are detected at 64, 67 and 70 m at a depth approximately the same. Reflectors also observable with the 200 MHz antenna are the ones located at 56 m with a depth of 2 m and at 62 and a depth of 4.5 m.

6. DISCUSSION

The investigations were mainly concentrated on the critical part of the channel where the problems occurred. Several ground penetrating radar surveys were carried out at different frequencies for observing the underground conditions and drillings were made for core samples as well as for piezometer installation. For a detailed interpretation of georadar data, a basic understanding of the geology, geomorphologic processes, geophysical data and geotechnical information is necessary.

Surface geology was mapped in detail on the entire length of the channel with the purpose of defining the spatial relations of the units present in the area. Sketches were made perpendicular to the channel to understand the vertical arrangement of the defined units. Boreholes were completed, sampled, described and interpreted to understand the subsoil configuration. Different quality data gave different approaches to the investigation but provided a better understanding of the overall conditions.

The data obtained from the different methods used was analyzed, interpreted and correlated to evaluate the conditions of the underground near the channel. Also, the possibility of the detection of failure points along the concrete or probable cavities below the concrete. The different methods used for the investigations and their difference in quality generates data uncertainty that restricting the interpretation of the outcrop, drill core and georadar data.

The local stratigraphy was established with the mapping, with sketched profiles transverse to the channel, and also with the drillings made on the problematic zone of the channel. The radar profiles were correlated with the surface geology and drill core information for a more accurate interpretation. The stratigraphic scheme is based on the fluvial and alluvial character of the units found on site. Their correlation is suitable for the interpretation of the georadar data.

Surface geology and geomorphology mapping determined the presence and spatial relations of four units in the area of the Schütt Hydropower channel. Landslide deposits are the oldest unit, alluvial sediments were found as fills overlying the mass movement material. These units have been eroded by the Gail River that has deposited alluvial material in terraces as well as the most recent fluvial deposits.

The alluvial sediments forming a plain are possibly due to the damming of the Gail by the mass movement of the Dobratch. This allows the formation of temporal lacustrine and marsh environments. Sediments are deposited in the small basins of the hummocks of the landslide deposit that are filled as sediment accumulates forming flat landscapes. As the dam is breached by the river, the deposits of the landslide and of the alluvial plain are eroded. Further erosional and depositional processes lead to terrace forming events which are now decreased by the presence of a dam.

The nature of the deposits (grain size distribution, arrangement, porosity, packing, etc) makes it possible for them to have a high permeability. Water is infiltrated easily and sediments are able to be transported and removed by networks of passages in the underground. Further removal of particles increases the permeability and can cause voids and cavities that can manifest in the surface as sinkholes or collapse structures. Several sinkholes were found on the alluvial plains near the old section of the channel where the previous failures occurred. Fine sediment migration may be increased or may continue to occur by percolation of precipitation or infiltration of water from the channel if the concrete lining is damaged.

The cause of such cavities can be due to transported fines of the landslide deposit, by removing and destabilizing the arrangement of the matrix between the limestone and dolomite blocks of the original deposit. This process is thought to have occurred over a long period of time to be able to remove a large quantity of sediment in several locations. Failures and collapse are possible when the subsurface is destabilized affecting the constructions located above such cavities.

Georadar profiles were executed with antennas of a frequency of 200, 400, 900 and 1500 MHz for the surveying of the subsurface conditions, potential detection of cavities, and also for the inspection of the concrete lining of the channel. Lower frequencies were used for the underground characterization because of a greater depth of penetration but however possess a lower resolution. The higher frequencies had a smaller depth of penetration and higher resolution, and are useful in the inspection of the concrete lining and of the ground lying below it.

The establishment of the underground conditions by developing a better understanding of the surface and subsurface geology provides a better correlation for the evaluation and analysis of the georadar data. The local stratigraphy observed in the mapping and also in the boreholes correlated with the GPR profiles is useful for the recognition of the source of reflections and their interpretation. Radar structures and facies improve the understanding of the sequence of deposition and relations between the different units defined.

With the lower frequencies it was possible to observe the stratigraphy as well as sedimentary structures. Radar facies were defined depending on the configuration, continuity, relationship and geometry of the reflectors recognized on the radar profiles. The infill material used for the construction of the channel can be distinguished as well as basin structures, horizontally laid fine sediments and coarse grained sediments that may correspond to the landslide deposit. Few possible cavity structures were defined by the characteristic shape waves acquire when reflecting from a void.

Previous investigations have demonstrated that for the characteristic reflections of cavities to be observed the void size should be larger than the antenna’s wavelength in air. It has been also verified that for a given antenna frequency the pattern depends on the geometry of the cavity (the height must be greater than the horizontal length).

Because of the nature and high permeability of these deposits percolation may lead to the removal of fine sediments that can generate voids and cavities. This process of sediment removal and void formation is amplified if the water available for the transport of particles is increased. Cavities formed in the subsurface are manifested as collapse structures or sinkholes as observed in the alluvial deposits near the failure zone. Further infiltration could continue the development of such structures. The condition of the channel should be revised for fractures where water can penetrate the subsurface and cause the removal of particles.

