INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 6th International Conference on Geotechnical and Geophysical Site Characterization and was edited by Tamás Huszák, András Mahler and Edina Koch. The conference was originally scheduled to be held in Budapest, Hungary in 2020, but due to the COVID-19 pandemic, it was held online from September 26th to September 29th 2021.

P- and S-Wave Hybridseismics: Non-Destructive Geotechnical Site Characterizations Using State-Of-Science Surface Geophysics

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ABSTRACT: Geophysical ground investigations are not a substitute for boring and direct physical testing. Rather it complements a well-planned, cost-effective drilling, sampling and testing program. Geophysics, among the methods hybrid seismic, provide a continuous image of the subsurface rather than CPT point measurements. No one cares about geophysics unless it solves geological / geotechnical problems and saves resources: High resolution seismics is a legacy problem solver for the civil engineer community. Since 2000 hybridseismics - a simultaneously conduct of refraction- and reflection seismics followed by an intermeshed data processing scheme – represents the royal league of geophysical methods supporting site investigations. Hereby the underground is dual scanned by seismic waves revealing horizontal and vertical strata structures and rock velocity distributions hinting geotechnical unforeseen features in the underground. Hybridseismics works equally well with both body wave motions (compressional- and shear waves). Quality of results are achieved if field acquisition parameter harmonize with adequate near surface tuned data processing sequences (reciprocal velocity calibration, congruency between event location and anomaly shape). Consequently, subjective initial assumptions of geological start models inherent for seismic standard inversion modelling is omitted. By applying both wave types in one survey, spatial in-situ distributions of YOUNG-modulus and POISSON ratios reveal from hybrid seismic campaigns.

As it is difficult for a non-geophysicist to distinguish between 'authentic', 'sequential processed hybridseismics', and 'Hybrid Refraction-Reflection Seismic Method', a competitive contractor market offers all three for result oriented and problem solving geo-engineers. Standard procurement procedures (low-price policy versus economically most advantageous tender) allow performance ambiguities not assisting differentiation of geophysical contractors and offers.

This article will help to clarify advantages of 'authentic' hybridseismics as a non-destructive, least invasive, repeatable, in-situ mapping method for geogenic structures supporting acting civil engineers in endeavors and challenges of on-site investigations. Focused examples from geotechnical engineering of dams are shown.

Keywords: geophysics, geoengineering, hybridseismics, site-investigation, non-destructive

1. Significance of method

1.1. Term designation

The keyword hybridseismics is neither brand protected nor unambiguous. In recent geotechnical / -scientific literature the term is used many times over for:

Engineering structures & earthquakes: A family of coupled physical–computational simulations of seismic response, in which a part of the structural behavior is tested physically whilst other terms are modelled numerically. This definition includes pseudodynamic (PsD) testing (with or without sub structuring) and real-time hybrid tests (RTHT), [1];

Controlling bridge work: Hybrid strategy combining passive and semi-active control systems for seismic protection of cable-stayed bridges, [2] and [3];

Hydrocarbon Exploration: Deep ranging oil / gas exploration deploys this method to reduce expensive computer processing time for seismic imaging by combining different software performance tools [4], but also to describe a complex processing sequence to gain more information from deep-water hydrocarbon explorations [5], and a hybrid processing scheme for the denoising of industrial seismic mass data [6];

Geophysical field operations: A mix of cabled and non-cabled / wireless systems in the field during large seismic data acquisition campaigns;

As all above listed applications have minor relevance for commercial implemented civil construction endeavors, an ISC'6 relevant delimitation follows:

Site-investigations *and* **geotechnical / geological reconnaissance:** Engineering geophysics offers an advanced high resolution seismic strategy adjusted to a depth range less than 500 m by combining reflective and refractory responses from underlain geostrata; In 2000 the term was first coined by [7] and since found entry into the geotechnical / geophysical theatre [8] and into (*german language*) reference books, [9, 10]. The capacity for high resolution mappings of engineering geological relevant underground disturbances (voids, bedding faults, weathering zones, and karst) and non-destructive in-situ determination of soil engineering pertinent parameter (POISSON, rock quality [11], and anisotropy) label authentic hybrid seismics as *swissness* under the umbrella brand of geophysical methods for geotechnical engineering and engineering geology.

1.2. *The Good, the Bad and the Ugly*

Between July and September 2006 members of the British Federation of Piling Specialists were invited to complete a questionnaire designed to evaluate the adequacy of site investigation information received for piling and specialist geotechnical contracts, [12]. Respondents were asked to comment on the provision of geophysical investigations. They were undertaken on only 19 out of 221 projects (*8.5 % sigh!*) reported, and were considered to be of little use in 74% of cases. Whatever the merits of geophysical investigation techniques, their popularity in terms of provision and acceptance by those who design geotechnical products appears limited. There is no doubt that geophysical techniques have not gained as wide an acceptance in the field of civil engineering as their potential would permit. What are the reason for this blow below the belt of geophysicists? The authors believe in three external driving reasons and some self-inflicting mistakes within the geophysical community:

Stepchild site investigation: The basket of ignorance: existing inadequate awareness for importance of ground investigations, inadequate financing or focusing of resources, insufficient time and a lack of geotechnical expertise. These shortcomings lead routinely to poor planning and design, lousy execution, false interpretation and misleading communication in site investigation practice. Additional delays and costs do result, [13]. As well documented in 25+ publications dealing with forensic geotechnics and cost overruns, *e.g.* [14, 15], only 0.5 to 1.55 % of capital costs of a construction projects flows into site investigation. Amounts for art on the building are usually in the range of 1%. Capital fractions reserved of site investigations become even more distorted following findings from [16] – and lifetime building costs, commonly 25 years, are set to 100%. Under this scope site investigation costs represent 0.056 ‰. The market for site investigations is utterly underfinanced because it is not perceived as pivotal for building owners / awarding authorities / public hand. Manifold documented and statistical supported, inadequate site investigation contribute with 21% to the causes of time- and budget overruns. Already in 1994 a warning was communicated by [13] " *…Now, and in the future, it is vital that financial decision-makers appreciate that you pay for a site investigation whether you have one or not, and you are likely to pay considerably more if you do not, or if it is inadequately designed, executed or interpreted…*" Consequently, geotechnical geophysics – *especially hybrid seismics* – is fobbed with fractionated leftover crumps from the remaining 0.056 ‰ of capital costs.

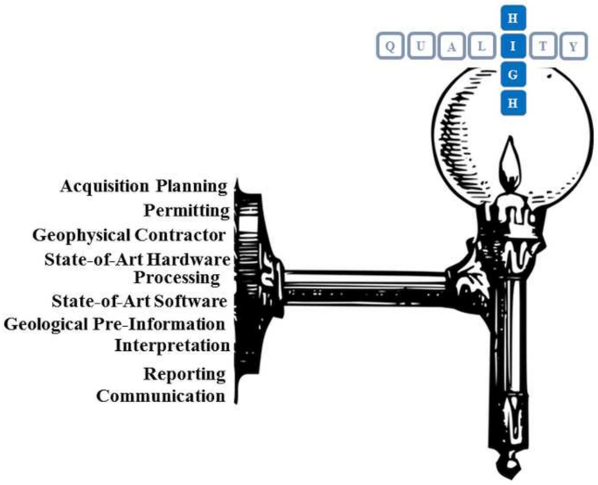

Figure 1. Hybridseismics: Quality constraining input parameter
Every work step of a seismic operation contributes as multiplication to the final quality product; redrawn on concept from [17]

Underestimated complexity: To proper design a geophysical - *especially hybrid seismic* - campaign will only work if all survey parameter are wisely chosen, dovetailed, and real-time quality controlled. Only then, a geophysical survey - *especially hybrid seismic* - becomes successful and delivers – *respecting applicability and limitations of geophysical methods most likely some minor curtailments* – the expected and implementable result. The purchaser will be placed in the bright light of high quality, *cf.* Fig. 1. This sub-process is outside of laymen / non-geophysicists capacity. The current (wrong) counterstrategy from geotechnical entities – *let's copy the last tender documents from legacy tender invitation again, again, and again:* Would anybody use a recipe for Breton fish soup to grill his Angus sirloin?

