Paper presented at the 4th International Conference on Geotechnical and Geophysical Site Characterization (ISC'4) at Porto de Galinhas, Brazil, 18-21 Sept. 2012

Methodology and Case History of Hybrid Seismic Surveying in Combination with Multichannel Analysis of Surface Waves (MASW): A Useful Tool for the Detection of Rock and Soil Instability Zones

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ABSTRACT: The acquisition of high resolution seismic reflection, seismic refraction tomography and MASW data can be carried out simultaneously by using modern recording equipment featuring 150 - 250 data channels. The implementation of a specially adapted roll-along recording technique not only reduces the field time for the seismic crew, but it also ensures a regular and continuous data coverage along seismic trajects several times longer than the active spread length. The data evaluation results of the three seismic methods are jointly presented for easier geological and geotechnical cross reference. Guide lines are provided for the appropriate choice of the field data acquisition parameters as a function of the required investigation depth and of the desired degree of imaging resolution.

1 INTRODUCTION

1.1 *Keywords*

High resolution reflection seismic profiling, seismic refraction tomography, Multichannel Analysis of Surface Waves (MASW), p- & s-wave velocity, roll-along recording, source-receiver offset, inline offset, velocity anomaly.

1.2 *Seismic methods applied in geotechnical engineering*

In engineering geology the advent of increasingly powerful and ever more affordable data recording instruments and processing facilities over the past 15 years have triggered the widespread use of high resolution reflection seismic profiling and state-of-the-art seismic refraction diving wave tomography. Both methods have their advantages and short-comings, which are summarized in Table 1 below.

As an obvious conclusion of the performance comparison of the two methods in Table 1, their field data acquisition and interpretation procedures have been combined, which has resulted in the technique of hybrid seismic surveying.

In hybrid seismic surveying the disadvantanges of one method are compensated by the benefits of the other. Apart from the substantially lower costs by reducing the data recording work to one single field operation, the major advantage is to be seen in the enhanced interpretation reliability gained by the joint presentation of the results of the two methods, which are completely independent of each other. For this reason they are truly complementary to each other and thus instrumental for reciprocal calibration purposes.

2 DATA ACQUISITION PARTICULARS FOR HYBRID SEISMIC SURVEYING

2.1 *Generic considerations*

The resolving power of hybrid seismic data is proportional to the spatial data density, defined by the spacings between the receiver stations and between the source points. The smaller the separation between the geophone stations, the higher is the imaging resolution of the seismic data, provided the frequency content of the source signal is commensurate with the desired image resolution.

The attainable depth of seismic refraction tomography, on the other hand, is a function of the length of the active spread lay-out.

Therefore, even with close receiver spacings, it has to be ascertained that a long enough active spread is to be laid out for attaining the desired investigation depth. For this reason an adequate number of data channels and geophones is mandatory.

Based on the desired depth of investigation, the following rules apply for acquiring hybrid seismic data:

Table 1. Performance ratings of seismic reflection profiling and refraction tomography inversion

SURVEY REQUIREMENTS & OBJECTIVES	Reflection seismic profiling	Refraction tomography inversion
High resolution at shallow depths (< 10m)	**LIMITED**	**GOOD**
High resolution at greater depth (> 20 m)	**GOOD**	**LIMITED**
Attainable depth of investigation	**HIGH**	**LIMITED**
Rock/soil quality & rippability indicator	**POOR**	**GOOD**
Detection of velocity inversions	**POOR**	**GOOD**
Fault zone indicator	**GOOD**	**LIMITED**
Detection of decompaction zones	**LIMITED**	**GOOD**

1. The 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 on the complexity of the subsurface structures).

2. The length of the active spread should be at least 3 - 4 times larger than the desired depth of investigation.

3. The source point distance is to be chosen not larger than 1 - 3 times the receiver station spacing (depending on the locally attainable data quality and on the complexity of the subsurface structures).