7. PROPOSAL FOR FURTHER INVESTIGATIONS

When using ground penetrating radar techniques the frequency selected for the investigation should provide a maximum level of information concerning depth of penetration and resolution. The depths of penetration and resolution vary with frequency, compromising the possibility of detection of reflectors and possible structures in the subsurface. Because of the previous failure occurred in the channel, cavities were thought to be responsible of triggering the event. The detection of cavities with such a geophysical method was one of the primary targets of this investigation.

The combination of surface and borehole geology with geophysical information can provide accurate predictions of the location of subsurface geology and structures. The georadar method is suitable for shallow mapping applications. The assessing of geologic hazards like groundwater contamination, detection of faults and cavities are some of the fields of investigations appropriate for the ground penetrating radar.

It is possible that with a lower frequency antenna a georadar survey could penetrate to a greater depth and still acquire more information on the subsurface conditions of the areas around the failure zone of the channel. This however, would limit the resolution and cavities detected. The information can be corroborated with borehole drilling located in areas where cavities are suspected or near to where surface manifestations are observed.

For a better understanding of the subsurface additional borings and their corresponding logging and description are required. Boreholes should be located close to the sinkholes observed in the vicinity of the failures. However, the depth of these drillings should be greater that 6 m to be able to identify a larger portion of the natural ground. An approximate depth of 15 m is suggested if boreholes are to be located on the infill of the channel to be able to penetrate 12 m in to the natural ground.

The information obtained with these drillings is necessary for the evaluation of the conditions of the ground near the sinkholes and critical parts of the channel. The data can be used in the interpretation of ground penetrating information as well as with the surface geology. For this purpose, Georadar profiles with a greater depth are necessary; however the resolution of the information would be lower. Cavities to be detected would have to be significantly greater in size in order to be detected with lower resolutions. GPR surveys could also be executed below the infill at the foot of the channel and parallel to it to have information of greater depth.

The channel should be revised for cracks and fractures in the concrete. If present, they should be healed and sealed to prevent infiltration of water into the subsurface and causing of further damage. Piezometer reading should continue to check the hydrologic aspects of the channel and the ground water level changes throughout the year.

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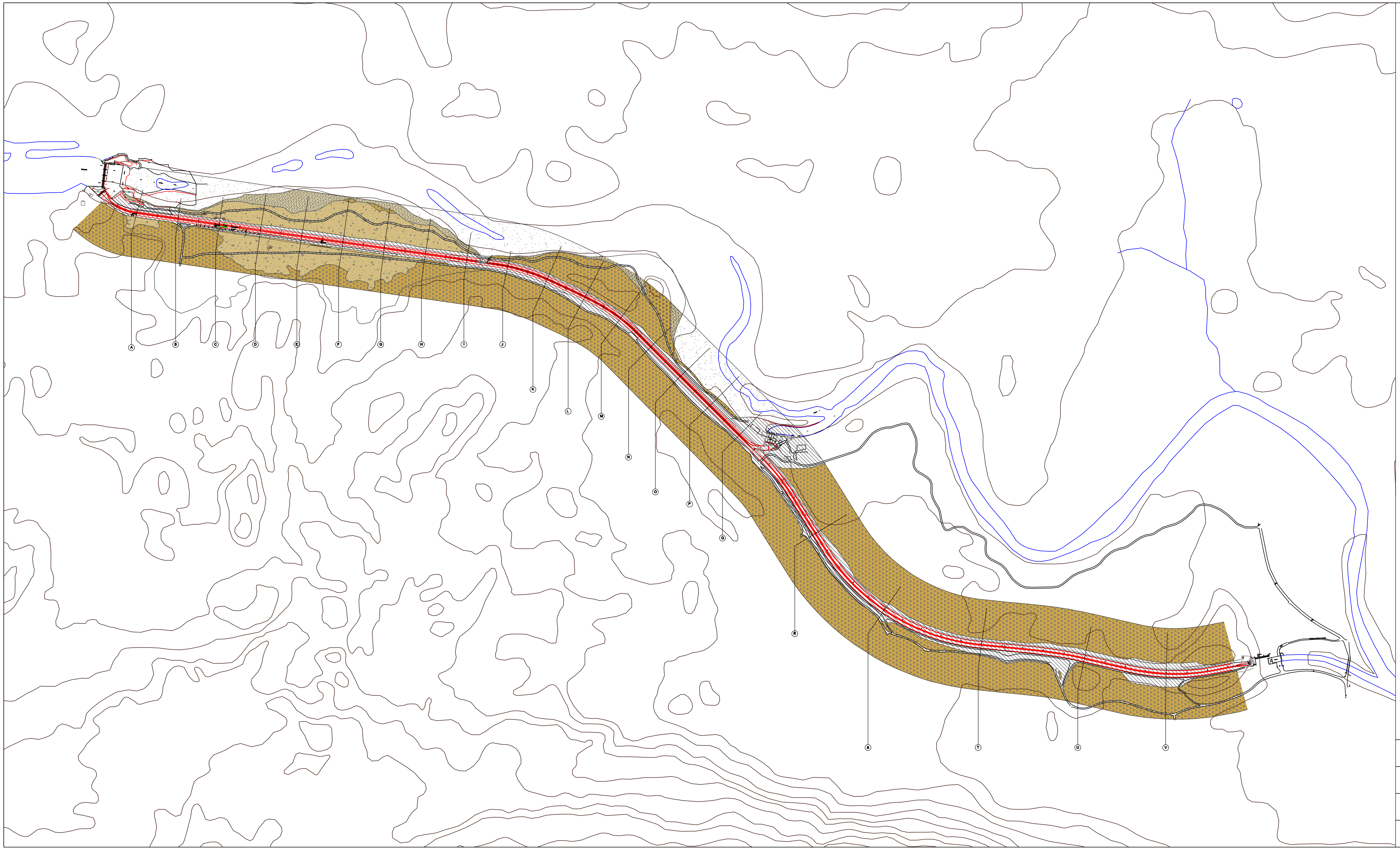
ANNEXES

