The use of dynamic moduli logging in large-scale geotechnical modelling

Irmina Pöschl
iC Consulenten ZT GesmbH, Salzburg, Austria

Walter Frei
GeoExpert AG, High Resolution Seismic Surveying, Embrach, Switzerland

ABSTRACT: The dynamic elasticity rock mass modulus was used as reference parameter for developing large-scale geotechnical models. Modulus values were derived from p- & s-wave seismic refraction surveys. Hybrid seismic surveying, an increasingly applied combination of refraction and reflection seismic testing, proved being a particularly helpful tool for delivering the data necessary for a comprehensive interpretation of modulus distribution. Seismic surveying provides large amounts of spatially continuous data coverage at relatively small cost and time effort. Due to the non-intrusive nature of probing, the recorded data type reflects in-situ conditions, not corrupted by invasive procedures. Adequately processed, the data can be directly transferred into digital models for visualization, evaluation and interpretation. The experiences made from survey programs with different investigation methods and targets opened new perspectives for rock mass characterization, but also disclosed limitations to be considered for a successful application.

Keywords: Elasticity modulus, hybrid seismic surveying, seismic refraction tomography, reflection seismic surveying, 3D modelling.

1 INTRODUCTION

The deformation properties of rock mass are particularly important for foundations of large civil structures. Static moduli are usually determined from cost and time-intensive in-situ tests, which are often difficult to perform at necessary scales and coverage. In contrast to static deformation properties, dynamic properties can be determined more efficiently by seismic surveys, covering extensive rock mass volumes and delivering large data pools.

1.1 The method of hybrid seismic surveying

Since the mid-1990s, seismic refraction tomography, a further development of seismic refraction profiling, came onto the market. It is now proving to be an indispensable tool for high-resolution mapping of the seismic propagation velocity gradient field for detailed geotechnical subsurface site characterization. Seismic refraction tomography is also of interdisciplinary significance for enabling the application of the reflection seismic method, the ultimate geophysical exploration tool in the petroleum industry. For the latter to be useful for civil engineering purposes, the accurate refraction seismic velocity field is the basic input ingredient for processing reflection seismic data in near surface depth range.

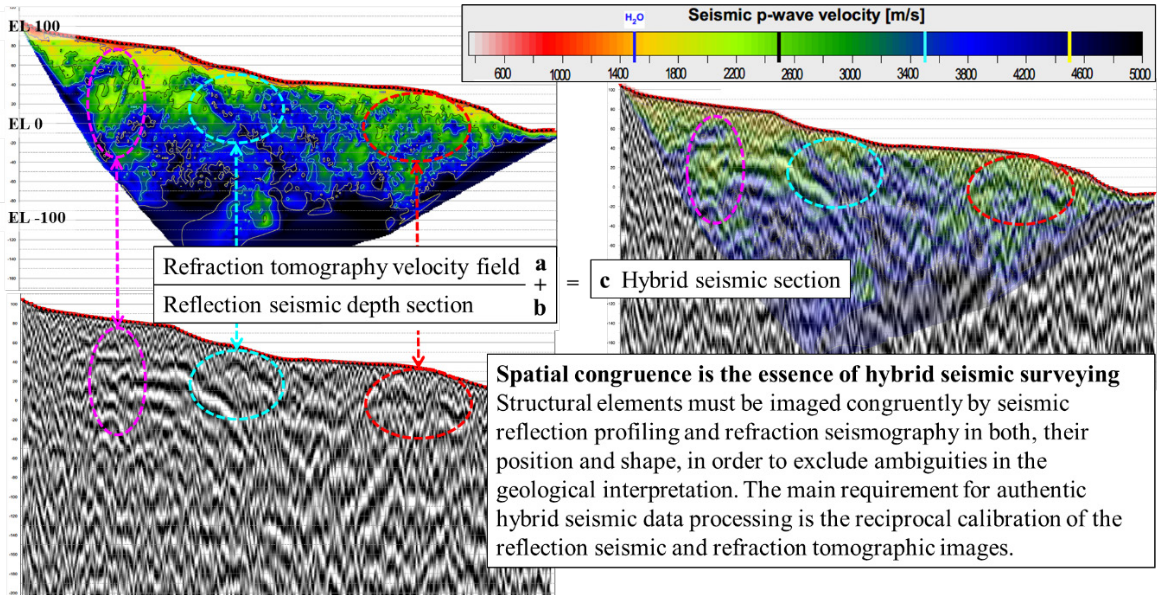


Figure 1. The principle of spatial congruence for verifying the authenticity of the hybrid seismic data.

