Geophysical prospection of rock dynamic parameters by VSP well logging and SRS - EXAMPLE

Final Report

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LIST OF USED ABBREVIATIONS AND SYMBOLS

Physical symbol	Unit	Description
c_u	[kPa]	(total) coherence
E	[MPa]	Young's modulus (of elasticity)
E_{dyn}	[MPa]	dynamic module of elasticity
E_{dseis}	[MPa]	dynamic module of elasticity by SRS or VSP
F_s	[Nm]	cone head skin friction
ϕ_{ef}	[◦]	effective angle of internal friction
ϕ_u	[◦]	total angle of internal friction
G_{dyn}	[MPa]	dynamic shear modulus
G_{dseis}	[MPa]	dynamic shear modulus by SRS or VSP
I_c		consistency index
I_d		index of relative density
V_P	[m/s]	velocity of seismic P-waves propagation
V_S	[m/s]	velocity of seismic S-waves propagation
ρ	[kg/m^3]	volume density
ν_{dseis}	[/]	Poisson's ratio
Q_d	[MPa]	specific dynamic penetration resistance
ρ_r	[Ωm]	resistivity of rocks
ρ_{app}	[Ωm]	apparent electric resistivity of rocks

Abbrev	Description
DPH	dynamic probing heavy, dynamic penetration probe in heavy variation
FD	frequency domain
gph	geophysical
GRM	(interpretation method) general reciprocal method
GT	geotechnical
gwl.	ground water level (HPV)
HG	hydrogeological
EG	engineering geology
N / S	North / South
pf	profile
SRS	(method) shallow refraction seismics
TDC	time distance curve
VSP	(method) vertical seismic profiling

1. Methodology of the prospection

The following combination of methods was chosen to deal with the problem set (see Introduction):

- The method of **shallow refraction seismics (SRS)** enables to determine distribution of the parameters of spreading velocity of a seismic P-wave (longitudinal wave) and an S-wave (transversal or shear wave) in rock and soil environments. According to the distribution of spreading velocity of seismic P-waves, the rocks and soils studied by this method can be divided, within the reach of the measurements, into quasi-homogenous blocks, and the rocks and soils can be classified according to the classes specified in client's report. It also enables us to derive the homogenity and relative density (compactness) and dampness of soils, the depth and condition of the bedrock subbase. It is also possible to perform vertical localization of the subsurface water level if it is within the reach of these measurements. When measuring the S- waves and P-waves, dynamic parameters of the rock environment ($\mathbf{E}_{d\,seis}$, $\mathbf{G}_{d\,seis}$, $\nu_{d\,seis\ldots}$) and attenuation parameters such as absorption coefficient of seismic energy $\boldsymbol{\alpha}$ (P-waves) can be derived.

- The method of **vertical seismic profiling (VSP)** enables to determine S-wave and P-wave velocities using well-logging sonde Seis3D68VSP with 4 seismic sensors (3 horizontal and 1 vertical seismic geophone cores) and S wave surface source
- Geological interpretation of all methods is based on a research of archive materials and geological maps and geological surface research of locality.

1.1 Shallow refraction seismics (SRS)

1.1.1 Principle of the SRS survey and the equipment used

SRS is a geophysical method identifying velocity distribution of a propagation of seismic waves in rocks under the measurement level and/or the depth of the surface of bed rocks, which are faster from the seismic point of view, under the ground surface. The input data are obtained by measuring the time interval between the moment of the excitation of the seismic waves on a selected site and their arrival to the geophones. The resulting parameters are obtained by investigating a converted problem of seismic waves spreading through the rock half-space.

The spreading velocities of the seismic P-waves and S-waves in rocks in natural environment generally increase with the depth. In the cover – the top layer of the earth surface consisting mainly of soils and weathered rocks – the spreading velocity of seismic waves is usually as much as 10 times smaller than in the rock bed.

Thanks to this great difference in the velocities, the waves spreading on the surface of bedrock subbase (or of subsurface water) outrun the waves spreading in the soils near the ground surface. A so-called head wave is generated.

Near the weathered surface (with the gradient of seismic waves spreading velocities) the fastest seismic waves noticed do not spread directly on the bedrock surface but they spread in a less disintegrated rock more deeply – a so-called refracted wave. This fact enables us to measure the seismic waves' propagation velocities even in greater depths below the bedrock surface and to classify the mechanic condition of rocks in the depth.

SEISMUT 6, a 50-channel seismograph, was used for these measurements. It is capable of measuring and exact adding of weak signals domains from individual impacts to the result in a final readable seismic record. Thanks to this function it is possible to replace the explosives formerly used (as sources of seismic energy) by a weaker mechanic source and significantly decrease noise produced in the environment.

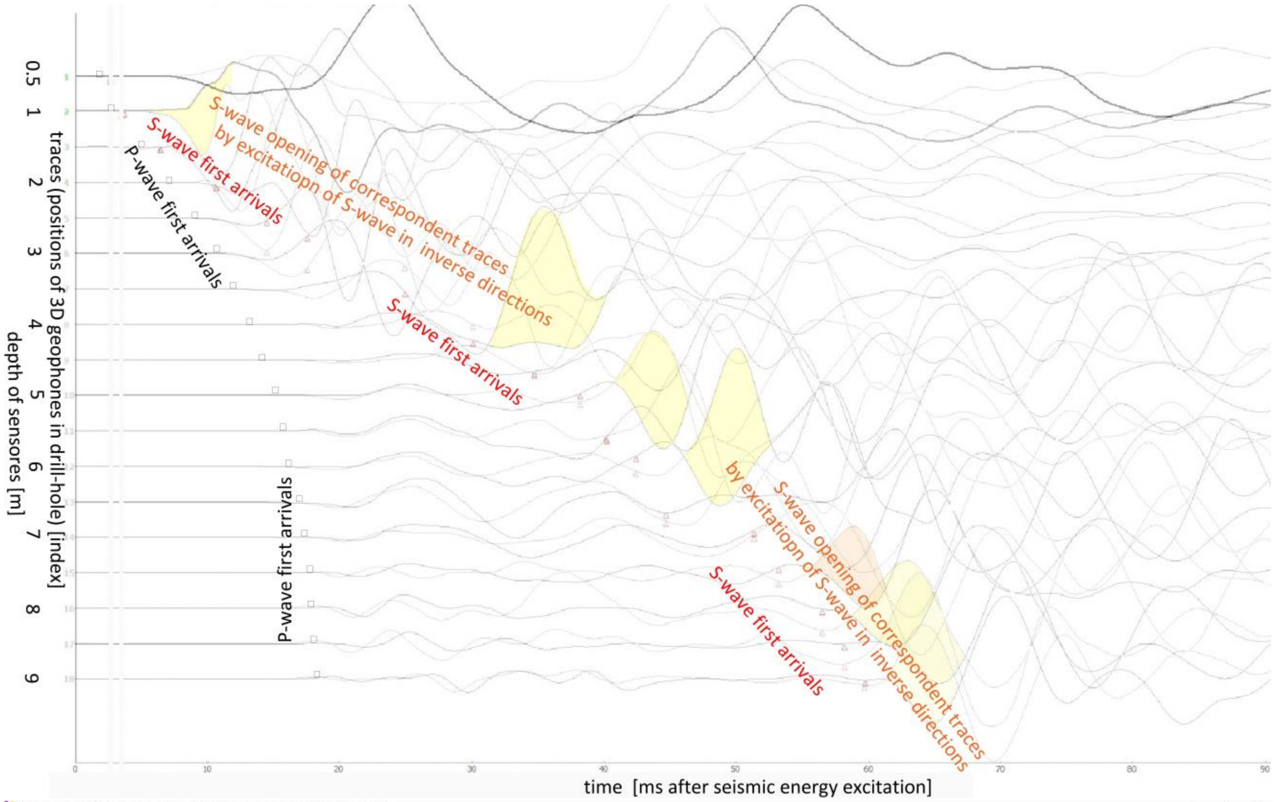
To record seismic P-waves and S-waves 3D geophones PE-6 (4.5 Hz 375 Wm) and vertical geophones PE-3 (10,5Hz) were used. We used RC seismic impact hammer 4 kg to excite seismic energy by 10 to 25 impacts at every shot position.