ANNEX 1 Geomorphological map



LEGEND

- ▨ Fluvial, sand matrix with gravel up to 10 cm in diameter, subangular to subrounded, sorted, matrix supported.
- ■ Aluvial, sand matrix with gravel and blocks up to 1 m in diameter, subangular to subrounded, unsorted, matrix supported.
- ▨ Aluvial, sand matrix with gravel up to 2 m in diameter, subangular to subrounded, unsorted, matrix supported.
- ■ Coluvial, blocks and rock fragments up to 5 m in diameter, angular to subangular, unsorted.
- ▨ Artificially leveled or built up area.
- Contact, inferred.
- ◎ Sink hole.
- Slide mass
- River, stream.
- ⊕ Borehole, number.
- ⊕ Piezometer, number.
- Profile location, number.
- Chainage station (km).
- Topographic curves.
- Road.
- ▭ Constructions.
- ● Failures.

SCALE: 1:5000

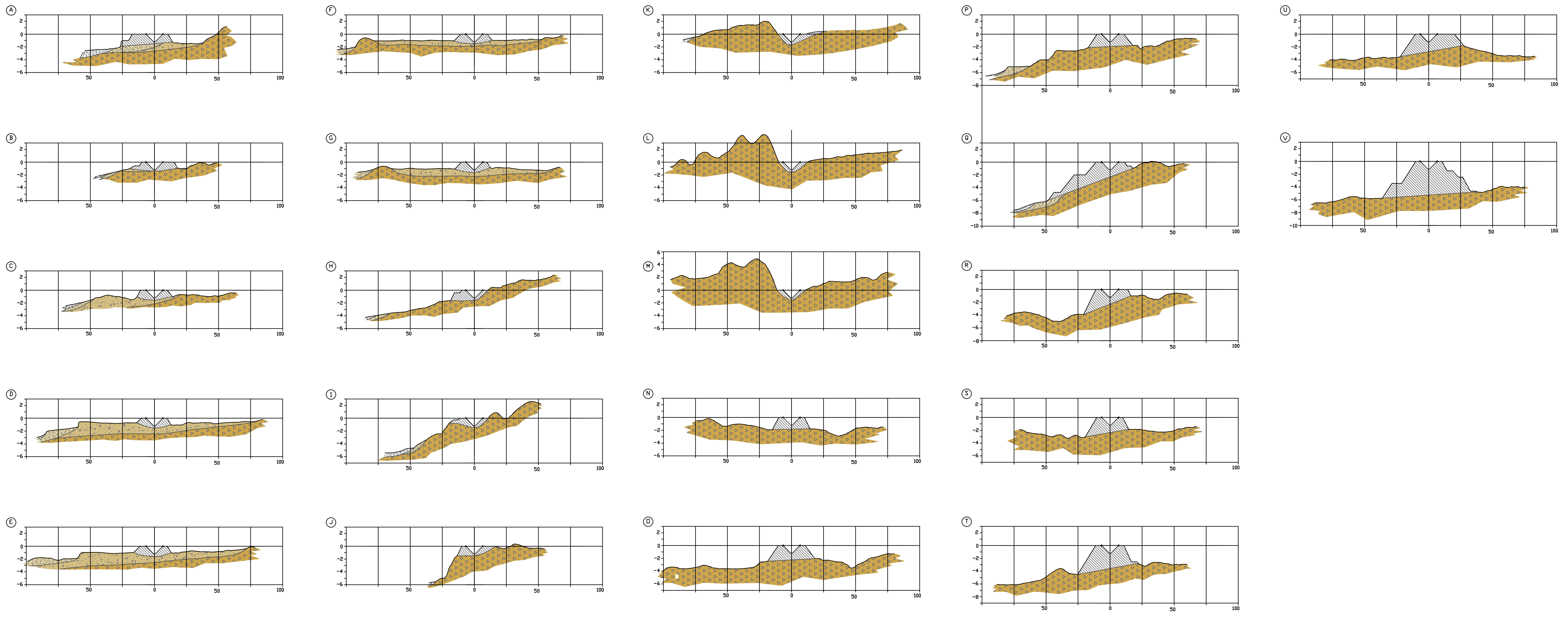
100 0 100 200 300 400

TECHNISHCE UNIVERSITÄT GRAZ

"GEOMORPHOLOGICAL MAP"

Schütt Hydropower, Carinthia, Austria	Master in Engineering Geology Institute of Applied Geosciences
Ana Regina Palomo Meza Ma. 0830235	February, 2010

ANNEX 2 Sketched Cross Sections



LEGEND

░ Fluvial, sand matrix with gravel up to 10 cm in diameter, subangular to subrounded, sorted, matrix supported.

