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You can leave your head on … Geophysics serves non-destructive in-situ inspections of ground anchors

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ABSTRACT: Higher awareness for awards of damages caused by public infrastructure forces public administration in the Republic of Austria for tighter monitoring intervals of existing ground anchors. In an Alpine country with denumerable infinite ground anchors, road office tradition and national standards request statistical selection of anchorages, restressing routines and documentation of tendon displacements. Conclusion when failed: Surgery successful, patient / anchor beheaded, slope destabilized by next thawing season, good business idea for construction companies as endless financial resources are available through the taxpayer. A contracted research project aimed to the development of a non-destructive in-situ measurement strategy for timeworn ground anchors. By combining geophysical field methods (in-situ resistivity / induced polarization, self-potential, acoustic frequency shifts) four risk classes were detected among single members of anchor ensembles. The applied strategy re-set the focus from individual anchor testing to the overall geogenic functionality while keeping the bigger pictures of the entire anchor wall. This strategy evolved by merging civil engineering experience (tunneling, mining, and geotechnical) with applied geophysics (survey strategy, data handling, simplified processing, interpretation schemes) and with operational viability of National road offices (legal frameworks, available resources, knowledgebase of staff, streamlined procurement, planning reliability). During autumn 2018, four case studies in Lower Austria showed: Geophysics delivered and satisfied public administration, and finally delighted the legal department.

Keywords: ground anchor; geophysics; in-situ testing; non-destructive;

1. Research significance

1.1. Problem to be addressed

Due to the Alpine geomorphology in the Republic of Austria, zillions of ground anchors were placed during the last hundred years to protect road and railroad infrastructure, to stabilize earthworks, and to safeguard engineered slopes. Today, most of the ground anchors have reached the second half of their projected lifetime (approx. 100 years). Anthropogenic changes near their original settings (road widening, adjacent buildings, new roadways, changed groundwater regime, civilization impacts) and natural degrading processes add additional strain on these legacy ground anchors. In addition, the technical causes for failures of anchored structures are multifold and difficult to characterize: Imperfections in installation, missing corrosion protection as well as bad workmanship induce failures either individually or in combination. As today's civil society increases its fidelity for court cases, a raising number of claims towards public administration is foreseen if damages can be associated with rock falls or hillslope movements.

This pushes public road departments into an uncomfortable situation – a swell of control work and documentations, outdated national building standards, standard drafting committees populated with lobby groups, and limited resources (staff, financial) are challenging ingredients for this forthcoming herculean workload.

Legal and operational realities constrain planned on-site operations: Lane narrowing on public primary- and secondary roads of less than two hours addressed in a legal sense as "*temporary averting of danger*". This is usually done as a mobile roadblock by regional road maintenance depots. Otherwise, any maintenance activity on roads longer than two hours needs Kafkaesque permitting procedures, driven by long lead times (up to six weeks for one site) multi-stake holder involvements (police, higher level representatives of district road departments, ruling mayors of villages in vicinity, local transport managers, and fire brigades). Consequently, the strategy for anchor control has to operate within a two hour time window.

Hence, a game change in anchor testing deemed necessary: A federal state in the Republic of Austria commercially contracted through its road department a group of international working senior geophysicists and requested to conduct desktop research *and* to develop an implementable strategy coping with challenges and shortcomings of current anchor testing praxis.

The given constrains for the strategy to be developed were *(i)* relatively low acquisition price of hardware and software, *(ii)* minimized operational costs, *(iii)* field work to be performed by foremen / non-academics, *(iv)* high conformability, *and (iv)* legally valid reporting to satisfy various court levels.

The driving force behind contracting an international geophysical team rooted in the core competencies of their vocational field: Developing survey strategies based on the collection of not too much and not too little raw data, automated processing of mass data, broad problem solving capacities for questions related to geogenic interfaces and geological boundaries, and expert knowledge in complex interpretation schemes. High awareness to minimize operational and field costs and cross-disciplinary communication skills translating and bridging between involved stakeholders (engineering geologists, geotechnical staff, civil engineers, inspection responsible, road department staff, and public procurement) added soft-skill amenities.

1.2. Work order

The governmental remitter wisely selected three case studies representing existing geological and operational conditions as well as one additional reference site as blind study (ground anchors placed recently: all technical parameter known for administration, but kept secret for the deployed geophysics serving as external quality control and plausibility checks). Field work was conducted during early autumn 2018. The project finished as scheduled and with success in 2018.11.

1.3. Literature (re)search

Ending the literature search in 2018.10, about 223 *(!)* scientific articles as well as well-selected chapters from ten reference books / conference proceedings formed the knowledge base of this project. The resulting screening specified only 15 relevant, forth leading scientific impact papers providing the necessary momentum for this commercial research project. The team experienced disenchantment which rooted in a considerable quantity of peer-reviewed papers with factually flawed content and scientifically non-relevant or less practical findings for any site operation. It was found, that current research work focusing on anchor testing is stove-piped and triggers minimal synergetic effects between different schools of thought. Deep gaps between pure university based science, operational on-site realities, and commercial conventions nursed by the *(non-subsidized)* construction industry became visible.

1.4. Stress on ground anchors

Reference books [1, 2, *and* 3] and national standards [4, 5] illustrate detailed sketches of ground anchors. These pictures are usually object focused and neglect or oversimplify surrounding geology, Fig. 1.

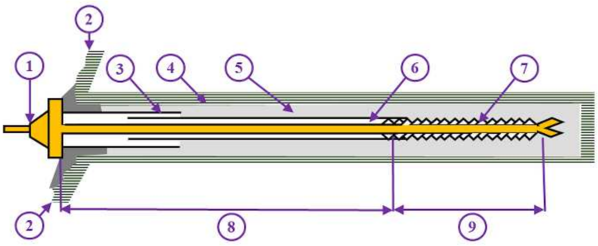


Figure 1. Schematic sketch of ground anchor elements as object focused drawing
redrawn on the basis of [4] – 1: anchor head with nut and bearing plate & end face of steel bar tendon; 2: generalized and minimized geology; 3: trumpet tube; 4: borehole wall; 5: grout; 6: decoupling sheath; 7: Encapsulation; 8: Free tendon / service length; 9: tendon bond length;

As such, the understanding of the problem is focused on the monolith. However, to understand on-site realities a grouted anchors needs to be recognized in a holistic way as the surrounding geology has a significant role in the long-term functionality of placed anchors. By nature, anchorages are placed into non-homogenous geological situations, e.g. across-different geological- and petrographical units and/or intersecting gradient weathering layers of one rock type.

In both cases, the initial drill hole of the rock bolt penetrates units with different petrophysical parameters (strength, hydraulic routing, and geochemical character) Fig 2.

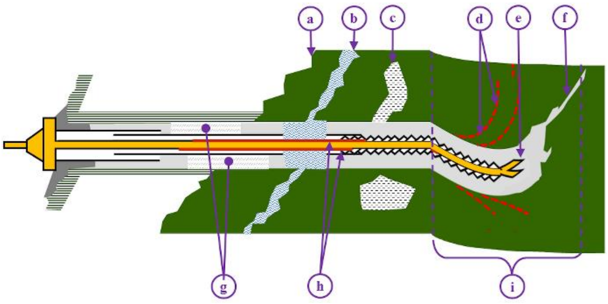


Figure 2. Geological near-space reality of an anchor - *redrawn on the basis of* [4] – a: boundary between geological entities; b: groundwater filled zone of joints; c: voids; d: field of mechanical forces inducing rock anisotropies; e: deformed anchor base; f: man-made fissures; g: short-range debonding; h: friction reducing mantle of corrosion / rust; i: sheared anchor due to fault movement;

Besides a pure static description of the geological near-space, the rock units respond differently to dynamic processes, e.g. settling, inner erosion, and hill creep. As observed by [6], the pre-stressed rock surrounding the anchor responds with gradient petrophysical changes and creates anisotropies which are accompanied by various degrading responses. Consequently, a geological near-space surrounding the anchor develops site-related parameter and external stress elements for every individual member of an anchor clusters, *e.g.*