The intertwined combination of these two methods, for both data acquisition and processing, led to the hybrid seismic survey method. This procedure is a combination of high-resolution reflection seismic profiling with the technique of refraction seismic tomography inversion. While reflection seismic surveying is instrumental for mapping structural features, refraction seismic survey is mainly used for detecting and defining zones of different rock mechanical properties.

The breakthrough for the application of this potent geophysical discipline at near-surface depths occurred in 2000 (Frei & Keller 2000), when highly detailed refraction tomography-derived velocity fields started being used for processing reflection seismic data. The method of refraction seismic tomography inversion is appropriate for deriving the velocity gradient field under complex geological conditions. Contrary to depth models based on traditional refraction seismic surveys, the results of refraction tomography profiling are not influenced by subjective assumptions and are for this reason more reliable. The seismic velocity field is a direct representation of rock rigidity distribution in the subsurface. The spatial congruence of the reflection seismically and refraction tomographically imaged structures in the subsurface is the essential criterion of an authentic hybrid seismic data processing strategy (see Figure 1).

Today, hybrid seismic surveying is a reliable and accurate geophysical tool for investigating subsurface structural and rock mechanical conditions. Compared to a single high-resolution reflection seismic survey, the additional effort for performing both reflection and refraction seismic techniques is negligible, since only one data set is to be acquired. However, this data set with a geophone spacing not larger than 2 m, must be sufficiently long to ensure that the desired depth of investigation is also attained by diving wave refraction tomography. A seismic recording system with at least 320 channels is recommended for ensuring expedient and cost-efficient data acquisition for hybrid seismic surveys (Frei 2010, 2012, 2019).

Limiting factors that often affect data quality include ground unrest from various external sources such as traffic, industrial, and agricultural activities. However, self-generated noise (e.g., ground roll) and contamination from ray geometrical artifacts due to complex subsurface structures are unavoidable, and their quality-degrading effects cannot always be satisfactorily mitigated during data processing.

1.2 Dynamic elasticity modulus as reference parameter

The dynamic elasticity modulus (referred to as Edyn) can be determined – so-to-say as a by-product - from a comprehensive seismic survey. Edyn is calculated (for an idealized isotropic material) from the compression wave velocity (Vp), the shear wave velocity (Vs) and the rock density (ρ):

$$\mathrm{Edyn} = \rho \mathrm{Vs}^2 \cdot \left(\frac{3\mathrm{Vp}^2 - 4Vs^2}{\mathrm{Vp}^2 - Vs^2}\right) \quad (1)$$

Seismic velocities Vp and Vs are directly recorded from seismic surveys. Rock mass density ρ is usually estimated from laboratory data.

Most geotechnical applications require the knowledge of static, rather than dynamic deformation properties. Usually, the static elasticity modulus (Estat) value is - for the same material - notably lower than dynamic elasticity modulus Edyn. Depending on the type of rock and on the rock mass conditions the ratio Edyn/Estat may vary widely, but (according to literature and project experiences) often ranges from 2/1 to 5/1. Ideally, the appropriate Edyn/Estat ratio for a particular project is verified by comparing Edyn and Estat values, that are determined by different kinds of insitu testing. The use of several testing methods is highly recommended to increase the reliability of the selected correlation factor.

Dynamic modulus logging was successfully performed and used for developing geotechnical models of large civil structures over recent years. The exemplary application of such an approach is presented further in this paper.

2 DYNAMIC MODULUS LOGGING FOR A DAM FOUNDATION MODEL

2.1 Project and applications

Hybrid seismic surveying was used for reviewing the geotechnical model of a dam foundation, that suffered severe settlements during dam construction. As initial step for a rehabilitation design, the observed deformations should be simulated in a large-scale 3D calculation, based on a suitable geotechnical model. For understanding the ground conditions causal for the foundation behavior, a comprehensive site investigation program along the dam foundation and at the wider dam area was developed and executed.

Because of the particular importance of the rock mass deformation properties and their large-scale distribution, it was decided to commence the investigation program with a geophysical survey campaign. This campaign included hybrid seismic lines with an accumulated length of 2350m. The main investigation line followed the upstream toe of the dam structure, comprising two profiles of ca. 500m length each. The investigation depth reached ~100m for Vs, ~200m for Vp by refraction tomography inversion and ~ 400m for reflection seismic surveys. For obtaining these investigation depths and for optimal imaging resolution, particular recording parameters had to be chosen: 1) The length of the active spread was 4 times the desired investigation depth. 2) The receiver station spacing was 2 m max. 3) The source point distance was not larger than 2 – 3 times the receiver station spacing.