▭ Aluvial, sand matrix with gravel and blocks up to 1 m in diameter, subangular to subrounded, unsorted, matrix supported.

▒ Aluvial, sand matrix with gravel up to 2 m in diameter, subangular to subrounded, unsorted, matrix supported.

▦ Coluvial, blocks and rock fragments up to 5 m in diameter, angular to subangular, unsorted.

▩ Artificially leveled or built up area.

╱ ContacT; inferred.

Ⓔ Profile number.

TECHNISHCE UNIVERSITÄT GRAZ

"SKETCHED CROSS SECTIONS"

Schütt Hydropower, Carinthia, Austria	Master in Engineering Geology Institute of Applied Geosciences
Ana Regina Palomo Meza Ma. 0830235	February, 2010

ANNEX 3 Drill core logs

PROJECT: SHÜTT HYDROPOWER

LOCATION: Arnoldstein, Carinthia

BOREHOLE: **KB - 1**

Page: 1 / 1

CLIENT: KELAG

COUNTRY: Austria

LOGGED BY: Ana Regina Palomo

DATES (BEG. - END):

ORIENTATION: 90 °

DEPTH: 6.00 m

ELEVATION: m

COORDINATES:

GROUND WATER LEVEL: m

SUPERVISED BY:

DRILL:

OPERATOR:

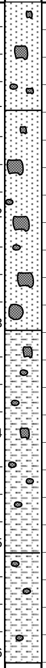
FRACTURING 1 2 3 4 5 | OPENING 1 2 3 4 5 | ROUGHNESS 1 2 3 4 5 6 7 8 9 | WEATHERING DEGREE 1 2 3 4 5 | ROCK STRENGTH 1 2 3 4 5

SOIL: TYPE OF SAMPLE | SAMPLE NUMBER | SET 1 (15 cm) | SET 2 (30 cm) | SET 3 (45 cm) | N VALUE | RECOVERY (cm)

SPT: 10 | 20 | 30 | 40 | 50 | >50

ROCK: DIAMETER | RUN Nº | RUN LENGTH (cm) | CORE LENGTH (cm) | RECOVERY (%) | RQD cm | % RQD

RQD/LUGEON: 20 | 40 | 60 | 80 | 100 | VALUE % / LUGEON UNITS

DESCRIPTION	ELEVATION mmsl	DEPTH (m)	CORE PROFILE
0.00-1.00 m. Rock fragments up to 5 cm in diameter, grey and brown, angular to subangular, with asphalt fragments.	-1,00	1	
1.00-3.00 m. Rock fragments up to 7 cm in diameter, grey, angular to subangular with poorly recovered sand.	-2,00	2	
	-3,00	3	
3.00-5.00 m. Fine silty sand , saturated, with rock fragments up to 4 cm in diameter, subangular.	-4,00	4	
	-5,00	5	
5.00-6.00 m. Fine silty sand with clay, moist, with rock fragments up to 2 cm in diameter.	-6,00	6	
	-7,00	7	
	-8,00	8	
	-9,00	9	
	-10,00	10	

PROJECT: SHÜTT HYDROPOWER

LOCATION: Arnoldstein, Carinthia

CLIENT: KELAG

DATES (BEG. - END):

DEPTH: 6.00 m

COORDINATES:

DRILL:

COUNTRY: Austria

ORIENTATION: 90 °

ELEVATION: m

GROUND WATER LEVEL: m

OPERATOR:

BOREHOLE: **KB - 3**

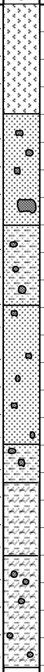
Page: **1 / 1**

LOGGED BY: Ana Regina Palomo

SUPERVISED BY:

DESCRIPTION	ELEVATION mmsl	DEPTH (m)
0.00-1.00 m. Concrete	-1,00	1
1.00-2-00 m. Gravel, grey, angular to subrounded up to 7 cm in diameter, with poorly recovered sand matrix.	-2,00	2
2.00-2.75 m. Silty sand, grey, with gravel and rock fragments up to 3 cm in diameter, angular to subangular, moist.		
2.75-4.00 m. Clay, grey, saturated with rock fragments up to 1 cm in diameter.	-3,00	3
4.00-4.30 m. Silty sand, saturated, with rock fragments up to 3 cm in diameter.	-4,00	4
4.30-5.00 m. Clayey silt, grey.	-5,00	5
5.00-6.00 m. Clayey silt, grey, with rock fragments up to 4 cm in diameter, angular to subangular.	-6,00	6
	-7,00	7
	-8,00	8
	-9,00	9
	-10,00	10