- **Fig. 02 / a:** A more or less distinct boundary between two geological units creating two half-spaces with different petrophysical parametrization;
- **Fig. 02 / b:** Intersecting a fracture system, with or without crack water; borehole wall effects may alter the original hydraulic conductivity and create a zone of higher hydraulic pressure;
- **Fig. 02 / c:** Air-filled open voids or zones with different void ratios providing a lower bulk density and hence a discontinuity of strength parameter *e.g.* reduced shear strength resistance;
- **Fig. 02 / d:** Drag force induced rock anisotropies changing petrophysical parameters like density, seismic velocities and resistivity;
- **Fig. 02 / f:** Partly grout filled fractal outbreaks at the bottom of a drill hole;
- **Fig. 02 / i:** By accidentally designing the bar tendon too short, Fig. 2 / e, the anchor may not pierce through the zone of instability. The resulting shear displacement deforms the anchor and crushes the surrounding grout mantle, [7];

In addition, an on-going internal degrading processes also reduces the planned functionality of a ground anchor, *e.g.*

- **Fig. 02 / g:** Interfacial debonding is one of the major failure modes of grouted rock bolt systems, [8]. Bond defect lengths influence the load–displacement response on all three parameters (adhesion, mechanical interlocking and friction);
- **Fig. 02 / h:** Corrosion on structural steel occurs in three effects – pitting corrosion, stress cracking corrosion, and surface corrosive actions. The rusting of the bar tendon is influenced by ground water composition, flow rates, groundwater pH, temperature, CO_2 content, surface condition, presence of corrosion inhibitors, applied stresses, residual stresses (from workings, forming or welding operations) and hydrogen sulphide concentrations, [9]. JIANG *et all* [10] recognized corrosion as the main source of failures for ground anchors. By glancing through manifold literature dealing with corrosive rock bolts and by interviewing field staff and governmental civil engineers, two conclusions emerge, namely *(i)* corrosion along tendon bars is not uniform and *(ii)* that +50 % of examined ground anchors fail on the very first meter after the anchor plate. Parallelizing the chemism of groundwater from Canada with groundwater conditions in Austria (both pH values are close to 7) allowed to use findings from [11] to estimate the rate of depth-/ and time dependent corrosion to approx. 0.0052 mm per year (!). Even though corrosion reduces mass and diameter of the bar tendon made from cold welded construction steel, the through rusting is addressed as not relevant for this project. The relevant failure mechanisms of a corrosion process is different: A thin film of rust around the tendon bar creates a local volume growth and a resulting pressure increase. This pressure increase reduces the static friction between grout and steel and finally leads to the malfunction (*slipping out*) of an anchor.

1.5. Model

The complexity of existing geoscientifically driven preconditions (geology, tectonics, petrophysical anisotropies, and local hydrogeological regime) and specific ground anchor effects (*cf.* Fig. 02a to 02h) requests a multifaceted survey program to strictly deal scientifically with known ground anchor malfunctions.

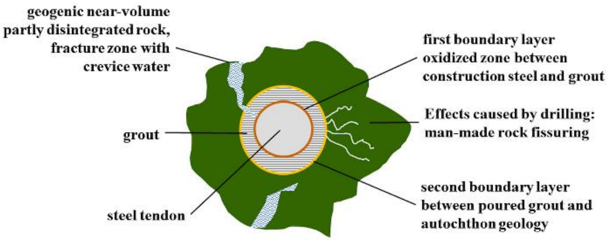


Figure 3. Anchor generalized as boundary problem

In geophysics the first step is the abstraction of a complex situation into a robust, simplified but usable situation. This is called model building. The derived model for a combined ground anchor / geology setting as basis for the development of non-destructive in-situ testing poses a double boundary problem embedded into disturbed autochthon geology, Fig. 3.

2. Routine control, reception, and conclusion

Approaching from afar the posed problem of in-situ, non-destructive ground anchor testing, additionally constrained by economic and on-site realities, creates an initial non-biased position with (*nearly*) naïve curiosity, which allows a critical evaluation of current five approaches for routine maintenance testing and service behavior monitoring of grouted anchors, [12]:

- **Visual examination**
  of physical condition of anchored structure and all protected individual anchorages,
- **Hammer test**
  Inspection of the anchor head above and below bearing plate of selected anchorages,
- **Geodetic deformation monitoring and analysis**
  Measurement of overall movement and local deformation of anchored structure,
- **Tendon displacement**
  Measurement of residual load and load-displacement behavior of selected anchorages;
- **Overcoring**

2.1. Visual examination

Visual appearance of anchor heads is seen as a useful indicator for the reworking of anchors due to corrosion. **Reception:** Already in 1975 [13] stated, that visual inspection can be deceptive by oversimplifying the damage analysis. For those outside of the field of the construction industry, it is difficult to understand how the visual inspection of anchor heads and plates provides information about deeper situated damages and defects and why this technique, after nearly half a century, is still highlighted in standards and technical textbooks.

2.2. Hammer test

Detailed investigation of anchor heads recommends hammering on anchor heads and plates. This rudimentary impact acoustic impact method delivers two different information states, a dull sound and a slightly lighter tone. **Reception:** Traditional technique for controlling rolling stock of railways, in which carriage examiners identified endurance failures on bogie wheels, seeams to be the root of this quality control. As the acoustic impedance contrast of (*railway*) steel against ambient air was nearly constant, it is understandable that these nearly constant survey conditions provided a reliable source of information about axles, wheels, and brake shoes. As both construction elements (steel, ambient air) have nearly a wide, nearly constant, acoustic impedance difference, this simple technique is explainable and constructive. However, these conditions are not found on ground anchors settings. Hence it is difficult for the laymen to understand the information reliability of this procedure.

To apply hammer tests for legally valid anchorage control, a more systematic approach is deemed necessary: Based on a standardized approach, the hammer type (wood, steel, rubber, and rigid plastic), strength and direction of the hammer stroke need to be pre-defined and controlled. As the normal human hearing is subject to changes (mood, health status, age) and only differences in frequency distributions are recognized, a compulsory reference test needs to be done first on a 100% healthy specimen of the investigated anchor cluster. Against this initial structure-borne reference signal, all other cluster members have to be compared and evaluated. This step is not necessary if professional musicians with a perfect sense of pitch conduct these anchor tests, and thus are able to quantify the signal-frequency distribution with their accurate ear. Mostly these specific employer requirements are seldom found among the public workforce serving field works in road departments.

The hammer test has also be seen critically from an acoustics point of view: It works only if the acoustic impedance between the placed anchor and the surrounding rock is larger than approx. 15%. In case of anchorages in hard rock settings, the individual anchor (steel type, thickness of rust mantle, various grouts with different water/cement ratios) may have a similar impedance as the „*fast and heavy*“ autochthone hard rocks (e.g. granite, limestone, crystalline: > v_p 4200 ms^{-1}). The hammer tapped signal will echo a superimposed signal from surrounding geology and anchor defects. However, hammer tests are still part of recommendations forming national standards and are consequently billed by the construction industry.

2.3. Geodetic deformation monitoring

A remarkable field technique with high accuracy, [14], and proven success. **Reception:** Outside range of this project as it violates the initial project constraints (low hard-/software price tags, minimized operation costs, surveys to be performed by staff on foreman level). In this project, also the specifics of Austrian geomorphology (narrow mountainous valleys, steep valley-flanks, counter slopes hardly accessible) make this method hardly applicable on a day-to-day basis.

2.4. Tendon displacement

After the grout developed its full operational strength, a mono-jack is connected to the anchor-head and the tendon controlledly pulled. This stressing of the anchor leads to tendon elongations, and correlates with overall functionality of anchor constructions. **Reception:** Literature gives the impression that testing equipment has not experienced technological changes during the last 27 years, *cf.* compare 1989 Figure 33 in Chapter 11 [4] with 2015 Figure 3, Page 13 in [15]. A cited private communication in [16] summarized the dominating disadvantage of destructive-risk related tendon displacement tests: "*Mechanical tests also poses the risk of damaging the anchor head, so they should be used sparingly..*". Therefore, this method is unsuitable for regularly applied long-term monitoring programs (time basis: 50 to 100 years). This destructive and invasive control (*beheading*) technique is part of a highly regulated / protected market segment within construction industries and little intention for changes from the public hand exists.