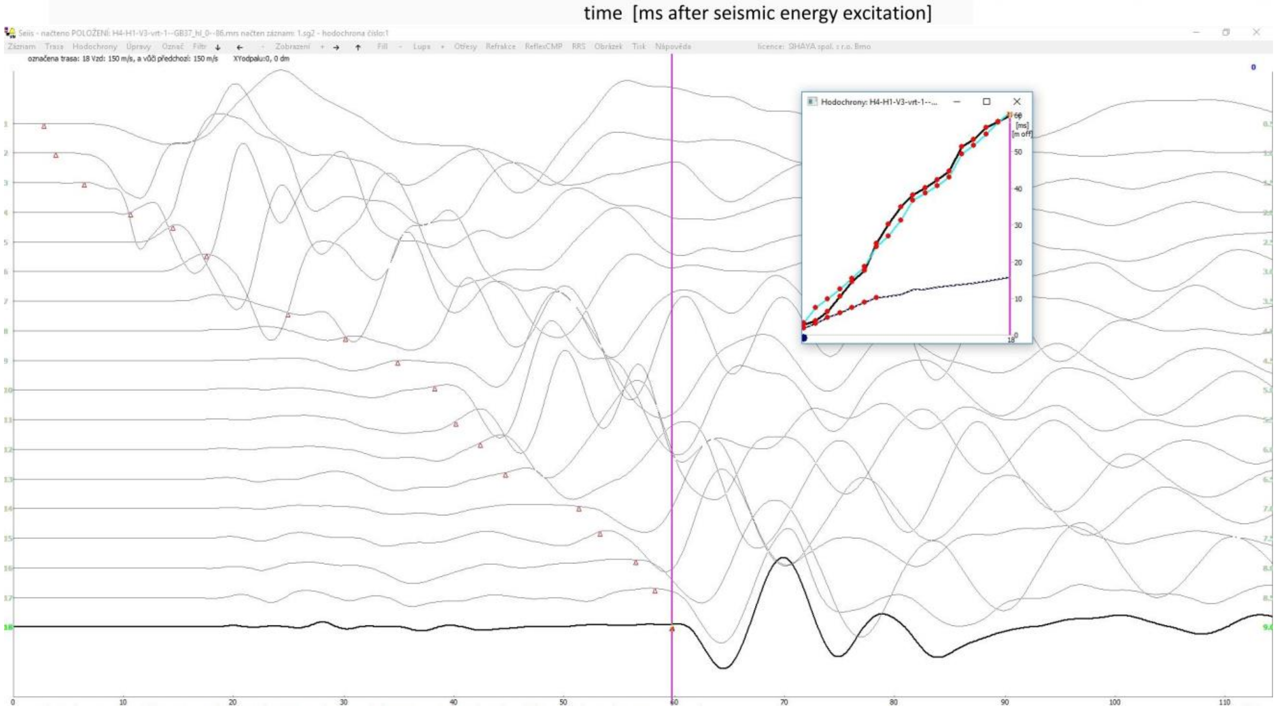
Fig. 2: SRS prospection using RC seismic hammer 3D geophones and S-waves source

1.1.2 Geometry used for SRS P-waves and S-waves measurements

On a direct 81 m long line with 28 vertical geophones (seismic vertical vibration sensors) with intervals of 1.5 m up 4.5 m were placed. This line is called "a seismic spread". At one seismic spread the seismic energy is excited by multiple impacts of a heavy hammer (vertically to excite P-waves, in the direction of axis of horizontal geophones and, afterwards, in the opposite direction to excite the S-waves) in seven points: in the middle, in the quarters, at both edges of the seismic spread and at selected points in a varying distance from 45 to 25 m behind both ends of the seismic spread.

Fig. 3: SRS – S wave extraction from 2 VSP records from GB 3-7 with opposite direction source records combined higher and lower subtracted