CORE PROFILE



FRACTURING 1 2 3 4 5 | OPENING 1 2 3 4 5 | ROUGHNESS 1 2 3 4 5 6 7 8 9 | WEATHERING DEGREE 1 2 3 4 5 | ROCK STRENGTH 1 2 3 4 5

SOIL: TYPE OF SAMPLE | SAMPLE NUMBER | SET 1 (15 cm) | SET 2 (30 cm) | SET 3 (45 cm) | N VALUE | RECOVERY (cm)

SPT: 10 | 20 | 30 | 40 | 50 | >50

ROCK: DIAMETER | RUN Nº | RUN LENGTH (cm) | CORE LENGTH (cm) | RECOVERY (%) | RQD cm | % RQD

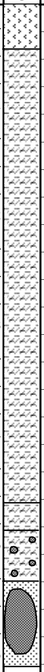
RQD/LUGEON: 20 | 40 | 60 | 80 | 100 | VALUE % / LUGEON UNITS

PROJECT: SHÜTT HYDROPOWER		**BOREHOLE:** KB - 2
LOCATION: Arnoldstein, Carinthia		**Page:** 1 / 1
CLIENT: KELAG	COUNTRY: Austria	LOGGED BY: Ana Regina Palomo
DATES (BEG. - END):	ORIENTATION: 90 °	
DEPTH: 6.00 m	ELEVATION: m	
COORDINATES:	GROUND WATER LEVEL: m	SUPERVISED BY:
DRILL:	OPERATOR:	

DESCRIPTION

ELEVATION mmsl	DEPTH (m)	Description
	0	0.00-0.40 m. Concrete.
-1,00	1	
		2.00-4.80 m. Clayey silt, grayish brown, moist to saturated.
-2,00	2	
-3,00	3	
-4,00	4	
		4.80-5.00 m. Clayey silt with sand, grey.
-5,00	5	5.00-5.25 m. Silty clay, with rock fragments up to 3 cm in diameter, angular to subrounded.
		5.25-6.00 m. Large block greater that 30 cm in diameter, angular.
-6,00	6	
-7,00	7	
-8,00	8	
-9,00	9	
-10,00	10	

CORE PROFILE



FRACTURING	OPENING	ROUGHNESS	WEATHERING DEGREE	ROCK STRENGTH
1 2 3 4 5	1 2 3 4 5	1 2 3 4 5 6 7 8 9	1 2 3 4 5	1 2 3 4 5

SOIL

TYPE OF SAMPLE	SAMPLE NUMBER	SET 1 (15 cm)	SET 2 (30 cm)	SET 3 (45 cm)	N VALUE	RECOVERY (cm)

SPT

10	20	30	40	50	>50

ROCK

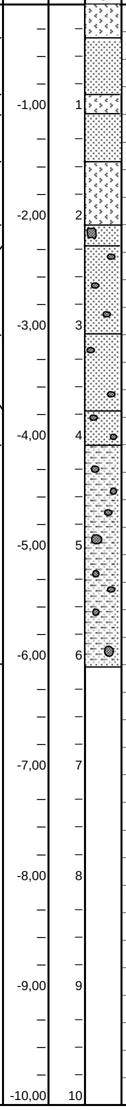
DIAMETER	RUN Nº	RUN LENGTH (cm)	CORE LENGTH (cm)	RECOVERY (%)	RQD cm	% RQD

RQD/LUGEON

20	40	60	80	100	VALUE % / LUGEON UNITS

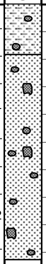
PROJECT: SHÜTT HYDROPOWER		**BOREHOLE:** **KB - 1 D**
LOCATION: Arnoldstein, Carinthia		**Page:** **1 / 1**
CLIENT: KELAG	COUNTRY: Austria	LOGGED BY: Ana Regina Palomo
DATES (BEG. - END):	ORIENTATION: 90 °	
DEPTH: 6.00 m	ELEVATION: m	
COORDINATES:	GROUND WATER LEVEL: m	SUPERVISED BY:
DRILL:	OPERATOR:	

DESCRIPTION	ELEVATION mmsl	DEPTH (m)	CORE PROFILE	FRACTURING 1 2 3 4 5	OPENING 1 2 3 4 5	ROUGHNESS 1 2 3 4 5 6 7 8 9	WEATHERING DEGREE 1 2 3 4 5	ROCK STRENGTH 1 2 3 4 5	SOIL: TYPE OF SAMPLE ROCK: DIAMETER	SAMPLE NUMBER RUN Nº	SET 1 (15 cm) RUN LENGTH (cm)	SET 2 (30 cm) CORE LENGTH (cm)	SET 3 (45 cm) RECOVERY (%)	N VALUE RQD cm	RECOVERY (cm) % RQD	SPT: 10 RQD/LUGEON: 20	20 40	30 60	40 80	50 100	>50 VALUE % / LUGEON UNITS
0.00-0.30 m. Concrete.																					
0.30-0.90 m. Gravel and rock fragments up to 3 cm in diameter, subangular to subrounded, with concrete fragments.																					
0.90-1.00 m. Concrete																					
1.00-1.40 m. Gravel, and rock fragments up to 2 cm in diameter.																					
1.40-2.00 m. Concrete.																					
2.00-2.20 m. Gravel and rock fragments up to 7 cm in diameter, angular to rounded, with fin sand matrix, moist.																					
2.20-3.00 m. Gravel and rock fragments up to 3 cm in diameter, angular to subrounded, poorly recovered sand matrix.																					
3.00-3.70 m. Sand matrix, saturated, with gravel and rock fragments up to 4 cm in diameter, angular to subangular.																					
3.70-4.00 m. Poorly recovered sand matrix with gravel and rock fragments up to 4 cm in diameter, angular to subangular.																					
4.00-6.00 m. Silty sand matrix, saturated, with gravel and rock fragments up to 4 cm in diameter, angular to subangular.																					