Further, the on-site situation may not always be favorable to connect pulling devices to the tendon: Either the free end of the legacy tendon is too short to force fit a jacking mechanism, Fig. 4, or on-site realities prohibit long and expensive preparations (scaffolds, service benches, road blocking over two hours), cf. Fig. 5.

Figure 4. Short-headed tendon face on legacy anchor

Figure 5. Example of operational reality

The successful investigation of fully grouted rock bolts - a type mostly found in Lower Austria - is jeopardized by the critical embedment length, [17]. The actual assessed functional length of the pull-out method using a hydraulic jack is usually less than one meter. Depending on the grout cement / water ratio and of the surrounding rock mass quality, a "*healthy*" grout collar of 0.30 m to 1.0 m, situated immediately behind the base plate, is sufficient to keep the tendon in place before the pull test reaches the limit of the steel bolt strength. This is in line with the orally reported results of pulling tests in Austria – usually the tendon steel rips off during pulling tests between .5 m and 1.0 m behind the baseplate.

The following generic example shall visualize this known situation: A seven-meter long anchor with meter-wide bond defects and a strongly corroded steel tendon in the encapsulation has a tight grout collar of little less than a meter behind the anchor plate / head. This anchor will positively pass the mechanical stressing pull test. This result may neutralize indemnity claims from aggrieved parties but does not reflect designed anchor functionality.

2.5. Overcoring

The exhumation of anchorages by drilling a large diameter core containing grout and tendon. Overcoring needs to be flushed with fresh water. **Reception:** Very expensive, fully destructive process performed on one representative reference anchor. In case of bent or twisted anchor tendons (drilling through the tendon made of cold rolled structural steel) success of method remains questionable – at least for the drilling crew. The estimated price tag for overcoring – if at all operational possible at the chosen site – will be in the range of 20 to 40 new anchor settings. Practically, this method is well beyond day-to-day realities and budgets of public administrations in Austria.

2.6. Sampling statistics

Depending on the country and applicable standards and codes of practice, an appropriate number of individual ground anchors needs to be singled out for statistical representative testing from the total number of anchor members. In step like arrangements, the amount of anchors to be tested is in the range between 2% to 10 % of the total anchor population at one anchorage site.

Drawing a statistically sound and representative sample without bias or false conclusions (*here*: identifying the right specimen/anchor to be tested) is a methodologically challenging task. First, an entire cluster of anchors needs to be numbered. Second, and assuming that all anchors *(i)* belong to the same generation group *and (ii)* have been placed into similar geological and hydrogeological conditions *with (iii)* same workmanship and similar grout water ratios, the right specimen needs to be identified in a purely randomized process. It is noted, that even random number generators in IT environments *strictly seen* generates only pseudo random numbers. The consequence for day-to-day operations: The envisaged specimen needs already be identified during desktop work before the maintenance field team moves out to the actual site. Consequently, when "*bad luck*" balanced serious economic concerns of public road departments, staff has to prepare all means and measures (scaffolds, boom lifts, climbing aids, and working platforms) to have the possibility to examine every single ground anchor in an anchorage cluster – especially the "*unfavorable and laborious* " ones the very top of the stabilized structure underneath the overhanging rock face. **Reception:** Operational everyday experience shows, that the selection of specimen is biased by the grade of accessibility, general workload, and availability of worktime. Consequently, the easily reachable anchors, *e.g.* at the toe of a landslide, are more likely to be examined than the ones high up at the crest or at the edge of the rupture zone.
A second problem remains unanswered – in Austria typically anchorage clusters consist of different generations and are constructed by different companies. As assumed by [18], the prevalent standard, different workmanships, and range of variation between documentation and implemented reality needs to be critically reflected. Hence the questions how to select a statistical sound specimen for invasive testing from an anchorage cluster made from n-generations ($n = 1, 2 \ldots$) of m-grouted anchors (m = 1, 2, 3, .. >50) remains – at least in Austrian national standards - unsolved.

2.7. Conclusion

To cope with operational on-site constraints, to account for the lack of definitions and instructions found in national standards, and with missing information in relevant scientific publications, only a simultaneous monitoring programme encompassing all site-members of an anchorage at once is deemed to be trendsetting.

However, the upcoming workload to test zillions of anchors can be turned into an advantage – a developed survey strategy can be rooted in to a large population, hence, statistical based qualitative testing and financially constrained strategy deemed to be the "*silver bullet*" for this operational theatre.

3. Geophysics

Applied geophysics offers a suite of approx. 18 different non-destructive and least invasive mapping methods for geogenic materials. All methods are comprehensively described in standard textbooks, e.g. [19, 20].

Any geophysical investigation is an indirect in-situ investigation of ground and/or built structures. If compared to standard destructive and intrusive investigation methods in geotechnical engineering, geophysics offers considerable time and financial savings. Applying geophysical means to in-situ investigations of existing ground anchors is neither new nor unique, but predefined project constraints need to be accounted for the selection of an appropriate survey sequence.

Also geophysicists are aware of the complexity of field survey conditions and the mean variation of results, this discipline cannot really couple with the expectations of civil engineers – one side is delivering results with ambiguity ready for iteration whereas the other side expects impeccable, centimeter accurate answers carved into stone. One possibility to foster communication between civil engineers and geophysicists is to categorize end results – instead of communicating numbers categories of better / good and worse / bad may assist in solving the posed problem. Unfortunately, applying geophysics to engineering or geotechnical problems has produced some disappointing results for the civil engineering community, [21]. This is usually the case *(i)* when wrongly selected methods and false data acquisition parameter did not satisfy the requested precision as requested by civil engineers, *(ii)* when the geological theatre is more complex as initially anticipated during the planning process, *or (iii)* simply, data acquisition planning and interpretation has been procured and conducted by non-geophysicists. The project team found that a combination of four methods are conducive for in-situ non-destructive anchor control:

- Spontaneous potential
- Geoelectrics
- Induced polarization

- High resolution seismics or acoustical examination

3.1. Spontaneous potential (SP)

When two metal stakes make contact with the soil, a natural electric potential difference develops between these two poles. The signal is usually less than a few hundred millivolts. The small currents flow as the ions attempt to establish an electric equilibrium between the two metal stakes. Usually the difference in the electric potential is caused by electrochemical reactions. The method is applied to measure spatial distributions of corrosion in existing concrete reinforcements [22: -440 mV *sic!*], in mineral exploration, in environmental plume mapping activities and spatial mapping of corrosion along pipelines [23]. **Significance:** In the case of standard corrosion conditions – tendon in contact with groundwater: At these anodic points metal ions enter into the surrounding salt-bearing groundwater (electrolyte) by giving out electrons. The free Fe2+ ions react with available oxygen in the electrolyte and form rust (corrosion). The inter electrode voltage of the developing self-potential depends on temperature, steel type, dissolved oxygen, chloride content of the bonding cement and also on the type of reference electrode used for the "*half cell survey*" e.g. -406 mV for a copper / copper sulfate arrangement and – 426 mV if a calomel reference electrode is used, [24, 25].

For this pilot research a "*hands-on*" approach was used to define electrical self-potential value used as an orientation value for the later categorization of the corrosion status. It was anticipating that tendon steel and cement mix remained constant within the investigated area and its test sites. On test site 3 the anchor #304 was placed intersecting a visible and accessible rock interstice. The partly exposed tendon steel was rusty. By defining this anchor as reference, the measured electrical self-potential value was in the range of -450 mV ± 20 mV. Hence, a reference value of -440 mV ± 10 mV is used as (*arbitrary but knowledge constrained*) criterion for exclusion between a strong and week in-situ corrosion for steel tendons embedded into interstitial water conditions in hard rock conditions.

3.2. Geoelectrics (RES)

The resistivity method, also named vertical electrical sounding (VES) or latterly electric resistivity tomography (ERT), estimates the subsurface in-situ distribution of rock resistivity by measuring a decay of an electric potential generated by an electrical direct current sent into the ground. The analyzed apparent subsurface resistivity distribution can be interpreted as a distribution pattern of different geological entities (rocks, strata layers, and if loaded with salt tracers: velocity and the direction of the salty groundwater plume correlating with the groundwater flow fields, [26]). Hence, four electrodes are necessary for this type of survey – two electrodes to send a primary current into the ground and two electrodes to measure the voltage differences. Based on Ohms law, the quotient of the measured voltage decay and the known electric current of the primary field is the apparent resistivity between the latter electrodes. Usually the four electrodes are small metal stakes just long enough to allow current feeding and voltage measurements.