Working example based on the above given rules for a desired investigation depth of 100 m:

- A receiver station spacing of 2.0 m is appropriate (see rule 1. above).
- The spread length must be 300 - 400 m, which means that with a geophone spacing of 2.0 m, the active lay-out consists of 150 - 200 geophones, i.e. a recording seismograph should feature this number of data channels (see rule 2. above).
- The source point distance should not exceed 6.0 m. Under very difficult conditions 2.0 m - 4.0 m is preferrable (see rule 3. above).

2.2 *Practical aspects*

The use of a roll-along recording technique with a move-up distance of half a spread length is recommended as follows (see Figure 1):

Recording cycle 1: Start recording in the first spread position with regular source point distances, as outlined under point 3 above, until the center of the spread. Then continue recording with twice the source point distance until the far end of the spread.

Recording cycle 2: Move the entire active spread forward by half its length and relocate the source (hammer or weight dropper) back to the rear end of the spread now in its new, second position. Continue recording at the source points at twice the source point separation distance, but in between the source points already used during the first recording cycle. Continue recording with twice the shot point distance until the far, forward end of the spread.

Recording cycle 3: As in cycle 2 move the spread forward by half its length and relocate the source back to the rear end of the spread now in its new, third position. Continue recording as in cycle 2 at every second source point and in between the points used in the previous cycle.

Subsequent recording cycles are identical to cycle 3.

This roll-along scheme of stationary spreads has the advantage that in each cycle maximum offset data both in the forward and reverse directions are obtained for continuous maximum refraction tomography penetration depths.

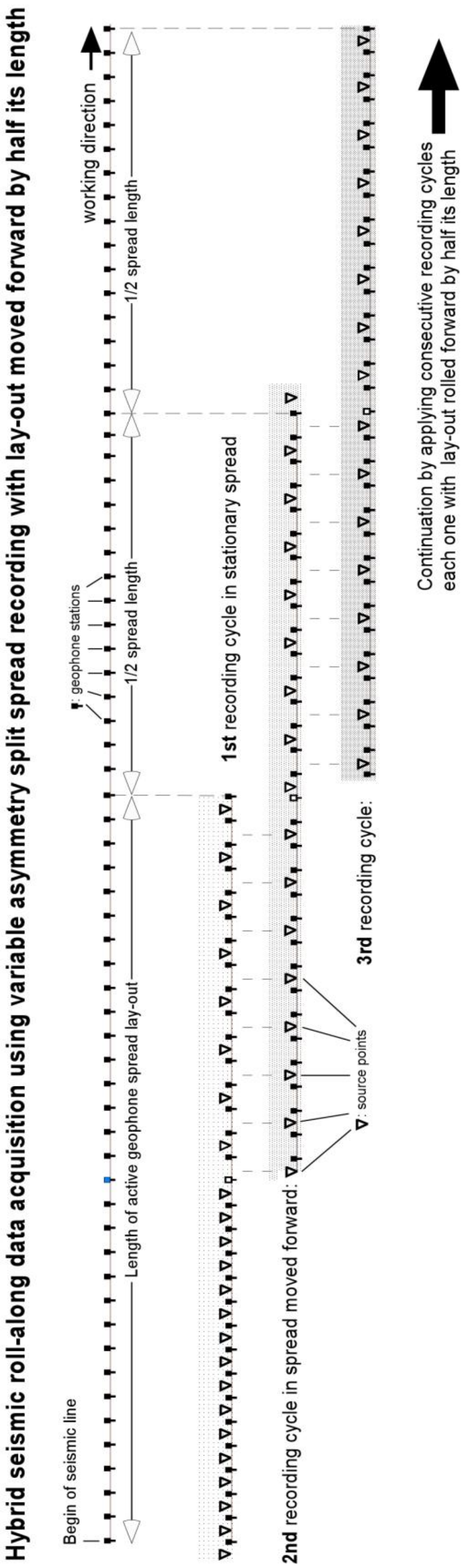

Figure 1. Recommended schematic hybrid seismic data acquisition procedure for full coverage of maximum source – receiver offset data along the entire length of a seismic traject being several times longer than the active spread lay-out.

In case the number of available data channels is insufficient for the required minimum spread length for recording refraction tomography data, it is common practice to simulate larger source-receiver offsets by allocating additional source points at various in-line offset distances from both ends of the active spreads.