Figure 2 depicts the compiled results along the left bank abutment of the dam structure. The pictorial sequence reflects the evaluation steps using the Vp and Vs velocity fields (Figure 2-a&b) according to equation (1) for deriving an Edyn modulus depth section (Figure 2-c). The general influence of density values on the calculation of moduli was assessed by using upper and lower bound density values at selected locations, where the vertical variability of rock mass parameters is visualized (Figure 2-e). The distribution patterns in the 2D value fields suggested heterogeneous and complex rock mass conditions, with sudden and locally inverse (decreasing with depth) changes in stiffness. Along some, non-linear meandering sections of the seismic lines sharp directions changes resulted in signal events arriving from different directions. Therefore, a strictly uniform polarity of shear wave signal events could not be maintained, Vs values were judged unreliable and Edyn moduli were not calculated (blank areas in Figure 2-c). When recording shear wave seismic data, it is thus recommended to avoid – where possible – non-linear geophone spread layouts.

Other causes for such constraints and for limitations in accuracy - for seismic s- and p-waves alike - are complex and irregular structural features in the subsurface creating ray-geometrical artifacts. When recording a single 2D seismic line, for example, reflected and refracted signal events emanating from structures in the 3D subsurface, which are located outside the vertical profile plane, are projected into the profile plane as distorted ray-geometric artifacts. These artifacts give rise to a confusing image with skewed structural elements that are not at their true depth. A grid of intersecting seismic lines can help for a more reliable interpretation of the data. If – as it was the case for this application – such an approach is not possible due to difficult terrain and existing man-made structures, the geotechnical interpretation must be supported by other investigation methods.

The understanding of the subsurface was further improved by interpreting structural features from reflection seismic data (Figure 2-d), which were processed in calibration with the tomography derived Vp velocity field.

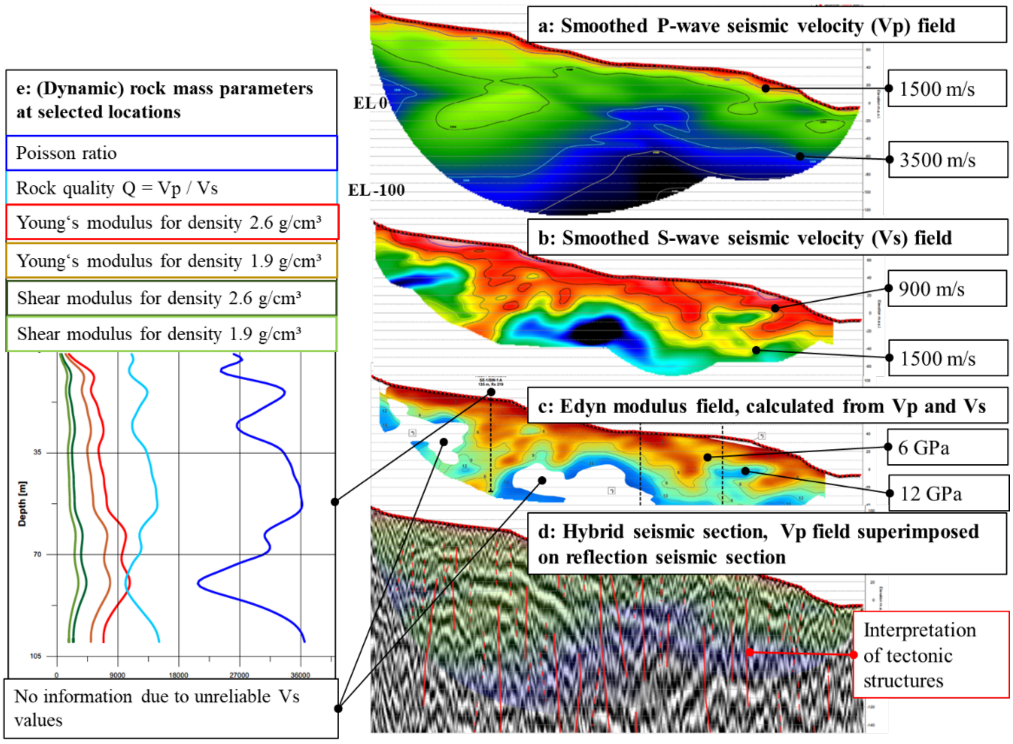


Figure 2. Results of hybrid seismic survey in a 500m long 2D profile.