The result of a geoelectrical survey is a spatial subsurface distribution of the apparent resistivity. In order to transform the values of apparent resistivity into a direct apparent bulk resistivity, a correction factor needs to be multiplied with the initial measurements. The correction factor is known as geometric constant k and solely depends on the position and the distance between the four electrodes. Golebiowski et al. showed [27] that rock-bolts in underground mine settings can be utilized as (very) long electrodes for full space RES surveys. Reducing the full space conditions into a vertical half space allows this experience to be applied for the in-situ control of grouted anchors. In-situ specific resistivity values range between a very few 10 Ωm (clay) to a few 10 k Ωm -100 k Ωm (igneous and metamorphic rocks), [28]. Also the specific resistivity of groundwater depends massively on its mineralization content, in Austria alpine groundwater has a specific resistivity around 40 Ωm. In this specific pilot survey performed in hard rock theaters, in-situ resistivity smaller than 300 Ωm are interpreted as groundwater soaked conditions.

However, in standard RES measurements the apparent resistivity distribution between two electrodes is determined. Depending on the distance between the measuring electrodes, this would give one apparent resistivity value integrated over a considerable distance. Under certain circumstances, a large spatial distribution would give false data for the geological near-space of the focus electrode representing one particular anchor. Thus, not the resistivity distribution between two electrodes is of interest, but the actual grounding resistance of one single anchor needs to be determined. Measuring the true single-electrode grounding resistance is not possible in practice, as only differential measurements are performed.

This problem parallels with RES measurements under high-resistance permafrost conditions and has been solved by [29] as *focus-one measurements*: Each electrode in an array is tested against all the remaining electrodes in parallel. The focus-one measurement is effectively a two-electrode measurement — current is transmitted across the same electrodes because they are used to measure the potential difference. However, the grounding resistance of half of the circuit is significantly reduced by connecting all electrodes in the array in parallel, except for the anchor under test (the focus electrode). This way, the grounding resistance of the focus electrode dominates the measurement. The reported error for focus-one measurements is in a range of ± 7%. **Significance:** In a dry environment the geological near-space surrounding an anchor will have a resistivity between 300 Ωm and 2000 Ωm. For contact resistivity smaller than 300 Ωm, groundwater dominated conditions – and thus: a more corrosive situation – are assumed.

3.3. Induced polarization (IP)

A geophysical method stemming from mineral exploration while exploring disseminated ore deposits. This method involves the slow decay of voltage in the ground following the cessation of a primary excitation current. Most of the stored energy involved with this method is of chemical nature, [30 and 31]. Significance: A high chargeability (+ 600 mV) is interpreted as a well-protected anchor. Negative chargeability correlates with direct contact between groundwater and the metallic tendon, which may stem from open bending or shear span fissures in the grout, [32].

3.4. High resolution seismic logging or acoustical logging (AE)

At present, the stress wave method and ultrasonic guided wave method are used to conduct non-destructive testing of the bonding quality of rock bolts. The principle is, that a guided wave is used for the inspection of embedded cylindrical structures. It uses P waves or S-waves, both excited from the top of a rock bolt, which give information about the bonding quality of the rock bolts according to the amplitude of reflected wave, [33]. **Perspective from Geophysics:** This method appears to have some principal shortcomings and special care for measurements need to be exercised.

Firstly: Measuring an amplitude decay is difficult, especially when the exciting hammer stroke is not standardized.

Secondly, this method assumes that the wave-types do not change or transform along its travel path within the tendon grout system. The initial hammer stroke is a DIRAC impulse containing all frequencies in equal proportion at zero phase. The travel of different frequency packages along the tendon / rust mantle / grout cylinder is governed by phase velocity and by wavelength (dispersion). Hence, even a delta function generated at the tendon head, the echo will return as a stretched wave train.

Thirdly, a simple hammer stroke – or even a perfect force-fitted mechanical wave generator – is not broadcasting pure P- or S-waves into the anchor system, but a superposition of P-, S- and rotational wave packages with symmetric and asymmetric oscillation modes. Primary wave types will split into secondary types and will have different rates of amplitude damping. This phenomenon is well studied and understood in earthquake seismology.

Polish and British scientists [34, 35] observed the problem associated with amplitude damping and prioritized measurements of energy leakages, Fig. 6.

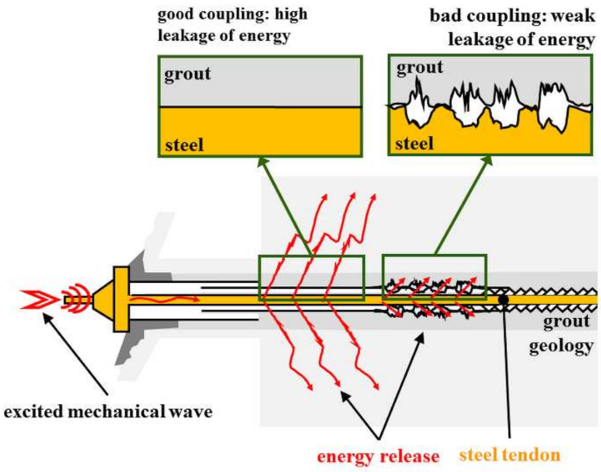


Figure 6. Wave leakages at interfaces steel bar / surrounding anchor body and near-space geology – *Generalized and redrawn after* [28, 29]

The exited guided wave in the tendon propagates along the longitudinal axis. In the fixed part, the wave transmitted along the steel bar emits energy into the grout mantle and surrounding geological near-space. If the interfaces between steel / grout and grout / geology are undisturbed and mainly friction locked, most of the energy will propagate from the steel bar into the near-space. Thus, if the bonding quality is high, the transfer of energy from the steel tendon into the surrounding medium is strong resulting in a large wave energy leakage. However, if interfaces between steel / grout and/or grout / geology are non-uniform (voids, pitting, stress corrosion / grout cracking) force-fitting is neutralized, and the wave will be trapped in the steel tendon. Consequently, hardly any mechanical energy will be freely emitted into the near-space. The trapped energy will propagate back and forth within the steel bar only subject to damping characteristics in steel. From the perspective of applied seismology, the exited primary signal recognized by a large amplitude followed by time delayed smaller amplitudes representing the decaying oscillation of the trapped energy. In engineering seismology, this reverberation observed is an oscillatory effect produced by a narrow band filters and is known as "*ringing*".

This effect gives a rational interpretation scheme to the simplified hammer test – when the hammer tapped signal decays fast and the echo of the reverberant sound is dull and low, the investigated anchor is of good condition – as most of the mechanical energy will be broadcasted into the near-space. Opposite, if the hammer test responds with a clear and sharp metallic signal and has a long reverberation period (type high pitch triangle type of sound), the anchor is in quite poor condition.

By applying a FOURIER transform to the measured signal, hence shifting measured data from time-domain into frequency domain (*and after applying the* PARSEVAL'S *identity to the shifted signal*), the frequency energy distribution from the primary signal is recognizable. Bad coupling between the interfaces steel / rust / grout / geology will shift the spectra of the initial signal towards higher frequencies. Determining the rock bolt integrity via FOURIER transformed data is a well-documented tool for non-destructive in-situ measurements of anchorages, [36]. **Significance:** By assessing the answer spectra of a gentle hammer stroke on the end face of a tendon the coupling quality of the grouted anchor is deducible: If low frequencies dominate the answer spectra, the mechanical coupling between tendon / grout / geology is well bonded. If the spectra appears compact and the balance point shifts to higher frequencies, the tendon-grout-geology system is not well force fitted.