Procurement - cost minimizing but not quality / performance maximizing: Specifications often are written by engineers, their assistants or by commercial trained procurement staff who have little or no understanding of the "*whys*" and "*wherefores*" of geology and geophysics. The wrong technique is sometimes specified and a rigid tender submission style called for, usually utilizing an inappropriate Bill of Quantities to "measure" the amount of field work done. By just reducing during field acquisitions one single parameter (*e.g.* cover of fold, geophone spacing, shot distance, receiver spread, and profile lengths) an initial offered price will dump up to 50% but producing voodoo results populating the dark side of geophysics. As being outside of any yardstick, these are not useable for the end-customer nor for an impact on the project. Hence, why ordering for an extravagant gala concert four professional violinists with their Stradivari's (price tag approx. 0.1% from overall costs for a fabulous celebration), when a street musician with a rusted jaws harp plays the same waltz – *music is music and the listening pleasure and the show will be unforgettable!*

Poor result delivery: inadequate and/or bad planning of the survey; incorrect choice or specification of technique, insufficiently experienced personnel conducting and interpreting hybridseismic investigations, thwarting quality by populating underprizing tender stages;

In this paper, the authors aim to describe steps that are undertaken in planning an authentic hybrid seismic survey, highlight some considerations leading finally to a high quality, and delivery of usable and legally enforceable results to the geotechnical engineering community.

2. Site investigation, physics, and geophysics

2.1. *Body wave types*

For geotechnical geophysics two body waves out of four seismic wave types [17, 18] dominate shallow exploration campaigns, the P-wave and S-wave:

P-Wave: An elastic body wave in which particle motion is in the direction of propagation. The type of seismic waves assumed in conventional seismic exploration. Also called primary - / compressional -, longitudinal wave. P-waves are generated with standard vertical seismic sources – e.g. hitting the ground surface with a sledgehammer or using an accelerated drop weight; In isotropic homogeneous solids, the P-wave velocity V_P expresses in terms of elastic constants (Lame constant, Young's modulus, and Poisson's ratio) and rock density. The P-wave propagates as fastest wave through the rock material. Because of the large variations in P-wave velocities caused by porosity, permeability, fluid saturation, and confining pressure, P-wave velocity alone is not adequate to characterize the lithology and rigidity of a rock / soil column unambiguously. As V_P is usually measured more accurately than the other wave components (V_S, Rayleigh, Love), it is tempting to use Eq. 01 with E_D = dynamic Young modulus, ρ = in-situ density, $\mu_{D\ \mathrm{assumed}}$ = assumed Poisson ratio, V_P = compressional rock wave velocity:

$$E_D \approx \rho\,(V_P)^2\,\frac{(1+\mu_{D\,assumed})\,(1-2\mu_{D\,assumed})}{(1-\mu_{D\,assumed})} \qquad \text{Eq. (01)}$$

This may provide reasonably accurate values, [19], for strong, dry, massive, unweathered rock masses, where Vp is in excess of 3000 m s^{-1} and Poisson's ratio is expected to be between 0.1 and 0.2. However, where the rock mass is composed of weaker rock types, or has relatively low Vp values because of weathering, alteration or fracturing, Poisson's ratio will probably be within the range 0.2 to 0.4 and should be measured. To assume a value of 0.25 for μ_D, when the actual value is 0.4, would produce an error of + 80% in Eq. (01). Therefore, the measurement of both, Vp and Vs is recommended in cases where accurate values of Young's modulus are required by the geotechnical engineer. Below the water table, Vp should never be used without corresponding values of Vs to determine dynamic elastic moduli. In general the compressional wave velocity of the ground will increase with increasing moisture content.

Figure 2. Shear wave source
A square-shaped timber coupled to the ground and a 8 Kg sledgehammer impacts the end-grained side;

S-Wave: Shear-wave measurements appear to be more suitable for engineering purposes than compressional-wave surveys: The S-wave is a body wave in which the particle motion is perpendicular to the direction of propagation. Shear stress in a rock/soil column does not cause a change in the particle dimension or its volume; instead, it causes a change in the particle shape. The more the soil or rock column resists the shear stress, the higher the shear-wave velocity. The velocity of shear waves V_s is slower than the velocity of P-Waves. As a rule of thumb, V_s is between 40% and 60% of V_p. As the resolution is frequency dependent, the slower "*travelling*" of shear waves provides a better resolution. However the dominant frequency of shear-wave data is generally lower than that of compressional-wave data, which compensates for the fact that shear-wave velocities are lower than compressional-wave velocities in the same formations. In order to obtain the same resolution with P-waves, energy of very high dominant frequency has to be generated, with correspondingly greater attenuation in the subsurface.

Shear-wave velocities in alluvial, diluvial, and Tertiary layers correlate better with standard penetration test values (N-values) than compressional-wave velocities. Shear waves are absorbed less than compressional waves in partially saturated sands, boulder clay and gas-saturated sediments, with consequent improved transmission through these rock. When the ground is subject to dynamic loading, the shear modulus μ is required by the geotechnical engineer. This parameter is calculated directly from the shear-wave velocity, shown in Eq. (02) with Vs = shear wave velocity, μ = shear modulus, and ρ = in-situ density.

$$V_S = \sqrt{\frac{\mu}{\rho}} \qquad \text{Eq. (02)}$$

The shear modulus is required to assess the response of the ground to earthquake loading where geological faults are present, for the design of foundations for reciprocating machines, and when considerations have to be given to the possibility of destructive resonance effects, [20]. A shear-wave is generated from a horizontal seismic source: Anchoring with soil nails a wooden bar into the ground and hitting the grain-cut timber horizontal with a sledgehammer, Fig. 2. To register shear waves, vibration sensors with a pure horizontal sensitivity are necessary, *namely* shear wave geophones.

Two other types of seismic waves utilized in geotechnical geophysics, LOVE- and RAYLEIGH surface waves and their utilization in geotechnical engineering, are not subject of this publication.

2.2. V_p / V_s ratio

The POISSON's ratio (μ) of near-surface materials is one of the key parameters for geotechnical projects. It is broadly associated with the integrity of the materials from the geoengineering perspectives, [21]. The Poisson's parameter depends on the ratio of the S-wave – and P-wave, Eq. (03) with E_D = dynamic YOUNG modulus, ρ = in-situ density, V_P = rock compressional wave velocity *and* V_S = rock shear wave velocity:

$$E_D = \rho\, V_S{}^2\, \frac{3\left(\frac{V_P}{V_S}\right)^2 - 4}{\left(\frac{V_P}{V_S}\right)^2 - 1} \qquad \text{Eq (03)}$$

In addition, there is an discrete correspondence, [22], between the ratio from incompressibility (bulk modulus: K) and shear modulus (μ) versus V_p/V_s ratio, Fig. 3.