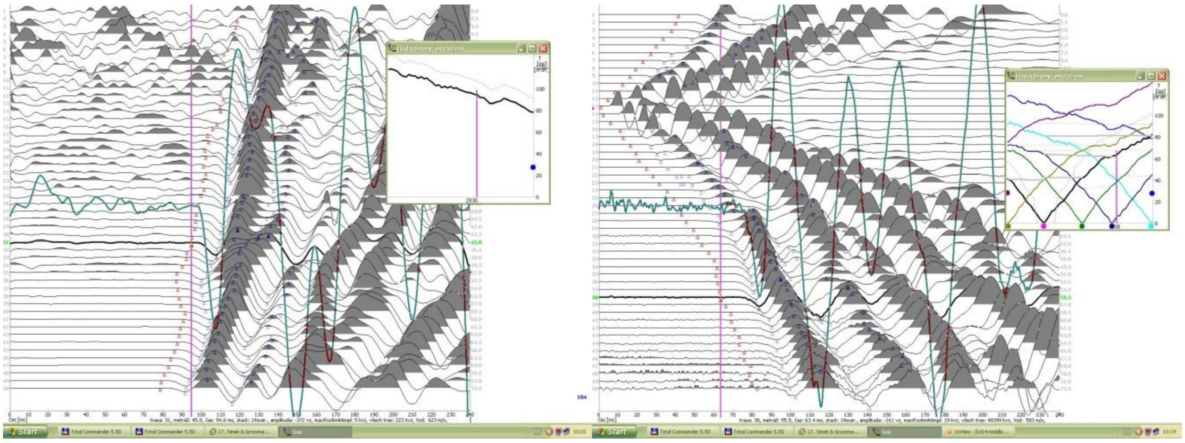




1.1.3 SRS processing

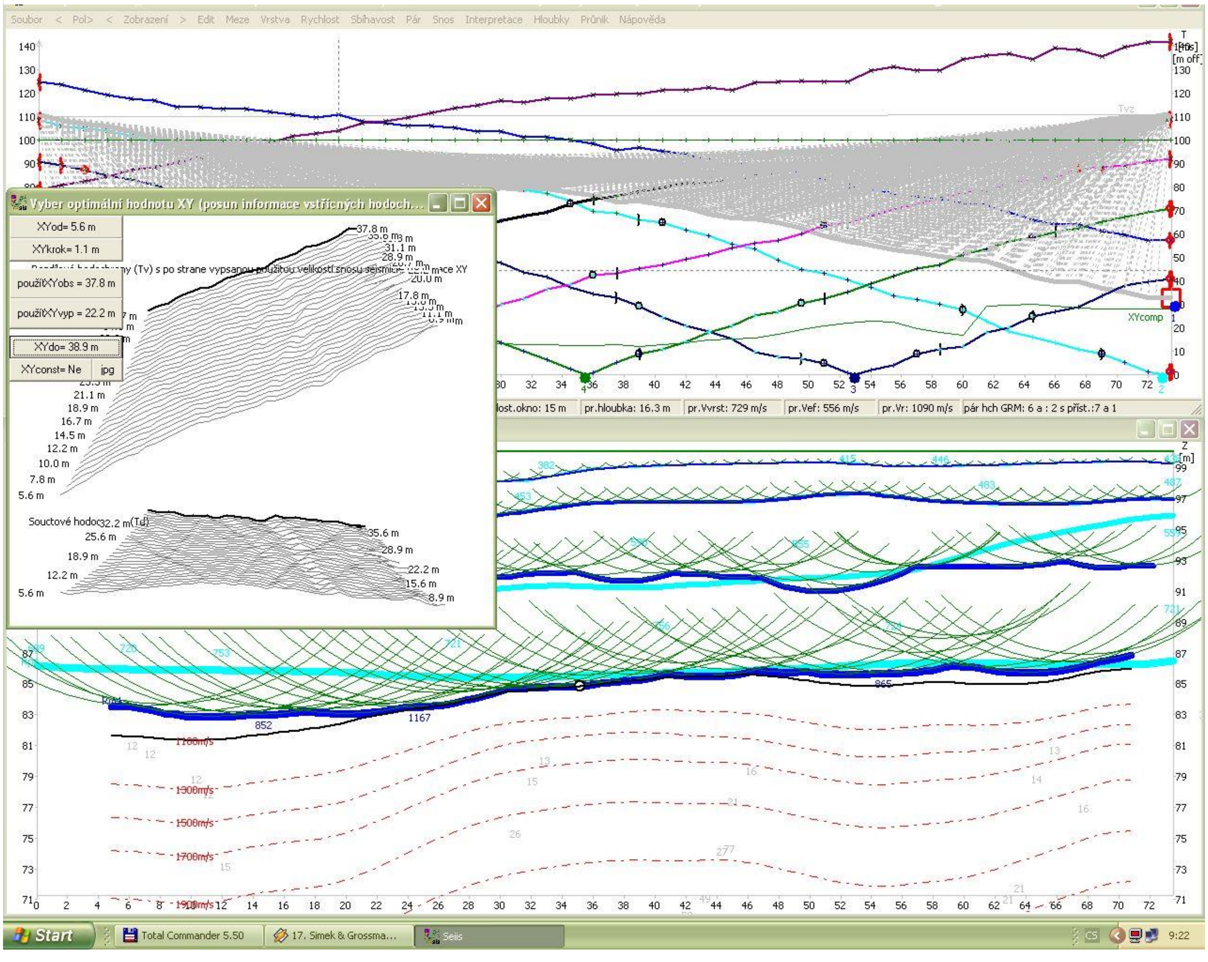
The seismic data records saved in a uniform file SEG2 are processed by interpretation program SEIIS (Valtr V., 2017) that was developed on the basis of Palmer`s GRM with an accuracy of approx. 5% of the depth.

Fig. 4: SRS processing – first arrivals picking



The result of the processing is a vertical section under the line of measurements with marked quasi-homogeneous blocks for which the average spreading velocity of longitudinal seismic wave has been determined.

Fig. 5: SRS processing – TDC interpretation by GRM



From the knowledge of distribution of velocity of propagation of the seismic P-wave and from additional complementary data some dynamic rock parameters can be derived. From those velocity of P waves sections (see Annexes 2) the position of bedrock surface and mechanical quality of cover and of bedrock can be derived.

1.1.4 Relation between the propagation velocity of P-waves and geotechnical parameters of rocks

The resulting seismic parameters of the rock environment are the velocities of propagation of longitudinal or transversal waves, the frequency characteristics of the environment and the loss of amplitudes noticed.

Due to a higher effectiveness the findings of first P-waves are particularly the results of **determination of spreading velocities of P-waves** (**Vp**) along the profiles measured in the depth of as many as 20 m.

This parameter (Vp) correlates with the volume weight ρ mostly according to the relationship:

$$\rho = a * V_p^{\,n}$$

where the constants **a** and **n** are determined empirically and rank among material constants. When not performing laboratory tests, the relation between V_p and ρ can be used for relative differentiation of lithologically similar rocks by their volume weight

V_p depends also on the elasticity parameters of the environment:

$$V_p = \sqrt{(E * (1-\sigma) / ((\sigma+1)*(1-2*\sigma))} \quad ,$$

Where σ is Poisson's ratio and **E** is Young's elasticity module. From the knowledge of spreading velocities of longitudinal and transversal seismic waves certain values of these elasticity parameters can be identified.

Furthermore, **porosity and filling of the voids (pores)** influence the Vp value. Generally, it is true that the Vp velocities are higher in less porous and water-bearing rocks than in rocks with a high porosity and non-water-bearing rocks.

There is a direct proportion between V_p and **the pressure** influencing the rocks and/or the age of the rocks decreasing the porosity and/or increasing the cementation.

V_p is also directly proportional to **soil compacting** and this dependence can be derived, provided that the soil dampness is approximately constant, by means of gauging by a penetration measurement. (This V_p dependence on compacting is also used by building compact meters.)

Rocks can be classified according to distribution of velocity of spreading of seismic P-waves and according to DPH results:

Workability class I. (in section annexes only in legend by black number 1) – excavation can be made by usual excavating mechanisms like bulldozers, diggers, manually).

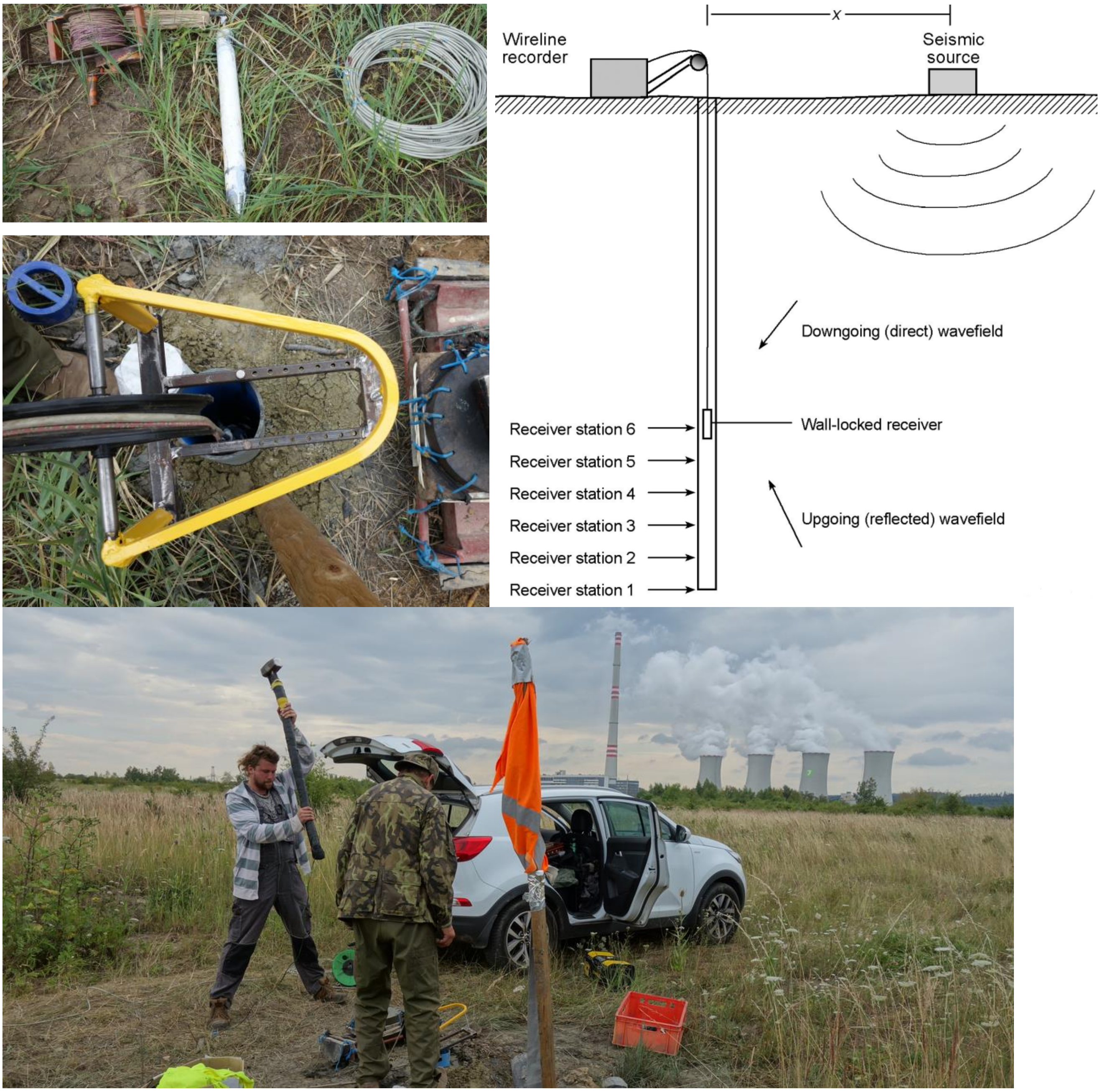
Workability class II. (in section annexes only in legend by black number 2) – for excavations special excavating mechanisms are necessary (like ripper, rock hammers …), and is possible to use also explosives if it is economically advantageous.