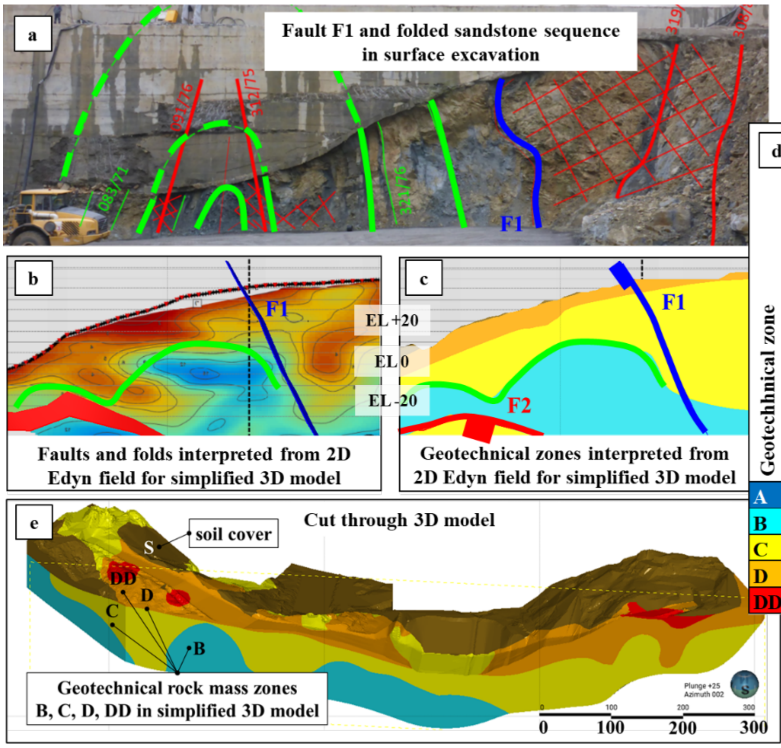
2.2 *Data evaluation and interpretation*

2.2.1 *Lithology and faults*

Once distribution patterns of Edyn were visualized in 2D profiles, the results were put in context to the geological data available from other investigation sources.

A dense grid of boreholes and geoelectric survey lines established a clear relation between typical Edyn distribution patterns and particular lithologies. More homogeneous but generally lower Edyn values were measured, where the rock mass was dominated by claystones and siltstones. Wide ranges of Edyn values with heterogeneous spatial distribution (Figure 2-c) were associated to a folded sequence, where sandstones prevail over siltstones and rare claystones. Accordingly, three distinct geological domains could be distinguished at the dam site for further geological modelling.

The geological domains are separated by faults. Where hybrid seismic survey lines cross faults, E_{dyn} fields often displayed sudden lateral and/or horizontal changes (Figure 3-b). One of these faults was also prominently exposed in surface excavations (Figure 3-a).



d

Geotechnical zone	Dynamic elasticity modulus from seismic survey	Static elasticity modulus, Edyn/Estat = 5/1	Characteristic static elasticity modulus for geotechnical zones
	Edyn	Estat	E
	MPa		
A	>9000	>1800	3200
B	5000-9000	1000-1800	1600
C	2000-5000	400-1000	700
D	1000-2000	200-400	300
DD	<1000	<200	160

Figure 3. Faults and geotechnical zones interpreted from Edyn logging for large-scale 3D model.

2.2.2 *Static elasticity modulus E of rock mass*

One of the most important and most critical issues was the translation of Edyn (available from seismic surveys) into Estat (required for numerical calculations, also referred to as E). By comparing Edyn values from seismic surveys and borehole suspension logging (in 6 boreholes) with $Estat_t$ values from dilatometer tests (113 in 25 boreholes) and jacking tests (6 in trenches, 4 in investigation shaft), a correlation factor Edyn/Estat = 5/1 was established. This comparatively unfavorable factor implied very low static elasticity moduli E throughout substantial volumes of the dam foundation (Figure 3-e). The selected factor was repeatedly challenged throughout the process of geotechnical modelling but was defended by a statistically robust data base. Figure 4 shows the E values that were assigned to geotechnical zones compared to the statistic distribution of test data.