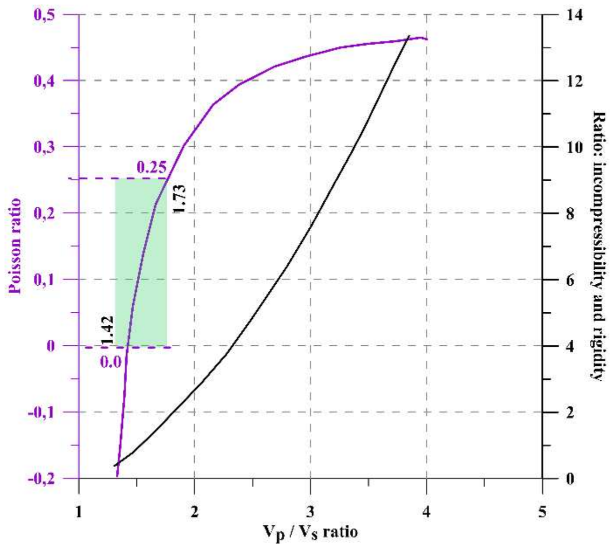

Figure 3. Relation between the velocity ratio V_P/V_S, and two other parameters, POISSON's ratio and K/ρ (the ratio of incompressibility and rigidity). Note the relatively linear relation between V_P/V_S and K/ POISSON's ratio especially for larger values of V_P/V_S and the **geotechnical sweet spot** for preferably foundations works, *after* [22];

Please note, that a V_p/V_s ratio around √3 = 1.72 equivalents to a POISSON modulus of 0.25, which is associated with dry, undisturbed, force fit geology favorable for foundation settings. A V_p/V_s ratio smaller √2 = 1.42 correlates to a negative POISSON's ratio, found only in anisotropic material, [23]**.** A hidden message in Fig 03- the green colored area stretched between the coordinates {0.0, 1.41} and {0.25, 1.72} represents a geotechnical sweet spot very favorable for geoengineering foundation works. Therefore, a seismic section showing the two-dimensional distribution of POISSON's values represents an invaluable element for foundation planning, CPT sample point coordination, drilling tenders, excavation costs, and for a quick impression of an investigated construction site, thus reducing financial risk appetites to anorexia.

2.3. Methods

Body-wave propagation gives rise to diffraction, reflection and refraction phenomena:

Diffraction is a wave phenomenon associated with energy that radiates outward from a sharp discontinuity in the subsurface.

Refraction Survey is the wave phenomenon associated with the fraction of incident-wave energy transmitted into the next (deeper) layer. The distance between seismic source and the receivers is larger than for reflection surveys and consequently, need for stronger seismic sources to excite the ground and to remain within a suitable signal/noise ratio. Travel paths in refraction work is mainly **horizontal**. Measured Parameter: Travel times of refracted seismic energy (p- or s wave). Physical Properties: Acoustic velocity (function of elastic moduli and density). Geotechnical Application**:** Acoustic velocity–depth model often with interpreted layer boundaries. Advantages are equipment more low-cost range, low number of channels (24, 48, 96, …), larger geophone distance (up to 6 m), processing and interpretation relative simple, integral picture of in-situ velocities, high day productivity, and relative low price tag. Disadvantages combine from wide spreads necessary (*approx. six times target depth),* geology must be strata bound, subjacent to increase of rock velocities with depth, low resolution, geological details may be lost, thin embedded layers may be missed, no information below shot point available, and a need for an energy-rich seismic source (> 500 m line spreads: accelerated drop weight).

Reflection Survey is the wave phenomenon associated with the fraction of incident-wave energy returned from an interface that separates two layers with different elastic moduli. The distance between the seismic source and the receivers (geophones) is relative small. In reflection work, the seismic waves predominately travel along **vertical** ray paths. Measured Parameter: Travel times and amplitudes of reflected seismic energy (P- or S-wave). Physical Properties**:** Density and acoustic velocity (acoustic velocity is a function of elastic moduli and density). Geotechnical Application: Acoustic velocity–depth model often with interpreted layer boundaries. Advantages are high vertical resolution, compact field geometry (approx. two times target depth), high information density, relatively weak seismic source (*e.g.* 8 Kg sledgehammer). Disadvantages combine from a higher operational complexity, small spreads but high channel numbers (196, 256, 512, …), more operational challenging, higher price tag, planning and in-field quality control needs assistance from professional geophysicist (birddog), survey quality correlates strongly with contractor choice. Table T1 contrast advantages / disadvantages of both reflection- and refraction surveys.

The comparison of refraction- / with reflection seismics finally lead to the development of an authentic hybridseismics: With in-field costs being the highest component in seismic surveys, why not maximize information collection for the customer by recording and later using all wave field components with hardly any extra costs?

Survey Requirements & Objectives	Reflection Seismic Profiling	Refraction Tomography Inversion
High Resolution at depths ≤ 10 m	😐	🙂
High Resolution at depth > 20 m	🙂	😐
Reaching exploration depth	🙂🙂	😐
Rock / soil quality indicator	☹	🙂
Detection of velocity inversions	☹	🙂
Fault zone indication	🙂	😐
Detection of decompaction zones	😐	🙂

Table T1: Advantages and disadvantages of reflection- and refractionseismic method;

Hence, the unknown substrata is simultaneously illuminated by (*mostly*) horizontal and (*mostly*) vertical rays providing double information from one single survey: The weaknesses of one method compensates for the advantages of the other.

3. Operationalizing authentic hybridseismics

However, the first step involves consideration of four fundamental factors of any geophysical survey, these are:

(i) penetration
(ii) resolution
(iii) signal-to-noise ratio
(iv) contrast in physical properties

If an educated / registered geophysicist confirms the principle feasibility of a seismic survey, the discussion can progress to the conduct of a specific hybridseismic survey. Also different in their direction of seismic energy through-transmission (reflection: vertical; refraction: horizontal), an authentic hybrid seismic survey conducted with p- and s-waves has five implementation stages:

3.1. Planning

Desk top work and one on-site visit: Signal/noise situation, start / terminating access and operational permitting, definition of acquisition parameter *such as* setting and location of seismic lines, number of geophones, type of geophones s- or p-wave, spread type, inter shot point distance, spread length, geophone-spacing // *for authentic hybrid seismics between 1- 2 m* //, cover of fold // >30+ //, modification appetite for unforeseen permitting changes. *If available*: visit of ground truthing spots such as outcrops, quarries, drill holes, dive into available reports & literature, start-up of health-safety-environment (HSE) component, logistics and accessibility during field campaign;

3.2. Field data acquisition

Final selection of field parameter, Equipment deployment, huddle-test, noise analysis, preparation and handling of seismic sources (P-wave, S- wave, or both source? explosives?), field operation, recording. At the end of every production day: Assessment of day-collected raw data quality through a quick in-field processing (brute stack check), adjustment of operation and acquisition plan, densifying / thinning field geometry, undershooting plans for unforeseen problems, time & plan keeping, briefing of field safety and discussions of near-misses; Based on the planned exploration depth, three basic rules for acquiring hybrid seismic data exist. These three rules of thumb ensure adequate reflection seismic data density and the complementary refraction tomography investigation depth. Depending on the locally attainable data quality and on the complexity of the subsurface structures, the following three rules apply:

1st rule: Receiver station spacing should not exceed 1/50 to 1/30 of the required depth of investigation (depending on the locally attainable data quality and the complexity of the subsurface structures);

2nd rule: Length of the active spread should be at least 3 - 4 times larger than the desired depth of investigation;

3rd rule: The source / shot point distance is not larger than 1 – 3 times the receiver station spacing**.**

The following working example illustrates the application of the three rules - desired investigation depth is approx.. 100 m:

Application 1st rule: receiver station spacing of 2 m is appropriate;

Application 2nd rule: The spread length must be 300-400 m, which means that with a geophone spacing of 2 m, the active lay-out is to consist of 150-200 geophones. Consequently the recording device must feature this number of active data channels; Following the thumb rule from seismic operations, that a field crew has for spare and redundancy reasons 1.5 × the number of deployed geophone available on-site. Hence, a geophysical subcontractor should have 230 to 300 geophones delivered to his base camp – these hardware / equipment necessities also separate authentic hybrid seismics operators from other subcontractors.