3 USING HYBRID SEISMIC DATA SETS FOR MASW DERIVATION OF THE SHEAR WAVE VELOCITY FIELD

The data recorded by the acquisition scheme portrayed in Fig. 1 are amenable also to MASW evaluation for deriving the shear wave velocity field. Attention has to be paid to use geophones with a natural frequency of not higher than 10 Hz, since the penetration depth with the MASW method decreases with higher frequency geophones. The MASW investigation depth with 10 Hz geophones is around 15 - 18 metres. 4.5 Hz geophones are to be preferred if the emphasis is put on obtaining greater penetration depths of up to 30 m.

In Fig. 2 - 5 the results of hybrid seismic and MASW evaluations are presented for a 60 m long trajectory recorded in the residential part of a Swiss village, which was affected by a spontaneous sinkhole collapse in the front yard of a family home. A grid of six seismic lines covering an area of 120 m by 80 m was recorded.

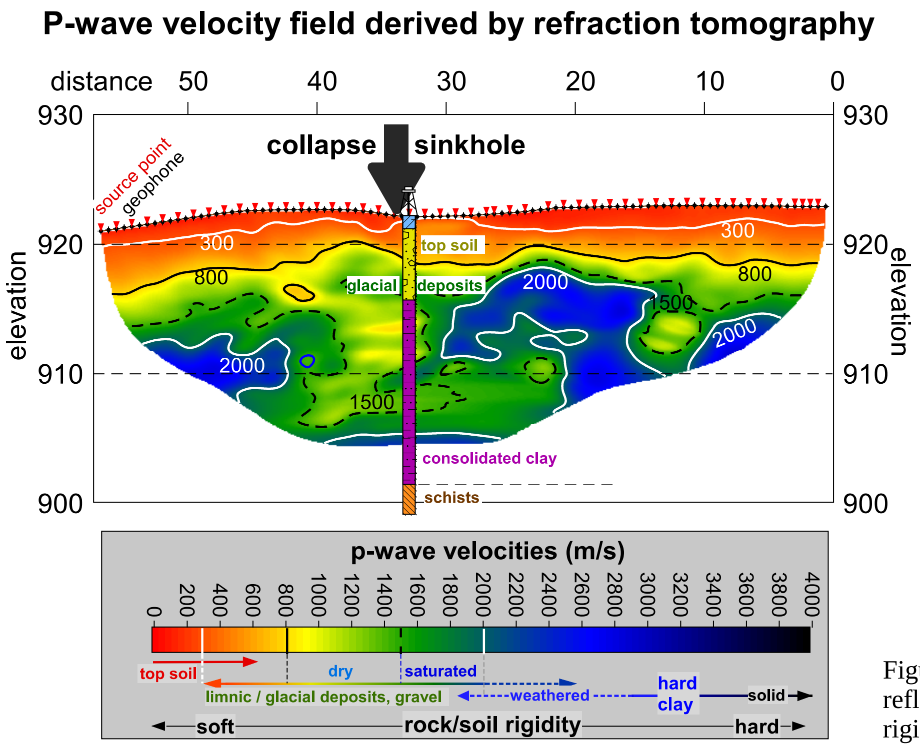

Figure 2. The colour encoded p-wave velocity field reflects the distribution of relative values of rock rigidity.