Workability class III. (in section annexes only in legend by black number 3) – for excavations explosives are necessary or other special technologies if explosions could endanger surrounding buildings and so on.

1.2 Method of the vertical seismic profiling (VSP)

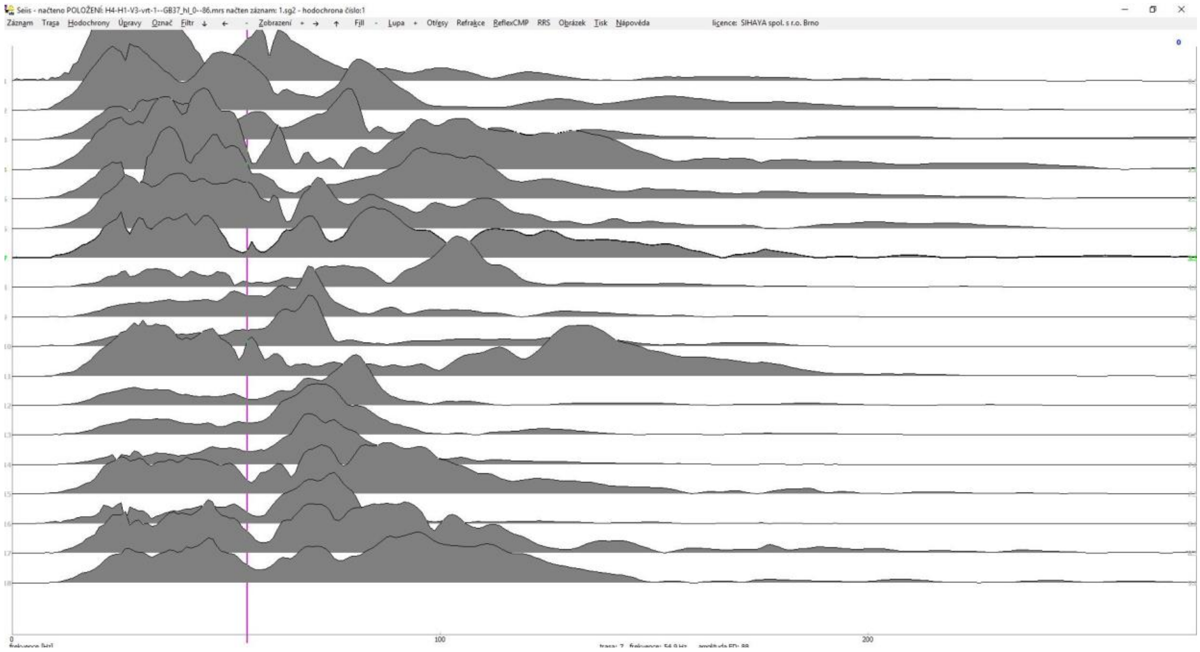
The method of **vertical seismic profiling (VSP)** enables to determine S-wave and P-wave velocities using well-logging sonde Seis3D68VSP with 4 seismic sensors (3 horizontal and 1 vertical seismic geophone cores) and S wave surface source, see fig. 6.

Fig. 6: VSP – Sonde Seis3D68VSP, scheme of work, jack roll, and VSP P-wave exciting



The shift of seismic energy source from drillhole casing was usually 0.5 m, the depth step of measurement was 0.5 m.

Fig. 7: FD at S-waves and P-waves (lower) records at drillhole GB 3-7 (for frequency range of VSP relevance)