Application 3rd rule: The source point distance should not exceed 6 m. Under very difficult conditions 2 m – 4 m is preferable.

3.3. Processing & Analysis

Processing is the transformation from cleaned seismic field -data into a final, self-consistent, and interpretable result with (stunning) clarity and resolution - what the customer requested. Processing work and utilized software tools separating wheat from chaff in terms of explanatory power, result quality, and final customer satisfaction: Processing is where value is added and geological / geotechnical theaters become meaningful. Processing shallow-seismic data is different from seismic data processing done in hydrocarbon exploration and geothermal exploitation, [23, 24]. Treating seismic data for the hydrocarbon / geothermal industry means enhancing existing reflections, omitting strong lateral and vertical velocity variations near the surface, and purging registered seismic events in the upper few hundred meters below the surface. This is a proven strategy for hydrocarbon promising targets (deep sediment basins, and steep flanks of salt domes). In contrary, near-surface seismic data need to reveal shallow seismic events, which are not initially visible in the first 100 m below the surface. Both processing targets need to apply different specialized, geared software tools (e.g. for shallow reflection seismics: SPW® from Parallel Geoscience Corp. Austin TX, USA; for refraction dive wave tomography: Rayfract® Seismic Refraction Tomography from Intelligent Resources Inc., Canada). Contractors habits to apply standard software packages from hydrocarbon industry (e.g. ProMax® from Landmark) for near surface- and shallow seismic data will result in near-surface specific erroneous artefacts. Practice, reports and literature mirror three different processing strategies for the simultaneous treatment of high resolution near surface refraction- and reflection data:

Hybrid refraction-reflection seismic: Stemming from Oil& and Gas industries, [26] suggest a simplified processing flow by translating seismic rock velocities into continuous reflectivity sections. It appears that this physical correct approach is too abstract for engineering geologists and geotechnical engineering;

Sequential processed hybridseismic: During one field layout both wave fields – *the refracted - and reflected sheaf* – are simultaneously registered. During the subsequent sequential data processing the refracted - and the reflected raw data are handled in two separated and decoupled data flows. The velocity pattern for refraction data derives either from model calculations or from tomographic inversions. The result is a topography corrected cross section of seismic velocity (1st velocity domain) versus depth. In a next step, cleaned raw data are processed to associate and analyze geological / geotechnical significance of these seismic data. Hereby the art is the selection of primary reflections and amplitudes and their association with continuous identifiable reflectors in the underground. By applying a time-depth inversion function (this time-depth migration creates a 2nd velocity domain) and accounting for seismic attributes (phase, amplitude, attenuation) hidden in the initial processed seismograms, slowly a pseudo-geological picture becomes visible. The intermediate result is corrected for topographic effects and plotted as seismic cross section with refractor velocities superimposed as single lines. The final picture is based on two different velocity distributions, (*one for the refraction data, and one from the depth migrated reflection data*). The principle of reciprocal velocity calibration is violated and conflicting spatial information about event locations and anomaly shapes occur.

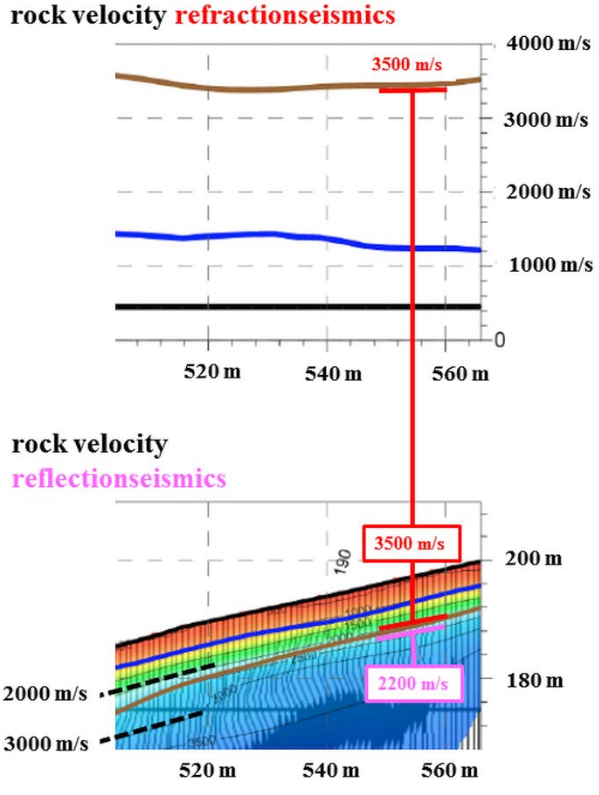

Figure 4. Sequential Hybridseismics delivers ambiguous velocity fields – velocity values derived from refraction tomography and values derived from reflection seismic processing occupying the same underground coordinate and violating rules of spatial congruency and reciprocal calibration. The velocity difference at one subsoil coordinate differs by 1300 ms^{-1};

An anonymous *leap-into-life* example from a commercial survey, Fig. 4, illustrates the problem for the geotechnical site engineer: Beneath profile coordinate + 555 m at sea level elevation of approx. 191 m, the refraction survey pinpoints a V_p rock velocity of approx. 3500 ms^{-1}, whereas the reflection processing displays a V_p velocity of 2200 ms^{-1} for the very same coordinate. If this geophysical survey would have been ordered and used for a basic estimation of rock-type and rock mass condition,

[11], the DEERE rock quality designation factor (RQD) would range from “Very Poor” ($V_{p\ \mathrm{reflection}} = 2200\ \mathrm{ms}^{-1}$) to “Fair / Poor” ($V_{p\ \mathrm{refraction}} = 3500\ \mathrm{ms}^{-1}$). The opinion of the geotechnical community summarized by [12] becomes comprehensible.

Authentic hybridseismic: The first step derives the velocity field from an iterative refraction tomography inversion (precise: refraction diving wave tomography). By avoiding *over processing* and numerical *over smoothing* only low-number velocity iterations are used for further work steps. Because the refraction arrivals are well defined, the seismic P-wave velocities derive up to a depth of a couple of tens to a few hundreds of meters below the ground. An example of a P-wave velocity distribution is Fig. 5.

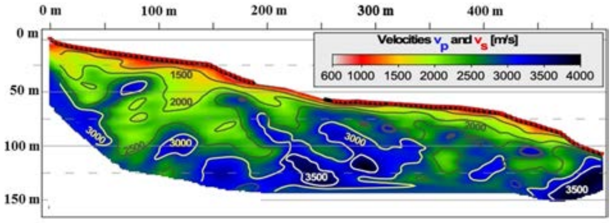

Figure 5. Example V_P field derived dive wave refraction tomography

The worksteps are repeated for the S-wave data, with the result shown in Fig. 06.