4. Field works & processing

By arriving on-site the first step is the identification and numbering of single anchors in an anchorage ensemble. The naming convention follows the principle

Anchor ID (n, m) [

with $n = 1, 2, \ldots 4$ specifying the site, and $m = 1, 2, 3, \ldots, 15$ identifying the individual anchor in the ensemble. Hence, anchor ID 415 specified the 15th anchor on site four. In a second step, a geometric reference point, $p_{reference} = \{x = 0.0\text{ m}, y = 0.0\text{ m}\}$ in defined in a CARTESIAN coordinate system, to address every anchor clearly by one pair of coordinates. The coordinate of the anchor will serve later as input for the calculation of the k-factor, which is needed for the processing of geoelectrical measurements.

Figure 7. On-site installation of electrodes for the subsequent geoelectric survey

In a third step, the **geoelectrical survey** is prepared by visiting all anchor with a portable hoisting platform, Fig. 7. This allows the removal of the rust film (battery driven grinder) and the good connection of the contact vices, Fig. 8. Depending on the electrode configuration preferred, one current electrode will be placed into infinity – meaning: a distance more than ten times the maximum distance between two anchors in the anchorage cluster.

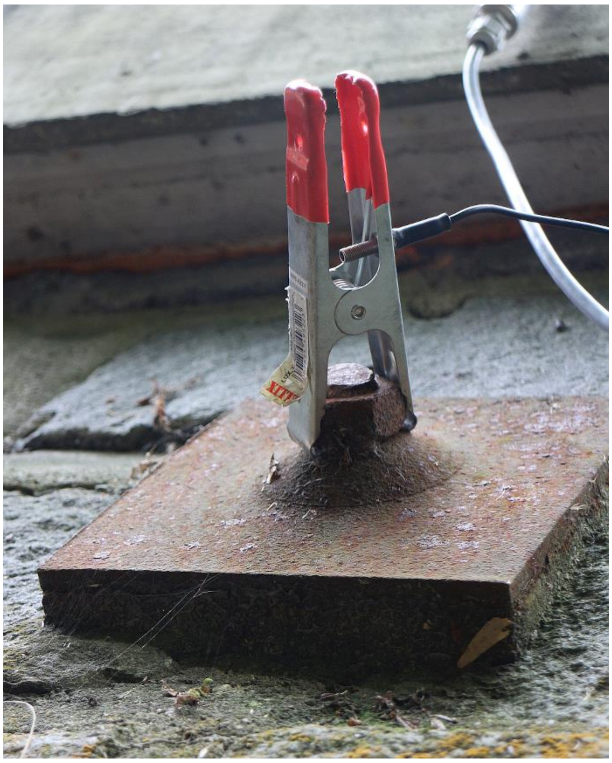


Figure 8. Connecting legacy anchor head for geoelectrical survey using a contact pincer.

The next step is the compilation of a control file – which is literally the chain of command which anchor is measured against its neighbors. Thus, the geoelectrical equipment is prepared allowing all four-point permutations to be measured. The actual measuring program will include the data collection from, all three geoelectrical methods (RES, IP, SP).

After an initial check of the contact resistivity – to control if all contact devices are well connected to the free end of the tendon – the survey is triggered and left unattended for a considerable time (4-8 hours). Prevailing field safety routines (*electro pathological risk while using input voltages up to 400 V!*) remain reinforced at all times. When the survey is terminated, and after performing a first rough quality test on the raw data, all electrodes are dismantled and collected from the site. **Equipment:** The deployed equipment (cables, electrodes, central processing / steering unit) is standard geophysical equipment and available from various suppliers as off-the-shelf-products.

Figure 9. Force-fitted installation of the accelerator sensor to conduct acoustic logging measurements.

If decided (*and financed*), the team will return to the respective site to conduct planned acoustic logging / seismic measurements. The accelerator sensor will be force-fitted to the anchor head, Fig. 9. A sharpened chisel (point source!) is placed on the anchor plate and very careful tapped with a small upholsterer hammer (hammerhead 200 g), Fig. 10.

Figure 10. Conduct of acoustic logging measurements.

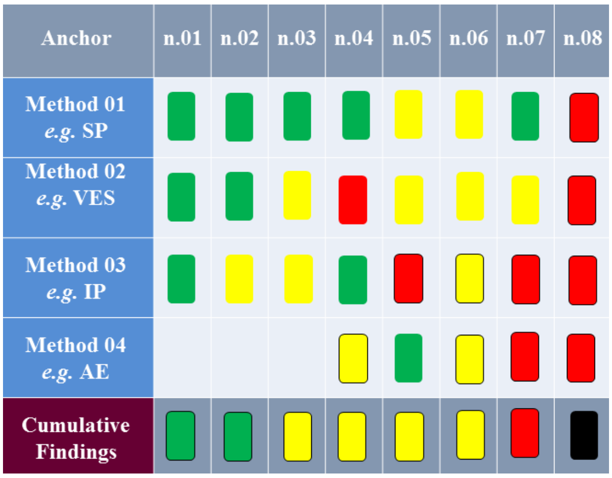
The signal is recorded using standard seismic gear and unprocessed data stored on a field laptop. Depending on accessibility of the anchor, one measurement, including an initial visual control of collected field data, will take around 30 minutes. **Equipment:** Available units and items, *e.g.* from commercial wireline logging equipment producers – need to be tailored to the specific needs of the foreseen monitoring activities; **Processing:** Geoelectric pseudosections and seismic raw data are processed following state-of-art standards in applied near surface geophysics.

5. Results

The jointly interpreted geophysical results (IP, SP, RES, and AE) lead to a categorizing / determination of risk classes. To ease communication, the categories have been defined following a three traffic light color scheme with a fourth color indicating urgent and immediate response (time scale for public administrations). The risk classes associate with monitoring periods are

greeen class	every 10 to 15 years
yellow class	every 5 to 10 years
red class	every 2 – 5 years
black class	compulsory fast response in less than two years

The individual findings derived from the four geophysical measurements are color coded and according to an overall interpretation scheme, Fig. 11, merged into one total finding. Only the final result is reported to the client.



Anchor	n.01	n.02	n.03	n.04	n.05	n.06	n.07	n.08
Method 01 *e.g.* **SP**	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟥
Method 02 *e.g.* **VES**	🟩	🟩	🟨	🟥	🟨	🟨	🟨	🟥
Method 03 *e.g.* **IP**	🟩	🟨	🟨	🟩	🟥	🟨	🟥	🟥
Method 04 *e.g.* **AE**				🟨	🟩	🟨	🟥	🟥
Cumulative Findings	🟩	🟩	🟨	🟨	🟨	🟨	🟥	⬛

Figure 11. Color scheme according to defined risk classes mearging into one cumulative / final result.

5.1. Geoelectrics - reference site

The reference site has been chosen by the client with thoughtfulness – all five anchors were placed shortly before the geophysical survey by a contractor known for its high reputation in workmanship and quality. The geological situation is a crystalline outcrop of the Bohemian massive. The site exposes non weathered rock with some water from imbibition. Anchors were easy accessible.

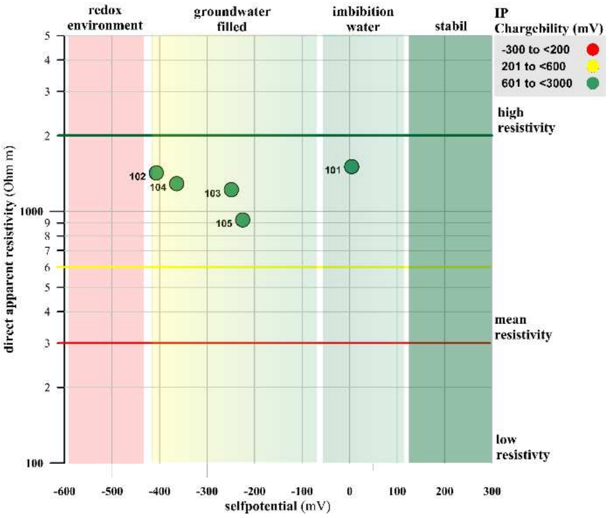


Figure 12. Comprehensive display of three geoelectrical results following geophysical standards (IP, RES, SP) – *here:* reference site 1 - 5 newly placed anchors

The geoelectrical data are represented in one x / y system, with the abscissa showing self-potential values and the ordinate showing direct apparent resistivity values. The IP data are categorized in three different chargeability classes and plotted as color fills. Typically, a geophysical drawing merges all three geoelectrical findings (SP, IP, RES) into one single plot, Fig. 12. This graphical representation is suitable for databank inputs, statistical treatments, and more complex re-processing work. However, it is found that communicating to laymen the phenomena of direct apparent earth resistivity and its dependency from groundwater mineralization plotted along a logarithmic scaled axis is an additional task on-top of the standard result communication. Following experience of everyday life " *... No one cares about geophysics unless it can solve geotechnical problems...*" a more generalized graphic transporting concise and meaningful key-information for executive decision makers outside the field of geophysics / geoscience is deemed necessary. Under standard circumstances, IP and RES values are opposing effects and direct apparent resistivity values strongly depend on the geological theaters of an anchorage site. Secondly, as the main effect of anchor failures is corrosion – understood as a specific electrochemical process - only SP and IP react sharply on ion-movements. Hence, the generalization concept skips RES findings and displays only categorized IP / SP ratios, Fig. 13.