PROJECT: SHÜTT HYDROPOWER		**BOREHOLE:** KB - 5
LOCATION: Arnoldstein, Carinthia		**Page:** 1 / 1
CLIENT: KELAG	COUNTRY: Austria	LOGGED BY: Ana Regina Palomo
DATES (BEG. - END):	ORIENTATION: 90 °	
DEPTH: 6.00 m	ELEVATION: m	
COORDINATES:	GROUND WATER LEVEL: m	SUPERVISED BY:
DRILL:	OPERATOR:	

DESCRIPTION	ELEVATION mmsl	DEPTH (m)	CORE PROFILE	FRACTURING	OPENING	ROUGHNESS	WEATHERING DEGREE	ROCK STRENGTH	SOIL: TYPE OF SAMPLE / ROCK: DIAMETER	SOIL: SAMPLE NUMBER / ROCK: RUN Nº	SOIL: SET 1 (15 cm) / ROCK: RUN LENGTH (cm)	SOIL: SET 2 (30 cm) / ROCK: CORE LENGTH (cm)	SOIL: SET 3 (45 cm) / ROCK: RECOVERY (%)	SOIL: N VALUE / ROCK: RQD cm	SOIL: RECOVERY (cm) / ROCK: % RQD	SPT / RQD/LUGEON
				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5 6 7 8 9	1 2 3 4 5	1 2 3 4 5								SPT: 10 20 30 40 50 >50 RQD/LUGEON: 20 40 60 80 100 VALUE % / LUGEON UNITS
0.00-0.40 m. Soil, silty sand, grayish brown, with rock fragments up to 3 cm in diameter, angular.																
	-1,00	1														
0.40-2.30 m. Rock fragments, angular to subangular, up to 7 cm in diameter.																
	-2,00	2														
	-3,00	3														
2.30-6.00 m. No recovery.																
	-4,00	4														
	-5,00	5														
	-6,00	6														
	-7,00	7														
	-8,00	8														
	-9,00	9														
	-10,00	10														



PROJECT: SHÜTT HYDROPOWER

LOCATION: Arnoldstein, Carinthia

BOREHOLE: **KB - 7**

Page: 1 / 1

CLIENT: KELAG

COUNTRY: Austria

LOGGED BY: Ana Regina Palomo

DATES (BEG. - END):

ORIENTATION: 90 °

DEPTH: 6.00 m

ELEVATION: m

COORDINATES:

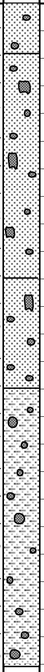
GROUND WATER LEVEL: m

SUPERVISED BY:

DRILL:

OPERATOR:

DESCRIPTION	ELEVATION mmsl	DEPTH (m)	CORE PROFILE	FRACTURING 1 2 3 4 5	OPENING 1 2 3 4 5	ROUGHNESS 1 2 3 4 5 6 7 8 9	WEATHERING DEGREE 1 2 3 4 5	ROCK STRENGTH 1 2 3 4 5	**SOIL**: TYPE OF SAMPLE / **ROCK**: DIAMETER	SAMPLE NUMBER / RUN Nº	SET 1 (15 cm) / RUN LENGTH (cm)	SET 2 (30 cm) / CORE LENGTH (cm)	SET 3 (45 cm) / RECOVERY (%)	N VALUE / RQD cm	RECOVERY (cm) / % RQD	**SPT** 10 / **RQD/LUGEON** 20	20 / 40	30 / 60	40 / 80	50 / 100	>50 / VALUE % / LUGEON UNITS
0.00-0.30 m. Soil, fine silty sand, brown, with roots and organic material, with rock fragments up to 2 cm in diameter, subangular.																					
0.30-2.50 m. Sand with rock fragments up to 10 cm in diameter, angular to subrounded, dry.	-1,00	1																			
	-2,00	2																			
2.50-3.50 m Fine sand and rock fragments up to 12 cm in diameter, angular, dry.	-3,00	3																			
3.50-6.00 m. Silty sand with clay and rock fragments up to 2 cm in diameter, moist.	-4,00	4																			
	-5,00	5																			
	-6,00	6																			
	-7,00	7																			
	-8,00	8																			
	-9,00	9																			
	-10,00	10																			