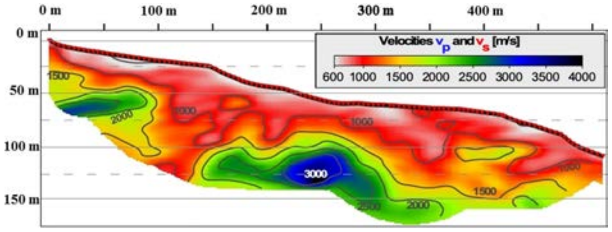

Figure 6. Example V_S field derived dive wave refraction tomography – please note higher resolution and more detail rich image as V_s is slower than V_p

The second step is the production of the reflection-seismic depth section. The most challenging issue in this work step is the transfer of the velocities (from the refraction tomography) to the reflection section to drive piecewise direct time-to-depth conversion without the typical automatic depth migrations. Finally a joint presentation of both results (refraction- and reflection-seismic survey) is achieved by transparently overlaying the velocity field from refraction tomography onto the converted reflection-seismic depth section. As last step in the analysis, a coarse raw interpretation sketch of revealed geological / geotechnical entities is delivered to the team geologists / geotechnical staff to prepare for final discussions and interpretations.

3.4. Combining P- and S-wave results

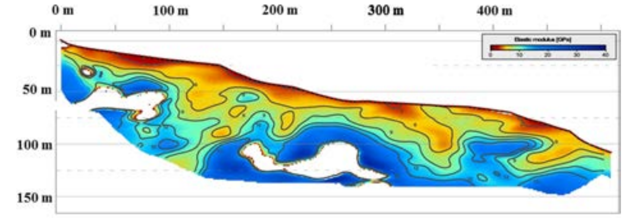

Figure 7. Section of spatial distributed YOUNG E modulus – derived from a combined V_P and V_S survey;

For the geotechnical relevant result, P-wave data and S-wave data merge into one dataset representing spatial variability of Young modulus, Fig. 7.

3.5. There is Interpretation ….

This is when the added value is generated for the project and the service purchaser: Deducting geological / geotechnical significance from the two complementary wave fields is the high order outcome of this last work step. As the actual geology is not fully known and/or the spatial distribution of geotechnical parameter data remain hidden beneath the investigated site, an interpretation cannot be judged as correct or incorrect, but - with some prior information - as consistent or inconsistent. Therefore a discussion of authentic hybrid seismic results include

- Peculiarities in the spatial distributed V_P and V_S velocity fields;
- Relationship between V_p, and V_s velocity field distributions and image of Poisson-distribution;
- Seismic attributes in the reflection section;
- Confirmation of spatial congruency of the results of seismic refraction tomography inversion and of high resolution reflection seismic profiling (essence of authentic hybrid seismic data processing achieved by reciprocal calibration), Fig. 8;
- Joint interpretation of V_P, and V_S, Poisson distribution and reflection seismogram in relation to ground-truth information (quarry, outcrops, CPT results, correlation boreholes, and excavated trenches / pits);
- Highlighting the unambiguous harmony between the geophysical model and the ground-truthing points;
- Reasoning of a derived geological / geotechnical start model;
- Spatial distribution of geoengineering parameter such as dynamic elastic moduli, highlighting possible soil-structure interaction problems, determine rock rippability, and rock quality;
- A duly made statement that the objectives of the hybridseismic survey were met and the question, if delivered report and presented results solved the posed problem and positively impact the geoengineering project;

- Reliability limit / error margins, zones of reduced information liability;
- Lessons learnt, any further comments, and some ahead looking recommendations / cautions.

These points are well in-line with legacy standards of the acting geophysical community, [27].

3.6. … and interpretations!

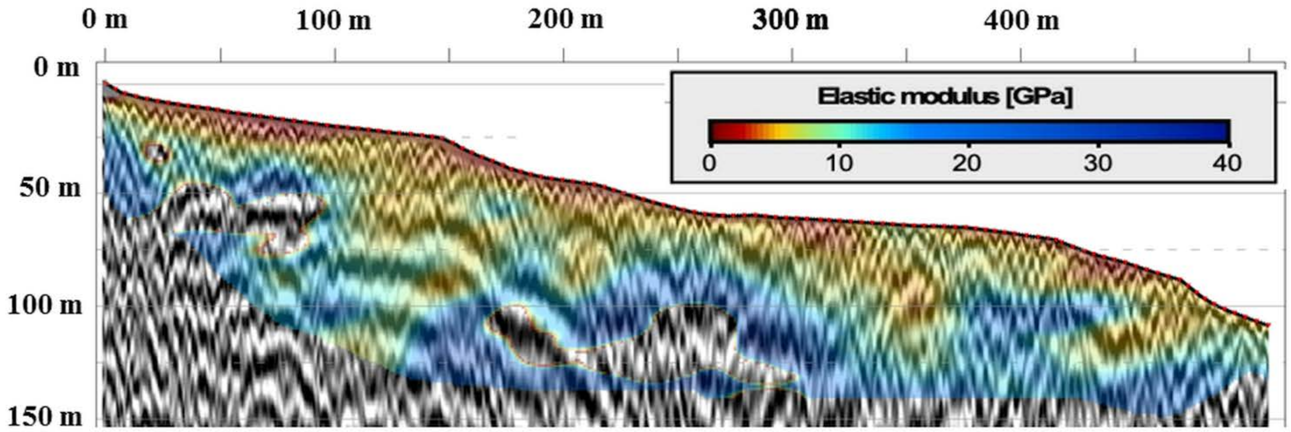

Figure 8. Result seismogram from authentic hybridseismics – principles of spatial congruency and reciprocal calibration are fulfilled;

As side effect to an almost ruinous price war among geophysical sub-contractors, most of the costs devote to field work, few resources to processing, hardly any amount for interpretation. As a result, the final derived geological model is not comprehensively ground truthed nor verified with existing geogenic reality. A second anonymous *leap-into-life* example, the product of a commercial sequential processed hybrid seismic survey illustrates in Fig. 9:

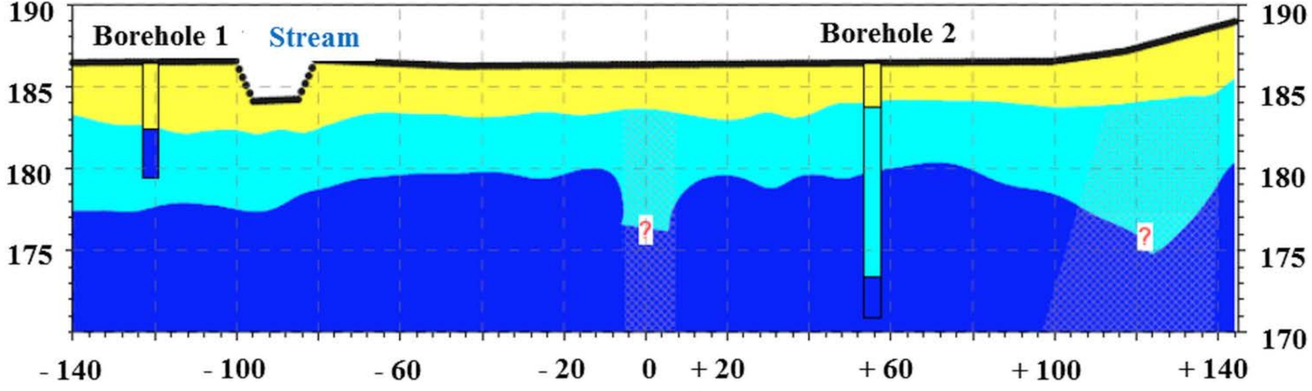

Figure 9. Result of commercial sequential hybrid seismic survey – mind missing correlation between seismic derived model and ground-truthing drill holes; anonymized end result from commercial survey. *Courtesy to 2015 student participants BOKU University;*

Drill hole information hardly correlates with the geophysical derived geological model. The result was accepted and paid by the buyer. The opinion poll from the geotechnical community discussed in [12] is supported from the side of geophysics.