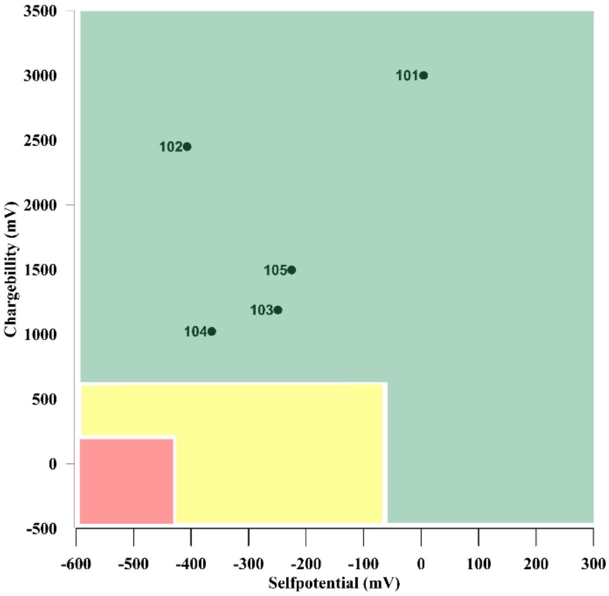


Figure 13. Executive / foremen display of two geoelectrical results (SP, IP) – *here:* reference site 1 - 5 newly placed anchors. *Note* risk categories and derived recommended observation intervals - green: 10 to 15 years; yellow: 5 to 10 years; red: 2 to 5 years.

As predictable for a new site, all anchors have high positive IP chargeability and SP values fare off the REDOX potential. As such, all five anchors are placed in a corrosion stable environment and are categorized with a "green" signal. As the geoelectrical survey generated three entries into the "green" risk categories, an additional AE survey is not necessary to complement or refine the geoelectrical findings. The reported result for the executive decision makers encompassed the recommendation to repeat a geophysical assessment in 10 to 15 years.

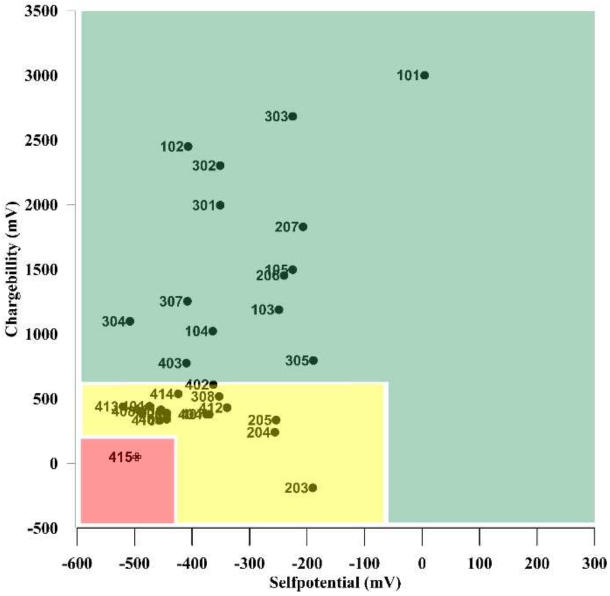


Figure 14. Executive / foremen display of two geoelectrical results (SP, IP) – *here:* merged plot of 32 anchors from reference site 1 and sites 2, 3, and 4. *Note* risk categories and derived recommended observation intervals - green: 10 to 15 years; yellow: 5 to 10 years; red: 2 to 5 years.

5.2. Geoelectrics - all sites

Displaying all 32 geoelectrical results from the anchor investigations in one scatter plot creates a high-level. planning tool for upcoming workforce- / budgetary predictions, Fig. 14. A senior manager will read that 43% of the examined anchors will not need any attention in the next 10+ years (green zone). Nearly the other half of the anchors will need some re-examination within the coming 5 to 10 years. One anchor, namely # 415, centers in the red sector – here some attention is necessary within the near future (2+ years). The attention scheme maybe either to launch an AE survey during the next year or to place a second supporting anchor into the close vicinity of this specimen. The money saving potential of this plot is the long lead-time to place orders and/or to piggyback the additional support of #415 during a future campaign in the same area. Anchor #203 in the yellow sector appears suspicious, having a medium low SP value and a very low IP chargeability. This can be interpreted as a direct contact between the tendon steel and the surrounding imbibition water but with hardly any on-going corrosion process. **Perspective from Geophysics:** This electrochemical inconsistency needs either further attention by conducting an AE survey or just a blunt replacement of the specimen.

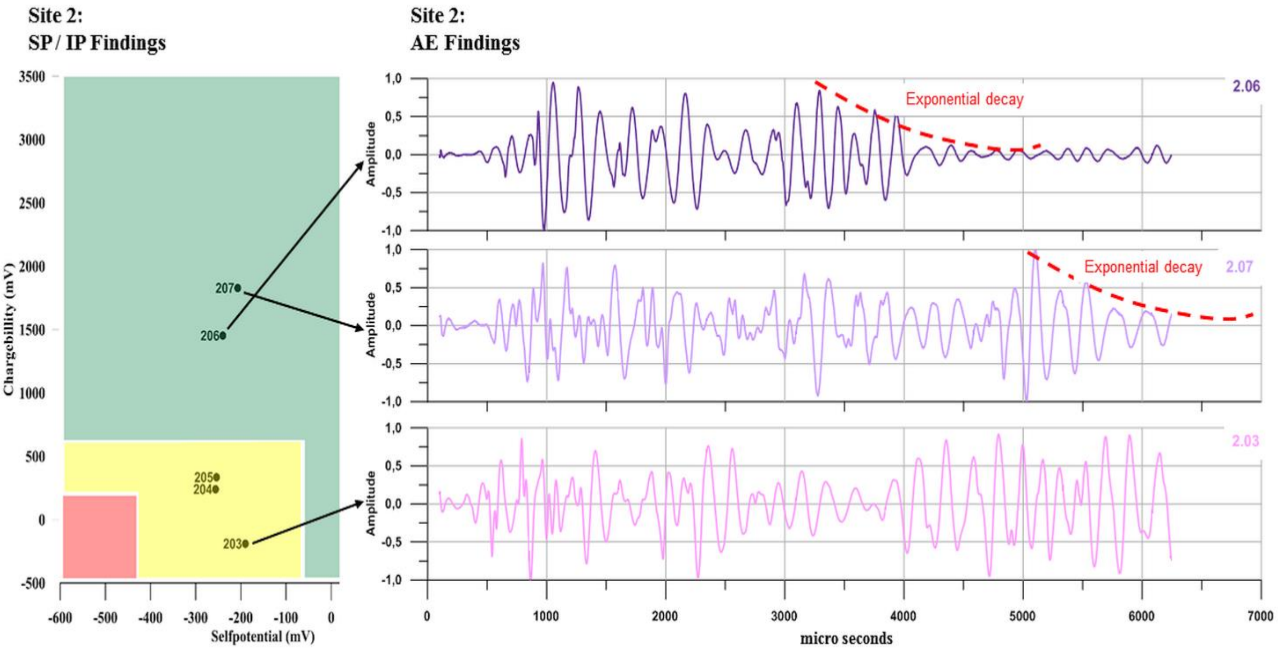


Figure 15. Correlation of geoelectrical findings (SP, IP) with acoustic logging results in the time domain - Example drawn from site 2: Note the exponential decay for the two "healthy" / well bonded anchors 206 and 207. The seismology known effect of **ringing** – *hereby* wave energy is trapped in the anchor body and cannot easily emit into the geological near-space - is observable in the high resolution seismogram of anchor 2.03 after 4000 µs.