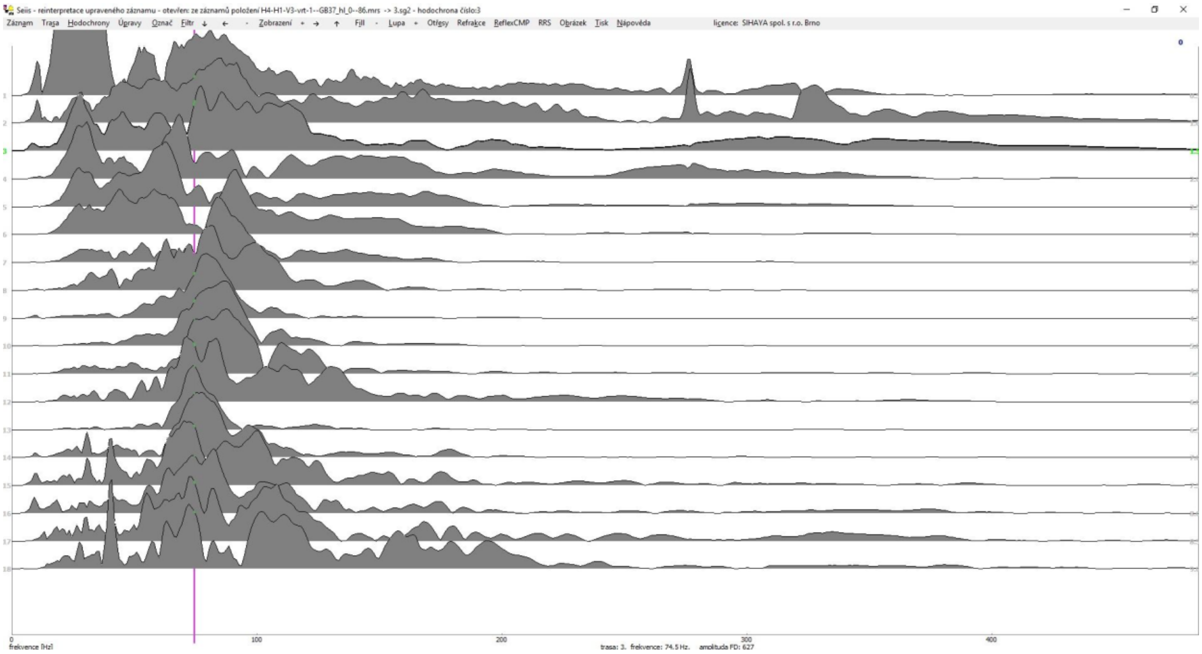
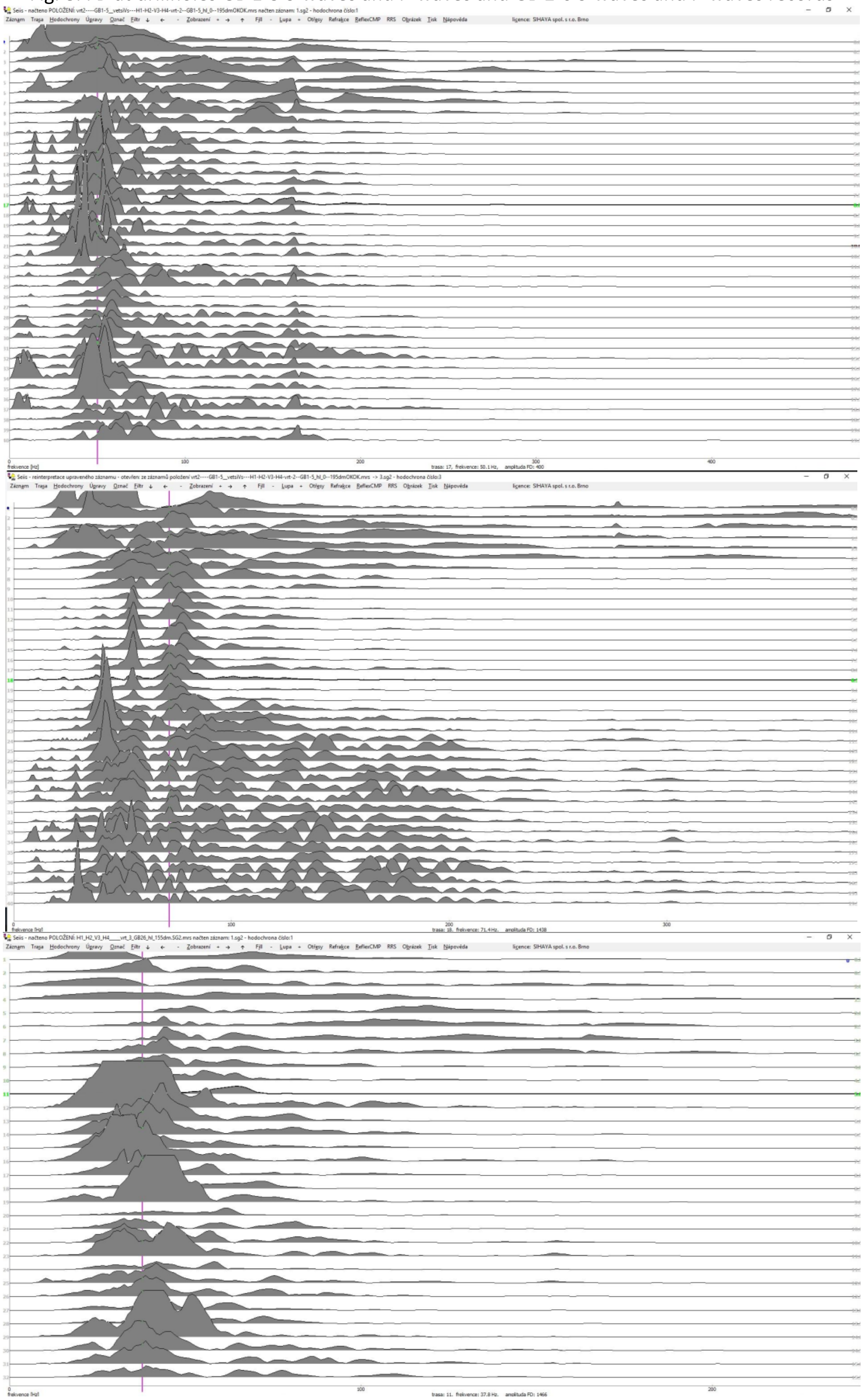
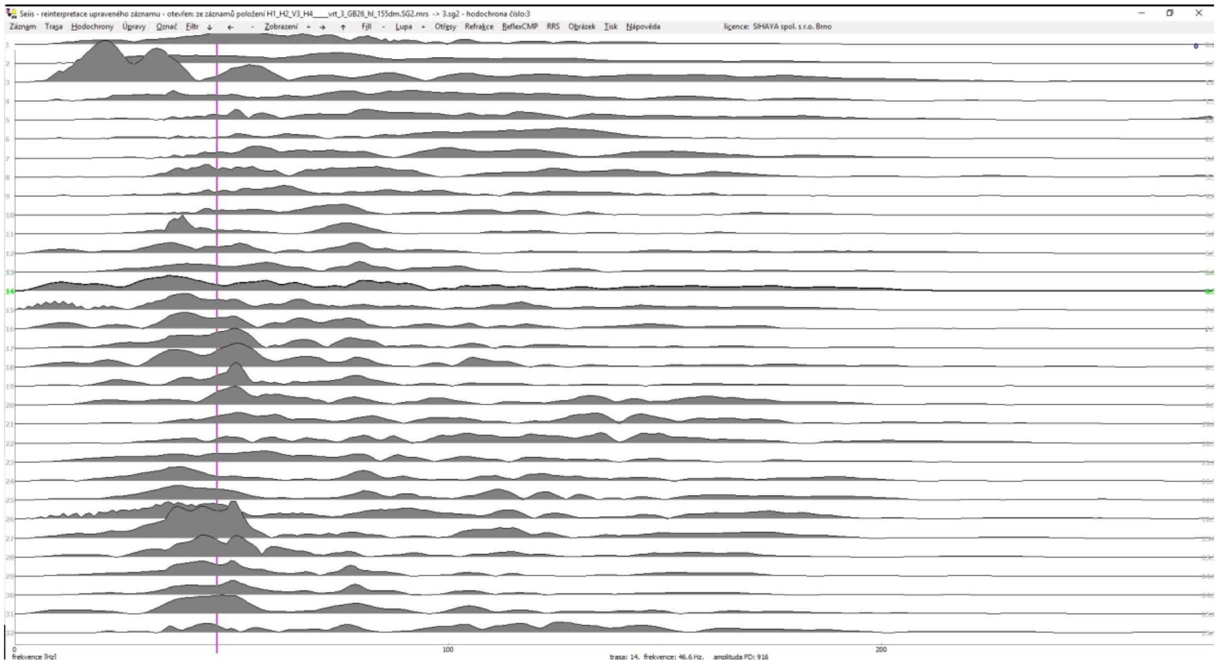


Fig. 8: FD at drillholes GB 1-5 S-waves and P-waves and GB 2-6 S-waves and P-waves records





2. Results of survey

2.1 Results of SRS survey

The situation of the SRS and VSP survey measurements is given in Annexes 1a – 1b.

Survey results measured by method of SRS are presented in a graphical form of geological-geophysical section in Annex **2b** and in Annex 2**a** there are 3 section schemes of 3 measured drillholes with dynamic parameters derived from S-waves a P-waves velocities (from SRS and VSP measurements) and volume densities (determined by client) in violet colour.

In overburden there were by the SRS method from 3 (S-waves) to 4 (P-waves) layers detected by following refractors (refraction interfaces):

- The shallowest refraction interface (the thinnest dark blue line for P-waves, for S-waves brown line) separates the most loose/soft layer of random fill material (interpreted number of soil 4) – the soils of the lowest mechanical quality – from a more solid base (see legend in Annex 2b).
- The second (and third) shallower refraction interface (the thicker dark blue line, for S-waves brown line) separates more dense, compact or damp eluvial-deluvial or alluvial soils in their subbase from more disintegrated or/and drier overlaying soils of cover.
- The deepest SRS interface (the thick blue line) represents the surface of the more solid subbase (like more tough clay? dump) under softer soils. It lies in the depth varying from 8 m to 18 m. Not far above this interface we can see anomalies at well logging curves. The shape of surface of P-wave and S-waves are very similar.

The environment of bedrock is divided by the isovels (isolines of seismic P-waves spreading velocity) into several quasi-homogeneous blocks with velocity gradient, the position of which corresponds with the disintegration of the bedrock (the lower is the same isovel the more and deeper disintegrated – of lower mechanical quality – is the rock), see the blocks description in legend in Annexe 2b.

2.2 Measurement and interpretation quality evaluation of SRS

The SRS measurement quality was generally good. The SRS was negatively influenced particularly by vibrations coming from the powerplant accessories and from the very dampening effect of dumps, which frequently caused polarities of geophones by its extreme varying of P-waves velocities.

The main problem was the velocity of seismic wave possible inversion in case of dumps in quarternary cover. The SRS in such case cannot see more disintegrated soils and rock deeper under such layer or blocks. This problem can be solved by VSP, which can see such layers.

The depth error of SRS is consequently estimated to be as much as 10 % +- 35 cm (reading of first arrivals of head wave error).

This expected mistake can be improved by interpretation calibration on the DPH or drillholes results.