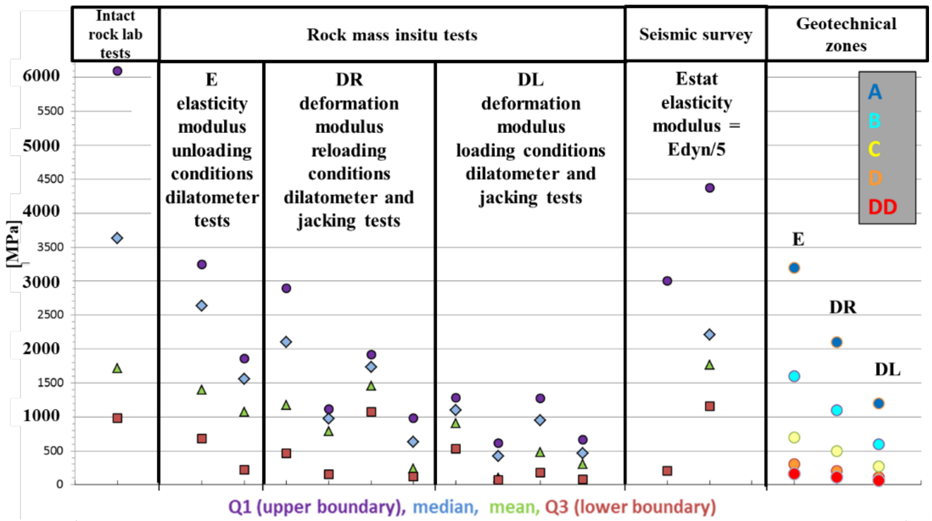


Figure 4. Moduli assigned to geotechnical zones compared to moduli determined by testing.

2.2.3 Geotechnical zones in large-scale 3D model

The main target of the investigation phase referred to in this paper was the establishment of a 3D geotechnical model, which was suitable for large-scale 3D deformation calculations. The calculation model was foreseen to comprise a volume block of approximately 1000m (along dam axis) x 250m (width of corridor along dam axis) x 90m (depth below dam foundation). The spatial distribution and the dimensions of geotechnical zones with characteristic rock mass parameters not only needed to appropriately describe the geotechnical foundation properties but were also required to accommodate the limitations of the 3D calculation software. For meeting these necessities, the complex foundation conditions were translated into a simplified geotechnical model that comprised 5 geotechnical zones (A, B, C, D and DD). The definition of these geotechnical zones – regarding geometry and deformation properties - was mainly based on the 2D continuous Edyn fields. Typical value ranges and characteristic design values of elasticity moduli were assigned to the geotechnical zones (Figure 3-d). The simplification process is exemplarily shown in Figure 3, where the interpretation of detailed Edyn fields (Figure 3-b) lead to the definition of geotechnical zones (Figure 3-c) and eventually to the development of a large-scale 3D geotechnical model (Figure 3-e).

3 CONCLUSIONS AND RECOMMENDATIONS

Dynamic modulus logging by hybrid seismic surveying was an important tool for developing a large-scale geotechnical dam foundation model. The complex spatial arrangement of rock mass volumes with similar deformation properties was imaged with significant reliability by continuous 2D distribution fields of dynamic elasticity moduli (Edyn). Supplemented and calibrated with a large data pool of static elasticity moduli determined by direct insitu testing, dynamic moduli Edyn could be correlated to characteristic static moduli (Estat or E), that were assigned to geotechnical zones. Both, the selected correlation factor and the geotechnical model were eventually proven appropriate by the results of subsequent calculations, that yielded deformation patterns and dimensions very similar to those observed during dam construction.

Coverage as well as cost & time efficiency of the hybrid seismic survey by far exceeded those of conventional testing methods for E modulus logging. The campaign would have been even more effective, if the survey had been carried out before the terrain was complicated by construction, which locally imposed avoidable limitations on survey processes and data evaluation. The experiences and lessons learned in this project lead to the successful application of modulus logging by hybrid seismic surveying at several other large infrastructure projects.

REFERENCES

Frei, W. 2019. Hybrid seismic surveying for detailed characterization of the shallow and intermediate depths subsurface. *MODERN2020 (2nd) International Conference about Monitoring in Geological Disposal of Radioactive Waste – Extended abstract poster session 9*. – 11. April 2019 – Paris.

Frei, W. 2012. Methodology and Case History of Hybrid Seismic Surveying in Combination with Multi-channel Analysis of Surface Waves (MASW) - A Useful Tool for the Detection of Rock and Soil Instability Zones. In: *Proceedings of the International Conference on Geotechnical and Geophysical Site Characterization (ISC'4), Porto de Galinhas, Brazil 18-21 September 2012, (CRC Press, ISBN 978-0-415-66070 9 (p. 1297ff, Vol. 2) or ISBN 978-0-203 073896*, (eBook).

Frei, W. 2010. Seismic surveying tools for the early detection of rock instability zones. Paper presented at the *European Rock Mechanics Symposium (EUROCK 2010)*, 15. – 18. June 2010, Lausanne, Switzerland.

Frei, W. and Keller, L. 2000. Hybride Seismik – eine verbesserte Methode zur Verwertung des Aussagpotenzials seismischer Daten (Hybrid seismics - an improved method for exploiting the informative potential of seismic data). *Bull. angew. Geol.* Vol 5, Nr. 2, pp. 229 – 236.