3.7. Strong reasons make strong actions

In most geoengineering projects no call is made on an engineering geophysicist during the proposal stage of an authentic hybrid seismic investigation, nor for in-field quality control and sub-project coordination during the other four implementation steps. It is hardly surprising therefore, that geophysics is often not used as a preliminary reconnaissance tool and savings potential remain untapped. When an **external engineering geophysical adviser (EGA)** was brought in for the authentic hybridseismic geophysical investigations, the geotechnical engineers / engineering geologists were generally more satisfied with delivered results and reports. The greatest value was obtained, when a EGA had been taken through from planning stage of the investigation to the final report delivery. This enabled the team to reject techniques known to be unsuitable at an early stage and shortlist those with potential value for improving the overall cost-effectiveness of the site investigation. In addition, the EGA usually breaks the habit of requesting additional claims caused by '*unforeseen*' and guarantees the contractual agreed geophysical quality during all work stages.

Also authentic hybridseismics is not hydrocarbon exploration – some crosspollination exists: Seismic data acquisition and processing quality supervision is a value adding aspect of any geophysical work, including authentic hybridseismics. The geophysical exploration industry use the term **birddog** , [28], for this control and guidance work. It is a convenient shorthand title to describe an experienced professional geophysicists whose full title is, and who acts as, the data acquisition quality control supervisor on a field seismic exploration crew. In addition, the term describe one person who is the client's representative on the geophysical subcontractor from cradle to grave. The functional translation for engineering geophysics would be ‘responsible site manager geophysics’- but the term birddog is shorter, long established, more descriptive but has the same mandate and responsibility as an EGA.

Figure 10. : Accelerated dropweight (4x4 light-weight truck mounted Bison EWG Mark III®) **as seismic source for a combined P-wave / MASW survey deployed in an Alpine karstified operational theatre**

4. Lessons learnt: MASW or Shear Waves?

Hybrid seismic surveying combined with s-wave velocity field derivation are instrumental both for diagnostic purposes and for planning preventive measures in areas with suspected ground instabilities. Using the principle of Multichannel Analysis of Surface Waves (MASW) is currently the most cost saving and hence long proven standard method for an in-situ determination of the geotechnical relevant the v_P / v_s ratio, e.g. [29, 30] and on text book level [31]. The clear advantage of MASW surveys is the ease of field operation – as RAYLEIGH waves are vertically polarized shear waves, they register at the same as P-waves and no extra equipment nor additional field work deems necessary – as long deployed geophone spreads are sufficient long and the inter-geophone distance is small. Typical field / equipment parameter range from 200+ active channels with 1 m geophone spacing. Besides typical field and processing constraints and challenges, [32], MASW has methodological limitations, [33]:

- **Principal Physics**
  The motion of Rayleigh waves are constrained to a vertical plane consistent with the direction of wave propagation. Only for the case of a solid homogenous half-space, the RAYLEIGH wave is not dispersive and travels at a velocity of approximately 0.9194 V_s when Poisson's ratio is equal to 0.25;
- **Hitting Geological Realities**
  In the case of one layer over a solid homogenous half-space, Rayleigh waves become dispersive when their wavelengths are in the range of 1 to 30 times the layer thickness. Longer wavelengths penetrate greater depths for a given mode, generally exhibit greater phase velocities, and are more sensitive to the elastic properties of the deeper layers. Conversely, shorter wavelengths are sensitive to the physical properties of surface layers. Therefore, a particular mode of surface wave will possess a unique phase velocity for each unique wavelength, leading to the dispersion of surface waves;
- **Operational Field Constrains**
  RAYLEIGH wave penetrate approx. one wavelength into the ground – which practical limits its depth resolution and informative value. Using a standard sledge hammer (3 kg - 8 kg, impact energy < 0.3 kJ) on a steel plate as a seismic source usually produces high-frequency skewed spectra. In case of a MASW survey, the deployment of an accelerated drop weight as seismic source (impact energy > 8 kJ, Fig. 10) is recommendable– as the generated seismic signals have higher portion of deep frequencies in their spectra. The need to work with low-frequency sources usually means to accept higher operational costs for a the seismic source other than a hammer, hence counterbalancing the initial financial advantages of having only one field spread laid and generating savings on field labor costs;
- **High-Quality Data Processing**
  To achieve an appropriate quality and a meaningful, robust result for the geotechnical engineer / engineering geologist and end-customers from civil engineering, considerable experience in the processing of surface wave data is key;
- **Current Quality Needs Of Geotechnical Community**
  The average the error margin of MASW derived V_s compared to borehole-verified Vs is at least in commercial field works ±15 %. As the MASW derived V_s appears as denominator in the V_p / V_s ratio, hence, considerable random variations and broader error margins in the insitu POISSON number distribution are foreseeable in the final geotechnical report.

With MASW subject to the above given restrictions, and in light of equipment prices coming down and higher quality consciousness of the civil engineers (*and their trailing legal departments*) emerge, the path to customers satisfaction lead towards direct measurements of V_s by deploying a shear wave source, *cf.* Fig 2, and operating with at least 150+ horizontal geophones on the seismic profiles.

5. Case study Dam 1: Foundation seepage control

As the expectations from civil engineers erecting dams towards geophysics is high, [34], case studies have been selected appropriately. The first case study, Fig. 11, documents the successful integration of authentic hybridseismics to prepare / assess uncontrolled flows through porous media beneath the dam foot. The decision to construct a partial cutoff depends on a number of factors, [35]:

- Economic comparison between the value of water loss and the additional cost for a complete cutoff,
- Susceptibility to backward erosion and piping of the materials located below the proposed tip of the partial cutoff,
- Time-lapse leakage monitoring;
- With a direct connection to the results of authentic hybridseismics – localization of sedimentary fines (silt and clay-sized particles) and post-identification of an intermediate impervious stratum of sufficient extent where downward tips of partial cutoff could be embedded / anchored into geotechnical friction-locked material / hydraulic tight strata.

On the soft skills, authentic hybridseismics bridges between the different geoscientific concepts of "*depth to basement*" (Engineering Geologists: Depth to the top of the weathering zone of the basement; Geotechnical engineering: Depth to engineering rock head).

5.1. Problem to be addressed

The main tasks of the survey were the detection of geotechnical / hydraulic weakness and instability zones by

- Spatial identification of structural discontinuities zones,
- delineating faults,
- Mapping engineering / hydraulic rock head,
- Determination of thickness of solid native Quaternary,
- Detailing of weathering layer covering basement rock,
- Assessing geotechnical ground stability (variation and spatial distribution) of Young's E-modulus.

Authentic hybridseismic results provide substantial subsurface information for an international geotechnical subcontractor supervising site constructions, Fig 11, to provide a comprehensive analysis of predicted dam subsidence phenomena.

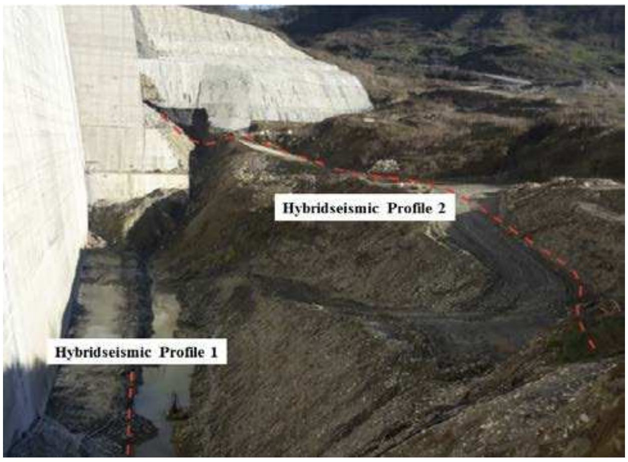

Figure 11. Case study 1: Dam site with position of two authentic hybrid seismic profiles

5.2. Results from authentic hybridseismics

Authentic hybridseismic profile parallel to the downstream face of the dam reveals two deep ranging zones with reduced YOUNG modulus zones, Fig. 12.