2.3 Results of VSP survey

The situation of the VSP probes is given in Annexes 1a and 1b.

Main results of VSP are tables in annexes 3a to 3c with all measured and picked up times of first arrival of S-waves and P-waves, with geometry of measurements. There are presented also for all determinated quasi-homogeneous blocks of soils (colour filled lines) derived and calculated results like S-waves and P-waves velocities, volume densities and following resultant dynamic parameters of soils:

E_{dseis}	[MPa]	dynamic module of elasticity by SRS or VSP
G_{dseis}	[MPa]	dynamic shear modulus by SRS or VSP
ν_{dseis}	[/]	Poisson's ratio

Those results are presented also in Annexes 2a and 2b (inserted in violet characters in sections).

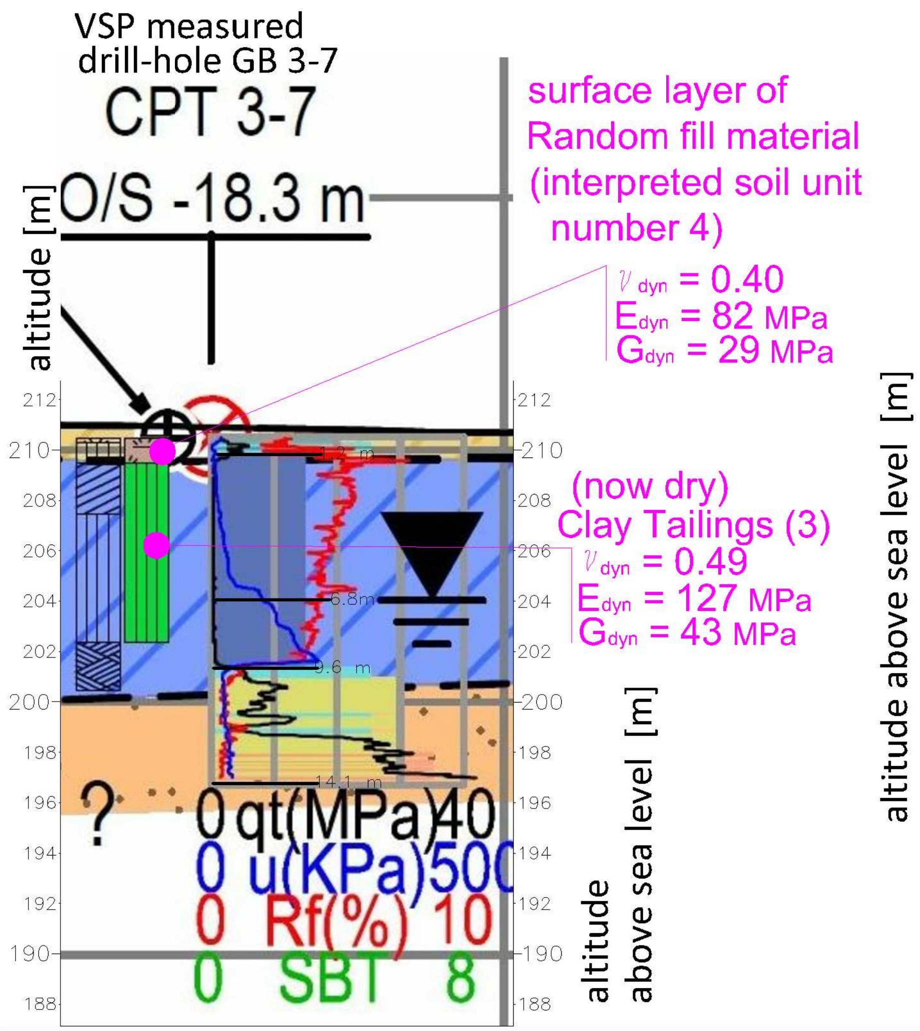
Attached annexes: 2b, 2c and 2d with results examples.