ANNEX 4 Drill core photographs

KB-1 WEHR

0.00-6.00 m

KB-3

0.00-6.00 m

KB-2

0.00-6.00 m

KB-1 DAMM

0.00-6.00 m

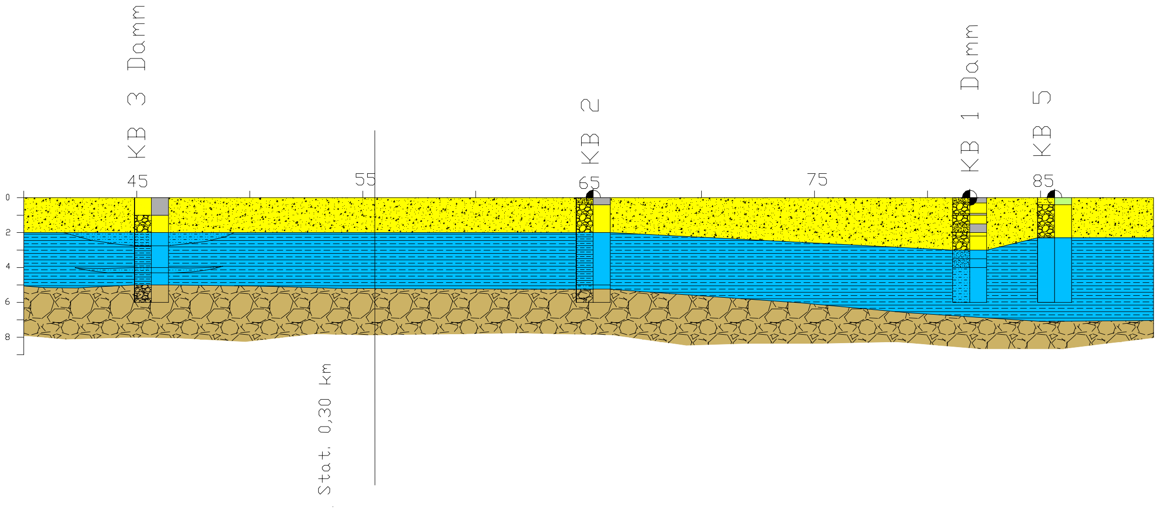
KB-5

0.00-6.00 m

KB-7

0.00-6.00 m

ANNEX 5 Schematic cross section of failure zone



LEGEND

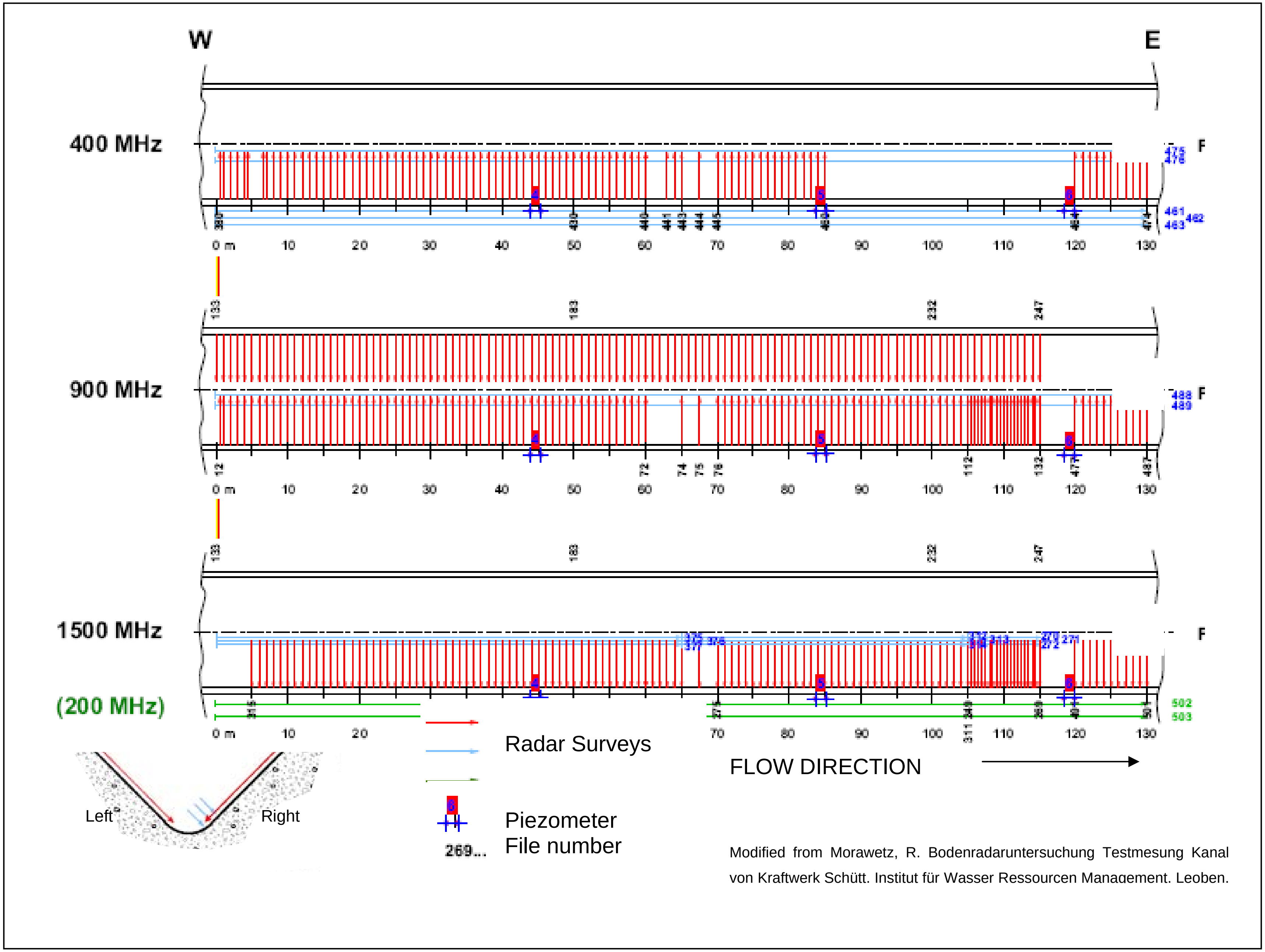
- ▩ Concrete
- ▨ Infill
- 🟦 Fluvial (sand and gravel < 10 cm)
- 🟦 Fluvial (silty sand)
- 🟦 Fluvial (clayey silt)
- 🟫 Landslide material
- 🟩 Soil
- ☐ No recovery
- ◐ Borehole, name
- ∼ Contact, inferred
- ⌊ 5 Georadar profile station (m)
- 0,30 km Channel chainage station (Km)
- 0 2 Depth (m)