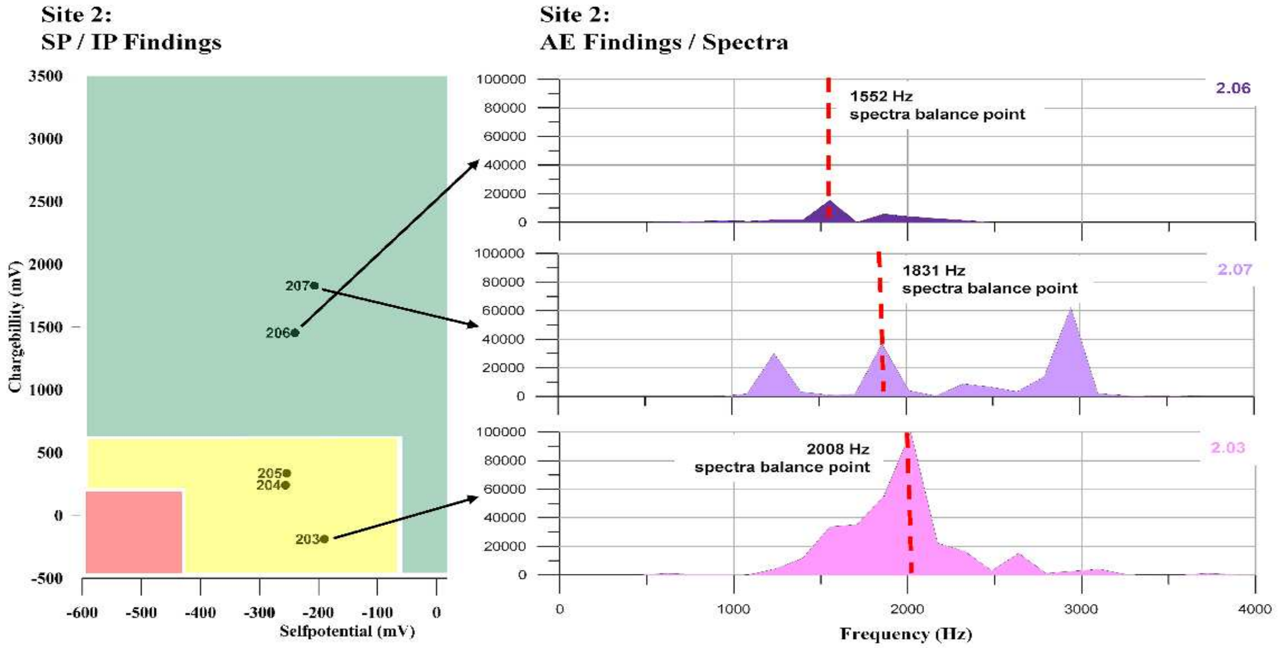


Figure 16. Correlation of geoelectrical findings (SP, IP) with acoustic logging spectra - Example drawn from site 2: Note the "smaller" spectral balance points of the two "healthy" / well bonded anchors 206 and 207. The spectra of these two anchors are characterized by secondary maxima. Anchor 203 - with bonding deficits - is not embedded fully force-fitted into the geological near space: The spectral balance point shifted towards a higher frequency (2008 Hz) and the spectra is dominated by one main maximum and two asymmetric subsidiary maxima on the higher frequency side.

5.3. Acoustic emission – example site

As construction details for legacy anchorages are unknown, it is not possible to determine the absolute damping constant of an anchor for deriving its in-situ grout / coupling quality. However, it is possible to compare the relative changes of damping characteristics of the specimen of an anchorage cluster against a reference anchor. The reference anchor should be the "*healthiest*" / least degraded specimen of an anchor ensemble. Taking indications from the geoelectric surveys (IP, SP), the reference anchor is easy selectable. As such, geoelectrics serves as a pre-selection *and/or* piloting method to judge the individual anchor quality of one anchorage site.

As example, the geoelectrical results from the second site of this project are used to clarify the selection process, Fig. 15 & 16: On site 2 five anchors, namely #203 to #207, have been investigated using geoelectrics. Two anchors, # 206 and #207, show very robust results. The already discussed anchor # 203 has a suspicious geoelectrical result and is earmarked for an acoustic investigation. Consequently, anchors #206 and #207 are selected as least degraded reference anchors to allow a comparison with the suspicious, more degraded anchor # 203.

The acoustic emission results of anchors #206 shows an exponential amplitude decay of the standardized seismic signal around 3400 µs. Anchor #207 appears similar – a first exponential amplitude decay is observable at an equal time window. A second and more pronounced decay the reverberated amplitudes occurs after 5000 µs. Shifting these data from time domain to frequency domain, positions of spectra balance points are between 1550 Hz and 1830 Hz. Both spectra balance points and both amplitude decay characteristics are defined as reference for this particular anchorage site, *again* Fig. 15 and Fig. 16.

Anchor #203 had suspicious geoelectrical results – hence it is compared against the two reference anchors. The acoustic signal has no noticeable decay characteristics of the standardized amplitudes. This observation is in line with the finding from [28, 29], as the bad mechanical coupling traps the energy in the anchor / grout system and allows the wave train to be reflected back and forth. The chaotic distribution of the standardized amplitudes and their swelling between 4800 µs and 5900 µs is explainable with the superposition of the echoes waves. As predicted, the bad mechanical coupling of anchor #203 with the surrounding geology *namely:* a deficit in functionality – traps the high energy content of the wave and consequently shifts the spectra balance point into higher frequency ranges. The frequency difference between a full functional and reduced-functional anchor is in the range of + 200 Hz. The reported result for anchor #203 would include a recommendation to reexamine this specimen within the next two years. A coarser but financially more viable situation would be the placement of an additional supporting anchor close to anchor #203 within the next two vegetation periods.

5.4. Final results – example site

Following the categorization principle to merge two results from geophysics into one actionable recommendation for the staff of the road department is the last step in the processing sequence. Being aware that the communication of quite abstract geophysical results across different staff groups and departments may raise misunderstandings, a simplified generalized way of representing geophysical findings is compulsory. One way to communicate the final product to on-site operations is given with Fig. 17: One digital photography of the particular site annotated with the anchor numbers in place, here site 2 with the anchors 203 to 207, overlaid with graphical summary of the detailed geophysical results and one final recommendation for every anchor deemed to be the best possibility.

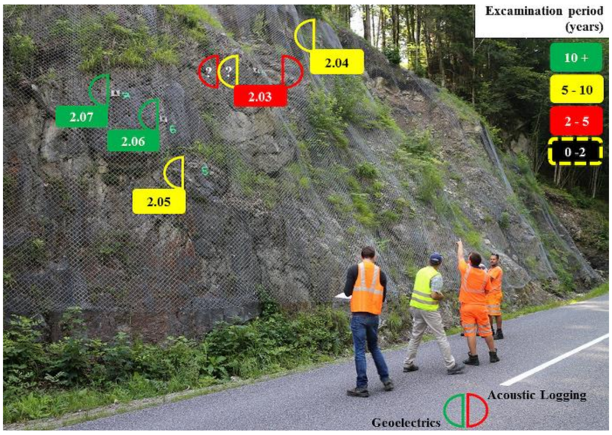


Figure 17. Concise representation of geophysical end results – Example drawn from site 2: To ease communication with executives / foremen four geophysical detail results (SP, IP, RES, and AE) have been generalized showing that only anchor #203 will need some quick attention within the next 2 -5 years.