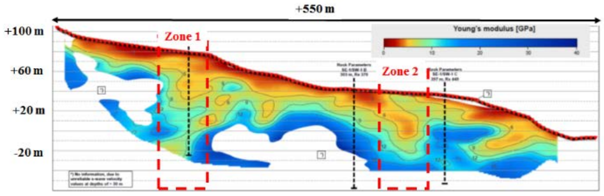

Figure 12. of dam case study 1: Spatial distribution of YOUNG modulus below Profile 1 – Note the two deep ranging pockets of weak quaternary material in the first third and in the last third of the profile.

As foreseen, the spatial distribution of Poisson-values correlate unambiguously with the mapped seismic reflectors delineating the quaternary filled pockets of the basement (zones 1 and 2), Fig. 13. The two locations needed some more detailed investigations with a follow-up ground truthing method, e.g. directed core drilling.

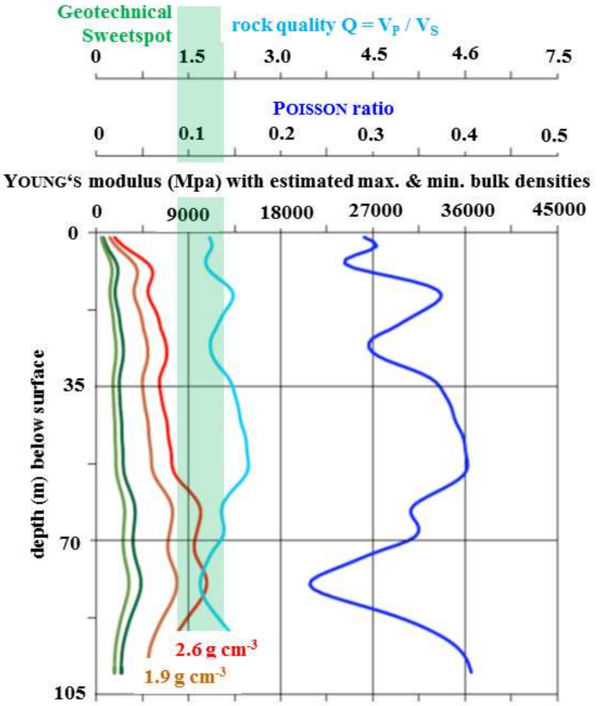

Figure 13. Profile 1 of dam casestudy 1: Pseudo wireline logging derived from subset data of Fig 13.

Fig 13 represents a subset of the YOUNG's modulus section from Fig. 12 – a strict one-dimensional representation as "pseudo drill log" confirms that the V_p / V_s relation of this particular site is outside of the geotechnical sweet spot. Consequently, more financial and technical resources will be needed for the hydraulic insulation of these deep ranging pockets and on detail-level, the pseudo-logging predicts the core loss zone for the subcontracted drill teams and the responsible engineering geologist. Authentic hybridseismics contributes to rationalize supplemental claim discussions.

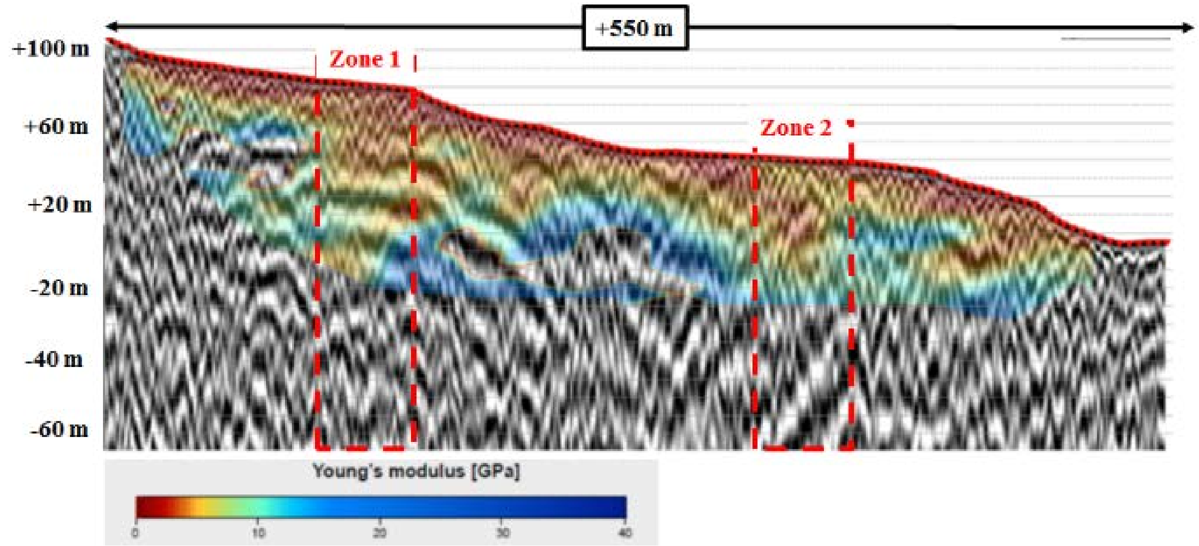

Figure 14. Profile 1 of dam case study 1: YOUNG modulus distribution (*based on assumed averaged bulk density*) overlaid on reflection seismic section. Note the good correlation of color progression representing the changing YOUNG'S modulus with the reflector horizons.

6. Case study Dam 2:

Early pre-Feasibility study

With more renewable energy from wind, hydro and solar floating through national grids, and the need for pumped hydroelectric energy storage possibilities (PHES) emerges. In steep alpine-like topographies, the potential is investigated by closing-off of smaller side valleys situated close to the main rivers. The geological / geotechnical situation prioritized from geoengineering consists of – from surface to ground – a drainage blanket, alluvial gravel bed, impermeable strata such as mudstone, dense silt-layers, or non-tectonized hardrock. In case of karstified geogenic theaters with their uncontrolled drainage patterns, the economic effort is jeopardized as the storage pond will not hold the water.

6.1. Problem to be addressed

The main tasks was to clarify the pre-feasibility of a PHES in a slightly karstified region, especially by providing information such as

- Spatial identification of karst zones and identification of delineating faults,
- Thickness of the quaternary valley fill,
- Stability of the valley side slopes.

As typical for pre-feasibility discussion circles, the decision making body consists of different disciplines e.g. economist, investors, process technicians, senior decision makers, hydraulic engineers, and landowners. The challenge was the crisp communication of authentic hybridseismic results: Geoscientific focused, but communicated in an understandable mode, Fig. 14 & Fig.15. As such, presenting pseudo-sections of dynamic POISSON-distributions and apparent rock velocities reversals would have demanded too much abstraction and geophysical knowledge from the high-level decision-making decision makers.