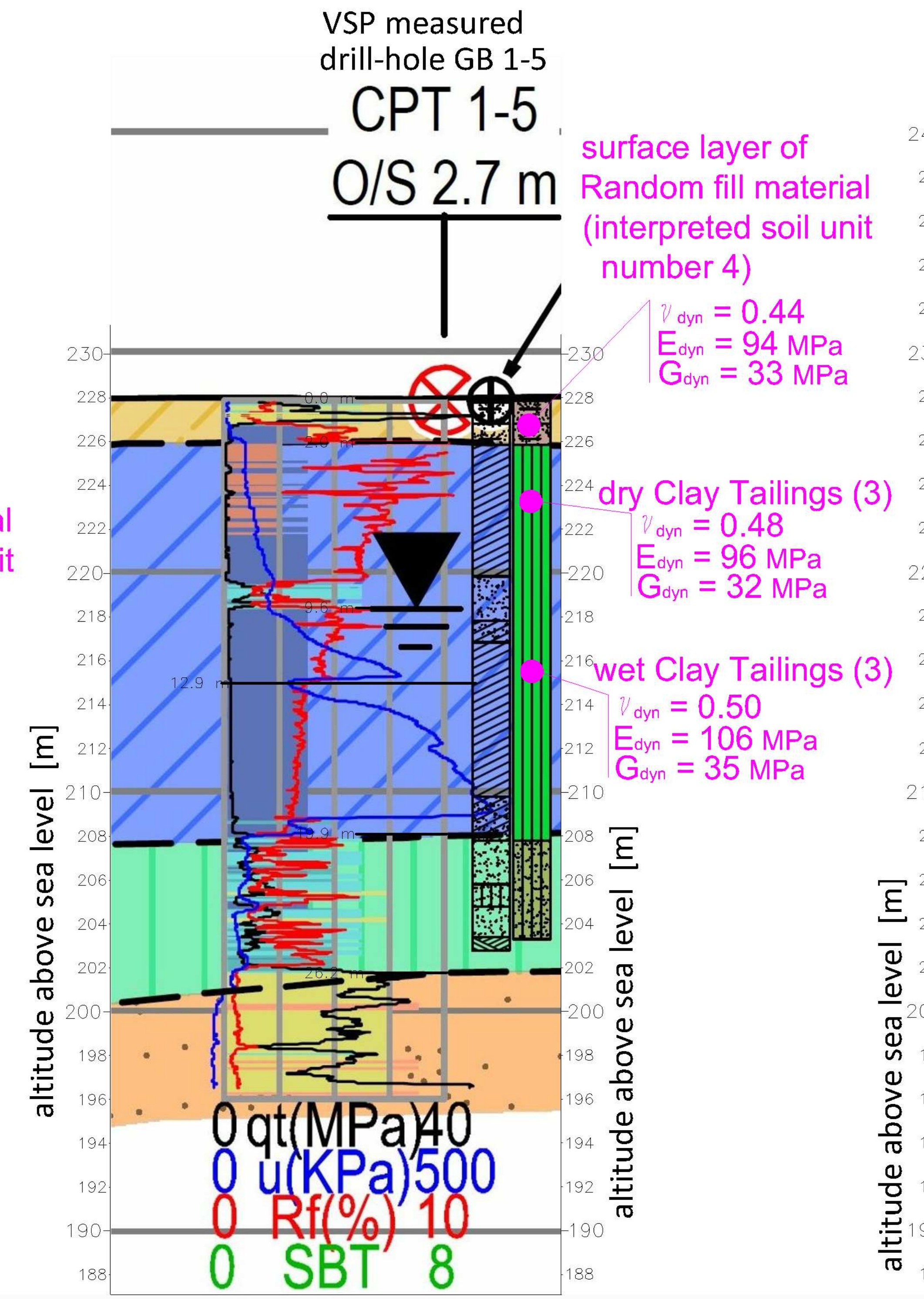
INTERPRETED SOIL UNITS

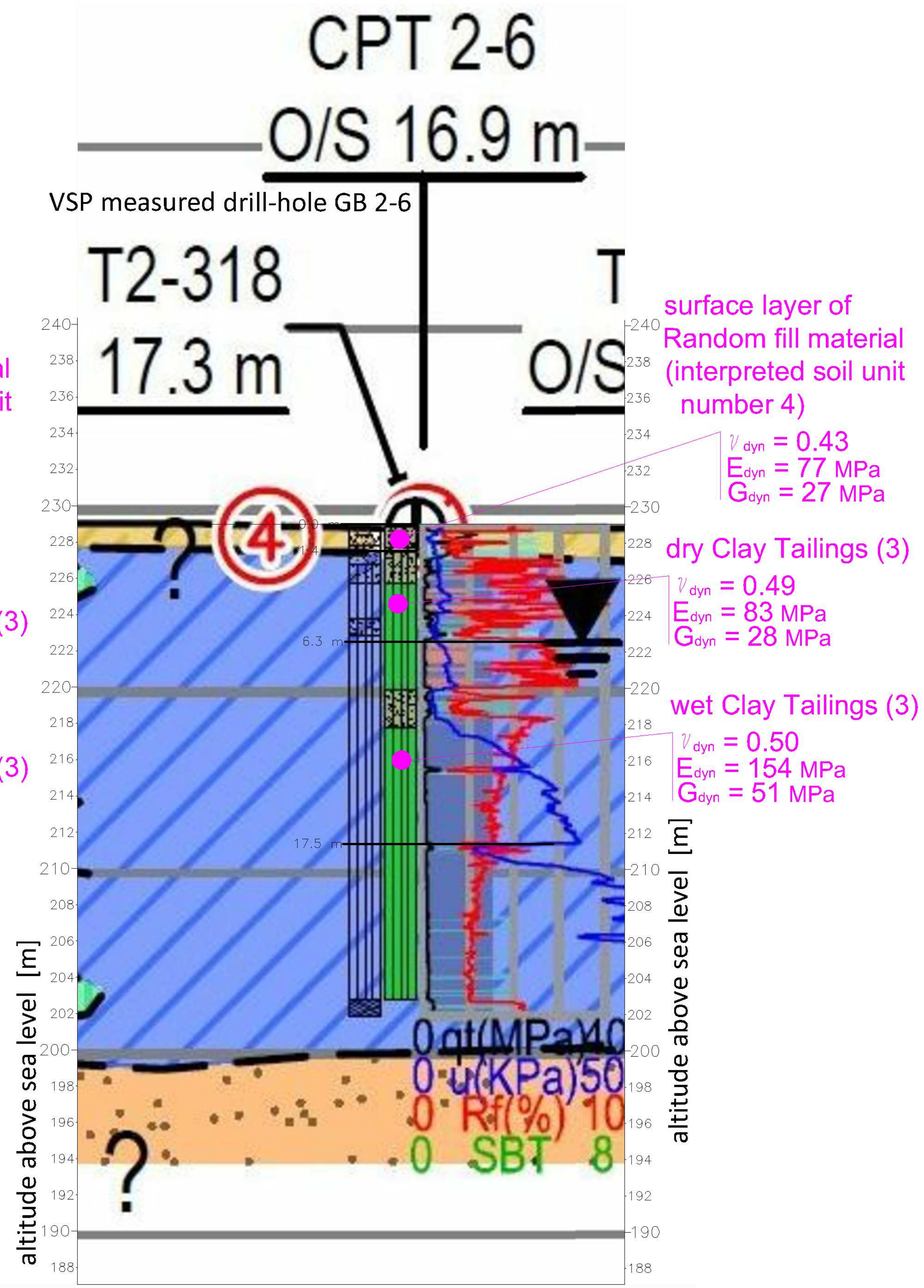
- Unit (1): Embankment Fill (compacted(?) sand tailings). Starter dam constructed from local native soils
- Unit (2): Interbedded silty SAND/SILT/CLAY tailings (typically becoming finer grained towards the center of the cell)
- Unit (3): CLAY tailings
- Unit (4): Random fill material (organics/loam/wood/brick/concrete fragments, etc.)
- Unit (5): Fluvial Sand (native soils)
- Unit (6): Claystone Bedrock
- Inferred Water level in CPT

Legend:

ν_{dyn} = ---dynamic Poisson's ratio
E_{dyn} = ---dynamic module of elasticity
G_{dyn} =---dynamic shear modulus
dry Clay Tailings-soil description according to drill-hole profile
(3)- (number of interpreted soil unit)



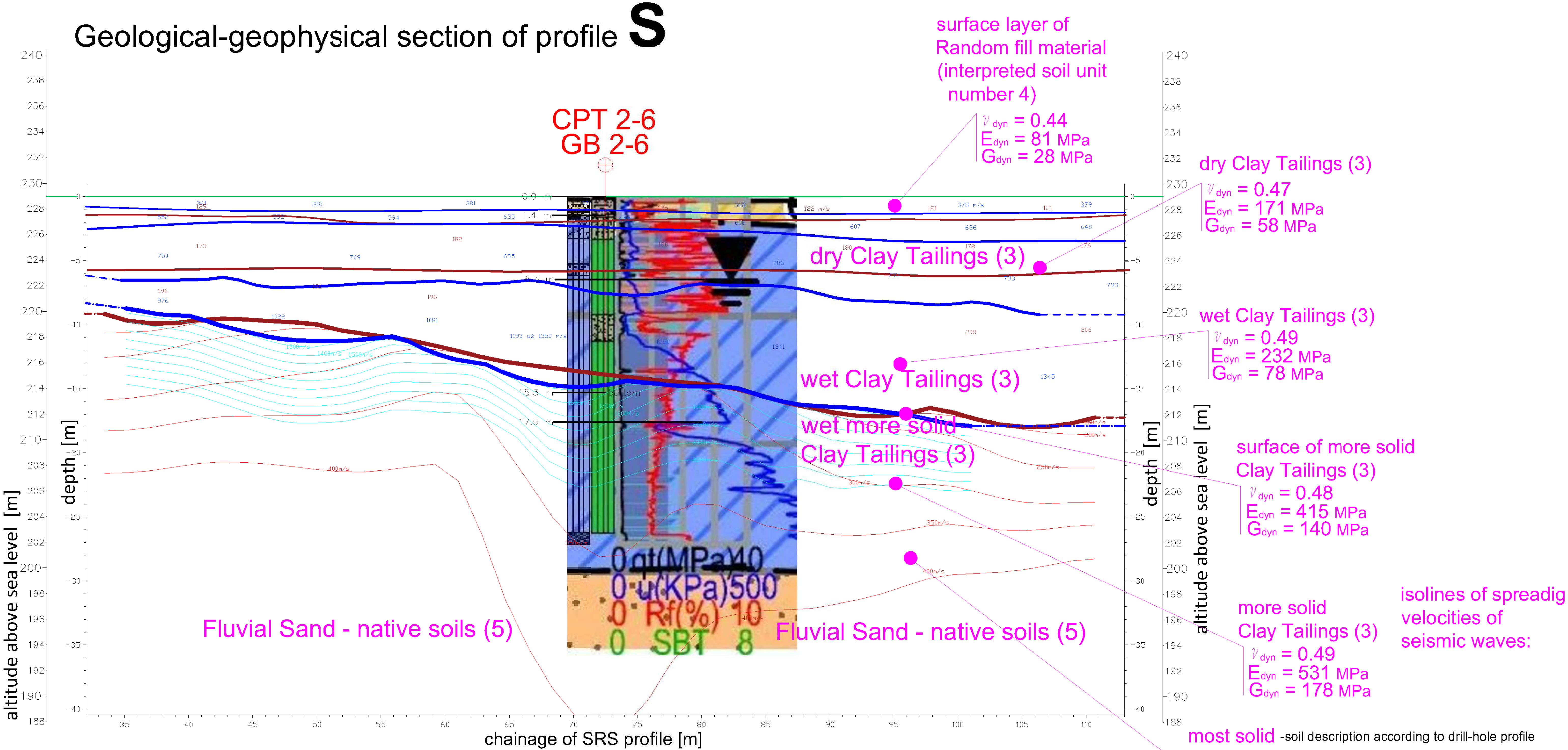




Other legend see annex 2b

Elaborated by: Mgr. Viktor Valtr	Job: Geophysical prospection of rock dynamic parameters by VSP well logging and SRS - EXAMPLE	Scale: 1:200 (A3)	Client:	Number: 2a
SIHAYA, spol. s r. o. Veleslavínova 6, Brno 612 00 tel./fax: 420 + 549 211 828 sihaya@sihaya.cz, www.sihaya.cz	Appendix name: Sections of VSP meas.drill-holes with dyn.parameters			