6. Implementation strategy

The geophysical survey strategy follows the principle that effort and financial inputs correlate with reached information depth and error margin minimization. Hence, the following sequential work phase is derive from the geophysical programme:

- **Phase 1**
  Geoelectric fieldworks
  The site to be examined is cabled with the geoelectrical system and from all anchors the SP / RES / IP values are determined;

- **Phase 2**
  Partial processing & interpretation
  From collected geoelectrical data only the SP and the IP values are processed. SP and IP values are plotted as Cartesian scatter plot and roughly interpreted. Results will have relative error margins between ± 10% to ± 15%. After some training this phase can be accomplished by internal staff on foreman- / field

assistant level. Anchors falling into the black / rotten class are replaced or supported by second anchor immediately;

- **Phase 3**
  Extended processing and interpretation
  In addition to the already processed IP and SP values, the RES raw data will be inverted into direct apparent resistivity and all three geoelectrical finding will be plotted in one categorized scatter plot allowing a comprehensive interpretation scheme. End results will have relative error margins between ± 5% to ± 10%. To accomplish this phase, training of internal staff must be more comprehensive and work needs to be performed by junior engineering personnel;
- **Phase 4**
  Planning anchor replacements
  All identified anchors in the black and red risk class will be replaced or secondary supporting anchors will be placed in the vicinity of the "*red & black*" individual anchor specimen accepting an error margin / false decision / financial tolerance between ± 5% to ± 10 %;
- **Phase 5**
  Acoustical logging
  In case the above mentioned false decision tolerance is not acceptable (*e.g.* very high safety standards, anchorage positions above primary roads with high traffic density, strategic infrastructure and/or higher impact on available maintenance budget) all "red" specimen as well as anchors with inconsistent geoelectrical detail findings will have a follow-up examination with acoustical logging. The comprehensive anchor assessment will be derived from four independent geophysical parameter (SP, RES, IP, and AE) and the resulting error margin will be approx. ± 2 %. Fieldwork, data processing, and interpretation is more labourious than the geoelectrical measurements and belong into the hands of trained senior geophysicists (professional experience anticipated 10+ years).

7. Perspectives

The authors are aware that operational / scientific findings based on 32 field anchors (as well as foregoing intensive lab experiments) are easily challengeable. As such, the proposed clustered geophysical non-destructive measuring methods are understood as an initial, but functional concept, which needs to be broadened by more fieldwork. However, further operational refinements already opened after the successful accomplishment of the four case studies, *namely*

- **Geoelectrics**
  As a fourth method *mise-à-la-masse* measurements can performed – hereby the anchor is used as an "*electric bollard*" illuminating the anchorage field. Initial field experiments developed promising;
- **Acoustic logging**
  Instead of using a small hammer a standardized seismic source either with clear defined excitation frequencies or with a frequency sweeping capacity may ease resolution and interpretation;

8. Rationalizing a myth

By tapping the anchor head with a hammer the mechanical wave package runs through the steel tendon, reaches the grouted end-plate and is back-reflected to the head. By recording the interval transit time of the impulse, and assuming a material constant of 5100 m s^{-1} for the wave velocity of steel, the length of the tendon is calculated. This is an easy to understand, well accepted, wrong method.

It remains unclear for the laymen how the length of a cemented steel bar is associated with the overall functionality of an anchor. An **analogous example** from everyday life will highlight this lack of understanding – after measuring the length of a car (bumper to bumper, in meters) nobody would expect to get a vehicle inspection sticker for two years proving that the motorcar meets road safety and emission standards.

In case of the anchorages, physics is more complicated than currently anticipated by construction industries. First, the acoustic logging showed, that a mechanical impact on the head triggers all sorts of waves (S, P, rotational wave, split waves) which have a different propagation velocities. **Second**, a wave package – unless it has frequencies well above 8000 Hz – will not travel in the center of steel tendon alone but along the boundaries of the anchor body (steal, rust mantle, grout, drilling fractured and fissured geology) and will depend on petrophysical realities (moisture content of the system and near field, and rock anisotropies), which reduces the anticipated mono-velocity of steel considerably. **Third**, as the waves spread by frequency dependent dispersion, not the first arrival of the phase velocity but the center of the wave group velocity needs to be recorded. **Fourth,** if the tendon is bent and deformed reducing its functionality, the wave package will not "see" the curves of the tendon. **Fifth** – not the first break but the time between the relevant zero-crossings (*phase neutral measurements*) needs to be determined.

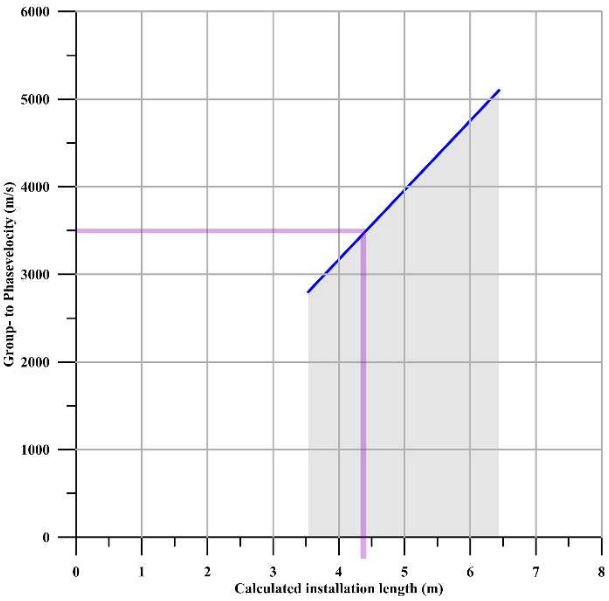


Figure 18. Concise representation of geophysical end results – Example drawn from site 2, anchor 206: Dependency of calculated installation risk from two-way transit time measurements – anticipated in-situ installation length of placed steel tendon varies with group- or phase velocity. In a sense of pure physics, all tendon lengths between 3.5 meter and 6.4 meter are scientific correct. For anchor 206 an advanced signal analysis of two phase neutral measurements *most likely* indicate a steel bar length of 4.4 meters.

In an initial lab-controlled experiment the group velocity in one 2 m long sample of tendon steel (collected from the main contractor doing most of the anchor placing in this part of Austria) was determined. Hence, in the four treated case studies during this pilot campaign, the observed group velocity of waves in this particular type of tendon steel averaged between 2800 ms^{-1} to 3500 ms^{-1}, hence 54% to 70% of the "pure" phase velocity in pure steel (5100 $m\ s^{-1}$). These findings visualize for anchor 206 the following situation: If phase and group velocity are mixed and/or not properly determined, the legal justifiable length ranges between 3.5 m and 6.4 m, Fig. 18. **Refined analogous example:** The length of the car (bumper to bumper) is determined with a rubber band having unclear linear dimensions (centimeters, inches, cubit, span);

Geophysical finding: Determining an average group velocity of 3500 ms^{-1} and measuring the time difference between two phase neutral measurements on unfiltered raw data gives a length between 4.25 meters and 4.57 meters for the tendon of anchor 2.6, *cf.* purple highlighted coordinates in Fig. 18.

9. Leap into Life

The geoelectrical methods satisfied prerequisites concerning time, work, and field efforts – connecting the electrodes to the anchors in the escarpments and the demounting took less than two hours per site. The measurement was triggered – and allowing for sufficient accuracy (excitation time for IP, stacking of RES values) – the actual survey time took about four hours. As with any geoelectrical measurement, as soon as the steering file is programmed, connectivity to the electrodes tested, and the actual raw data collection triggered, the actual survey continues unattended *(only caution for electropathological effects is needed!*). Consequently, field work satisfied the contracting body. The great potential of automating the data processing was identified during post-campaign discussions. The acoustic measurements were – as foreseen and predicted – more challenging and cumbersome: Especially as traffic noise adds to error margins and processing and interpretation needs finesse.

Finally, the presented strategy of combining various geophysical techniques with statistics and linking to categorizations was not convincing to the contracting body and did neither hit implementation nor further pilot operations: *Too complex, doubts about the legal quality of new techniques, too little accuracy, attributes need to be sharply defined, results too abstract, additional burden of ground truthing during ramp up phase* – the well-known canon in commercial applied geophysics. As a result, verification measures were abandoned and cooperation sieged.

This is well in line with analytical observations done by the Economist [37]: Building is an an industry that raises prices for clients / tax payers and mostly ignores tools that might improve productivity. "*While we are all using iPhones, construction is still in the Walkman phase*".

Refining the experience of everyday life quoted the chapter 5.1 finally reads " *... No one cares about geophysics, even it solves geotechnical problems...*".

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