6.2. Result generalization from authentic hybridseismics

As the magnitude of the Poisson distribution depends on density, detailed discussions would have been blurred by the representation of line droves, geoscientific correct but confusing for laymen. As such only the V_P / V_S ratio, the Q-value after BARTON, [11], ranging from 0.1 to 7, is presented,

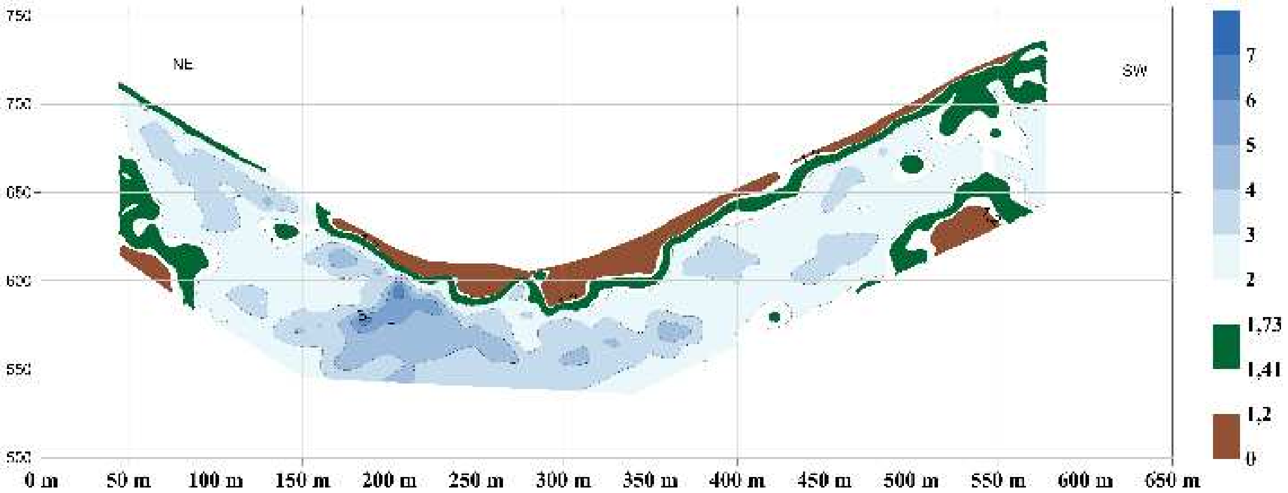

Figure 15. Dam case study 2: Generalized presentation of geotechnical significance based on Q-rock factor equal to V_P to V_S ratio.
Note the anisotropic character of the quaternary / recent valley fill material ($Q < 1.2$) and the thin green zone representing a favorable foundation scenario (Q between √2 and √3).

The geotechnical favorable zone (*vulgo* geotechnical sweet spot) between the Q-factors √2 and √3 is kept in green, the zone with the possibility for anisotropy in brown representing laymen's understanding of soil and quaternary, and the risk zone of instability blue prefiguring potential zone of enriched water percolations and geotechnical instability, Fig. 14.

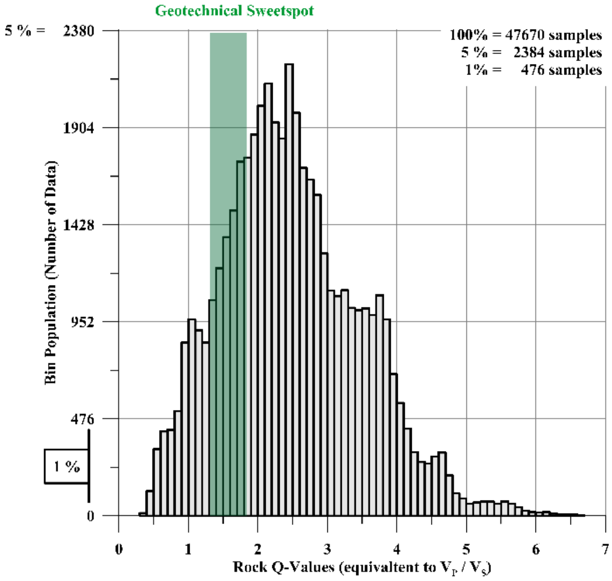

Figure 16. Dam casestudy 2: Further generalized presentation of geo technical significance beneath Profile 1. Classed distribution of Q-rock factor, equal to V_P to V_S ratio, showing that most of **the values are outside the favorable zone for foundation works.**

The take-away-message for non-geoscientists distills from Fig. 16 – a vertical histogram showing the classed Q-factors (V_P / V_S ratios) underneath the projected main axis of the earth dam: The distribution of geotechnical values lent to the petrophysical unfavorable side foreseeing laborious and expensive foundation works for the planned earth dam at this particular site.

7. Dam: Potential for new and novel applications

Road-building and bridge maintenance have experienced the problems already in the late 70's from concrete deterioration and from expansive concrete. Currently similar problems are surfacing within the community of dam builders. For a majority of dams subjected to concrete swelling the monitoring is normally restricted to 1D displacement measurement, [36], or multiple destructive penetrations into the destabilized concrete structure, *vulgo:* core drilling. (*sic!*). One of the practices to remedy is to slit an expansion slit into the middle of the endangered concrete structure. Hereby, all remedy operations assume a homogeneous non-anisotropic concrete body poured in one batch with the same material and equal hardening conditions. This simplified 1D model approach need to be challenged and replaced by a 3D model with risk zonation. This deemed to be necessary to guarantee the long-term stability of a concrete dam.

Swelling of concrete is accompanied by an increase of the seismic velocity, because the mechanical coupling between the cement minerals becomes tighter. An authentic hybrid-seismic survey, conducted as time-lapse campaign, assists geo-engineers to plan 3D distributed remedy operations. Citizen having their antrophosphere and their property downstream will be enthusiastic proponents for a non-destructive, scientific sound, and reproducible damage investigation – counterbalancing findings from [12].

8. Message to Take Along

Authentic hybridseismics, deploying reflection seismic profiling as well as refraction diving wave tomography inversion in one field operation, have their undisputed merits in their performance and represent the current state-of-art technique. Thanks to the recent technical advances implemented in modern seismic recording instrumentation and hardware, data acquisition for both methods combines into one single field operation eases, resulting in substantial costs reductions for field works and personnel costs.

By an appropriate sequel, but joint data processing procedure *(deriving the rock in-situ velocities from the refraction survey and feeding these directly into the depth-conversion processing of the seismic reflection data)* the full potential of the information contained in seismic data is extracted. Although the results of the reflection seismic data processing and the refraction tomography evaluation are based on the same data set, they are completely independent from each other. This reciprocal calibration of the two methods enhances the reliability of the latter joint interpretation. Consequently, the shortcomings of one seismic method is compensated by benefit of the other.

The resolving power of authentic hybrid seismic sections are directly proportional to the spatial sampling data density, which is defined by the spacing between the receiver stations (usually between 1.0 m and 2.0 m), by the overall spread length (+400 m) and by the distance between the source points (typically three geophone stations). The length of the active geophone spread (200+ active channels) determines the attainable depth of investigation.

If the authentic hybrid seismic method is jointly conducted in a P-wave mode with the similar registration of surface waves (Rayleigh waves) - *or if higher quality deems to be necessary* - in a joint P and S-wave campaign, the non-destructive spatial mapping of the in-situ distribution of geotechnical relevant parameter (Dynamic elasticity moduli: Poisson, E-Modulus, Young) is economically advantageous compared to the current conservative standard practice in geotechnical engineering, in which oversampling on dense regular inter-spaced drilling / CPT campaigns are still the norm.

Acknowledgement

The authors devote a hand of thanks to our colleague Adrian Ammon (M.Sc. ETH) for providing some of the figures, dedicating man power during field acquisition, and for his valuable support in writing / finalizing this publication. The authors express their thankfulness to the comments and guidance received from the anonymous reviewer of this paper.

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