Geological-geophysical section of profile S



most solid Clay Tailings (3) - soil description according to drill-hole profile - (number of interpreted soil unit)

ν_{dyn} = 0.48 ---dynamic Poisson's ratio

E_{dyn} = 949 MPa ---dynamic module of elasticity

G_{dyn} = 320 MPa---dynamic shear modulus

Legend:

-ground surface

Random fill material (4)-layer of backfill - of loose soils (number of interpreted soil unit)

635 -seismic P-wave velocity in loose cover 122 m/s -seismic S-wave velocity in loose cover layer

-surface of more dense/solid soils according to P-waves SRS

-surface of more dense/solid soils according to S-waves SRS

635/201 -seismic P-wave / S-wave velocity in cover

-layer of more dense/solid soils (dry Clay Tailings) according to SRS

-surface of more dense/solid/wet soils according to P-waves SRS - and the same according to S-waves SRS

-layer of more dense/solid/or wet soils (wet Clay Tailings)

-surface of the more solid solis (solid Clay Tailings)

-isoline of the seismic P-wave velocity (P-wave isovel) -surface of the more solid solis according to S-waves SRS

-isoline of the seismic S-wave velocity (S-wave isovel)

2900 m/s -seismic P-wave velocity

350m/s -seismic S-wave velocity on isovel

SRS:

pf **S** -name of the section mapped

GB-2-6-name of bore hole

-bore hole or penetration

-0,5 m -depth of the interface

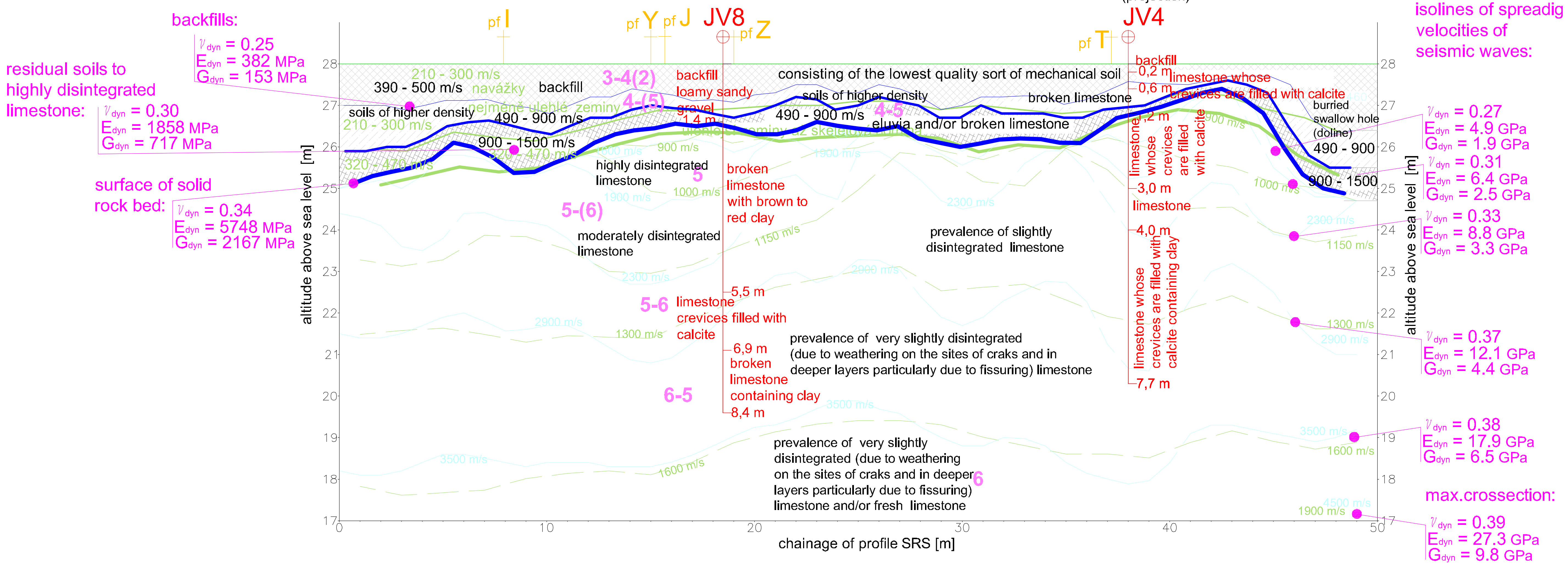
Clay Tailings -a simplified description according to the bore hole section or well logging

depth-6.3 m -interface according to dore hole core or well logging

Elaborated by: Mgr. Viktor Valtr	Job: Geophysical prospection of rock dynamic parameters by VSP well logging and SRS - EXAMPLE	Scale: 1:200 (A3)	Client:	Number: 2b
SIHAYA, spol. s r. o. Veleslavínova 6, Brno 612 00 tel./fax: 420 + 549 211 828 sihaya@sihaya.cz, www.sihaya.cz	Appendix name: Geological-geophysical Section - profile S			

section L
under profile

In accordance with the results of the measurements of the seismic P-wave velocity S-wave velocity



Legend:
SRS of the P-waves velocity:

- pf T -intersectionof the section with pfT
- -ground surface
- backfill ... -layer of backfill - layer of loose soils
- -surface of more density soils
- -layer of more density, solid soils
- -surface of the bed rock
- -layer of broken limestone or hard residual soil
- -surface of rock mass
- -isoline of the seismic P-wave velocity
- 2900 m/s -seismic P-wave velocity
- pf K -name of the section under profile K mapped

- JV3 -bore hole or penetration
- 0,5 m -depth of the intrface
- limestone + closed crevices filled with calcite -a simplified description according to the bore hole

crosshatching:

- -layer of backfill - layer of loose soils
- -layer of more density, solid soils
- - layer of broken limestone or sold residual soil reaching the stage of the rock mass

3-4(2) 4-5 -approximate classification accordig to hoistability by categories defined in the client, s report

Dynamic parameters detected by calculate from the spreading velocities of seizmic S- and P-wave and volume weight: (only pf Z a L)

the point of identification dyn.par.–
γ_{dyn} = 0.34 - Poisson s ratio
E_{dyn} = 12.9 GPa -dynamic moduls of elasticity
G_{dyn} = 4.9 GPa -dynamic shear modulus

Legend:
SRS of the S-waves velocity:

- backfill ... -layer of backfill - layer of loose soil
- -surface of more density soils - surface of the bed rock
- -layer of more packed, solid soils - layer of broken limestone or hard residual soil
- -surface of rock mass
- -isoline of the seismic P-wave velocity
- 2900 m/s -seismic P-wave velocity

Scale:	Elaborated by: Viktor Valtr	Job: / Name:	Number:
1:200 / 1:100	SIHAYA, spol. s r.o. Veleslavínova 6, Brno 612 00, Č.R. sihaya@sihaya.cz http://www.sihaya.cz	Geophysical prospection; Rijeka...EXAMPLE / GEOLOGIC-GEOPHYSICAL SECTION - profile L	2d