TECHNISHCE UNIVERSITÄT GRAZ

"SCHEMATIC CROSS SECTION OF FAILURE ZONE"

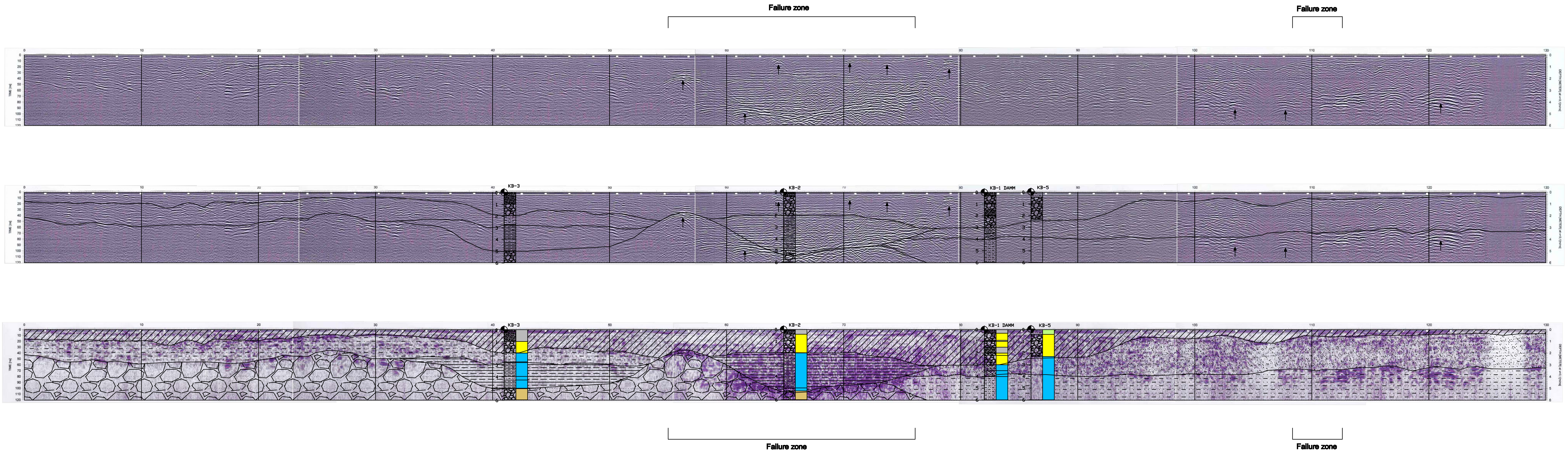
Schütt Hydropower, Carinthia, Austria	Master in Engineering Geology Institute of Applied Geosciences
Ana Regina Palomo Meza Ma. 0830235	February, 2010

ANNEX 6 Ground Penetrating Radar Measuring Scheme



Modified from Morawetz, R. Bodenradaruntersuchung Testmesung Kanal von Kraftwerk Schütt. Institut für Wasser Ressourcen Management. Leoben.

ANNEX 7 Ground Penetrating Radar Analysis



LEGEND

- ▨ Concrete
- 🟨 Infill
- 🟦 Fluvial (sand and gravel)
- 🟦 Fluvial (silty sand)
- 🟦 Fluvial (clayey silt)
- 🟫 Landslide material
- 🟩 Soil
- ☐ No recovery
- ◐ Borehole, name
- ~ Contact, inferred
- ⌴ Georadar profile station (m)
- ↑ Possible Cavity

TECHNISHCE UNIVERSITÄT GRAZ	
"INTERPRETATION OF GEORADAR"	
Schütt Hydropower, Carinthia, Austria	Master in Engineering Geology Institute of Applied Geosciences
Ana Regina Palomo Meza Ma. 0830235	February, 2010