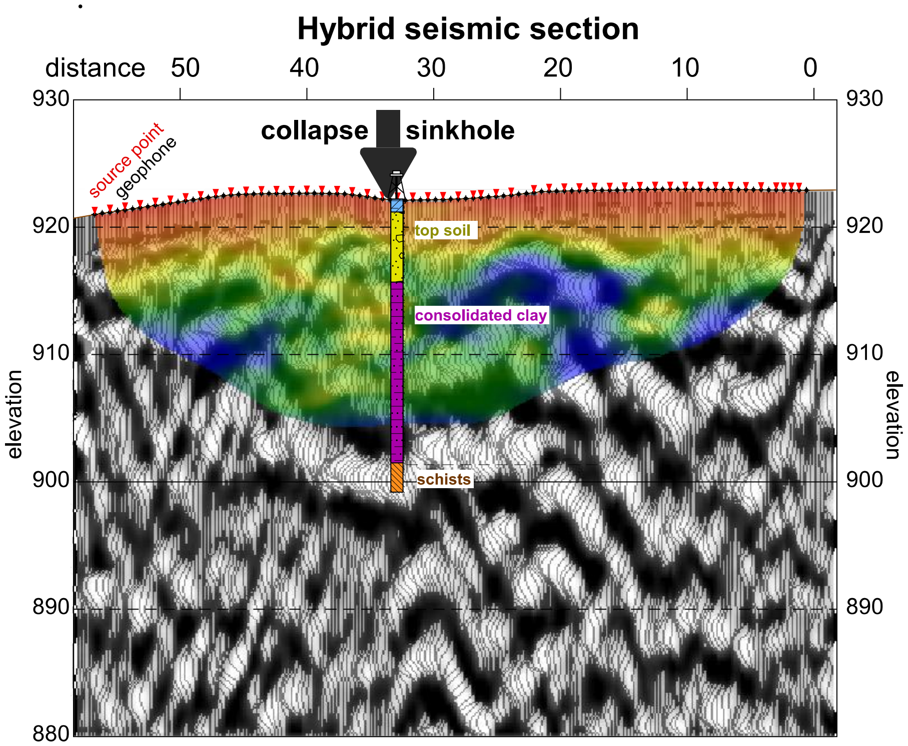

Figure 3. The velocity field from Fig. 2 is superimposed onto the reflection seismic depth section for a joint visualisation of the rock stiffness distribution in the uppermost 20 m and of the tectonic-geological structures over the entire depth range of the subsurface.

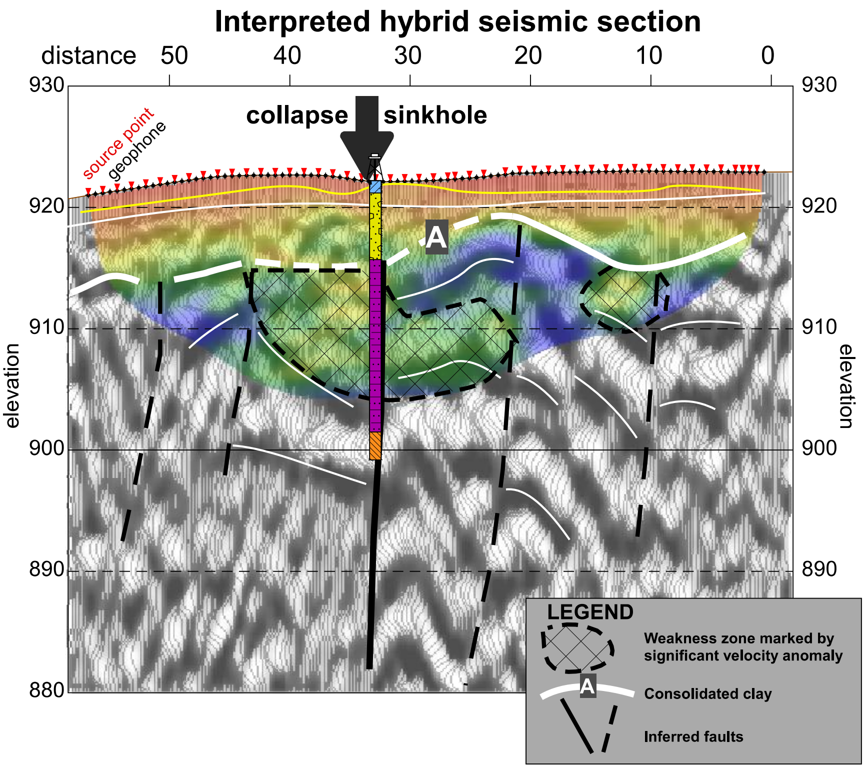

Figure 4. The interpretation is facilitated by visual correleation of the velocity field infor-mation (e.g. anomalies) with the x-ray type image of the reflection seismic section. On the latter the geological and tectonic structures such as faults and truncated layer folds can be readily identified. The well drilled near the sinkhole found the consolidated clay surface as indicated by the reflector A.

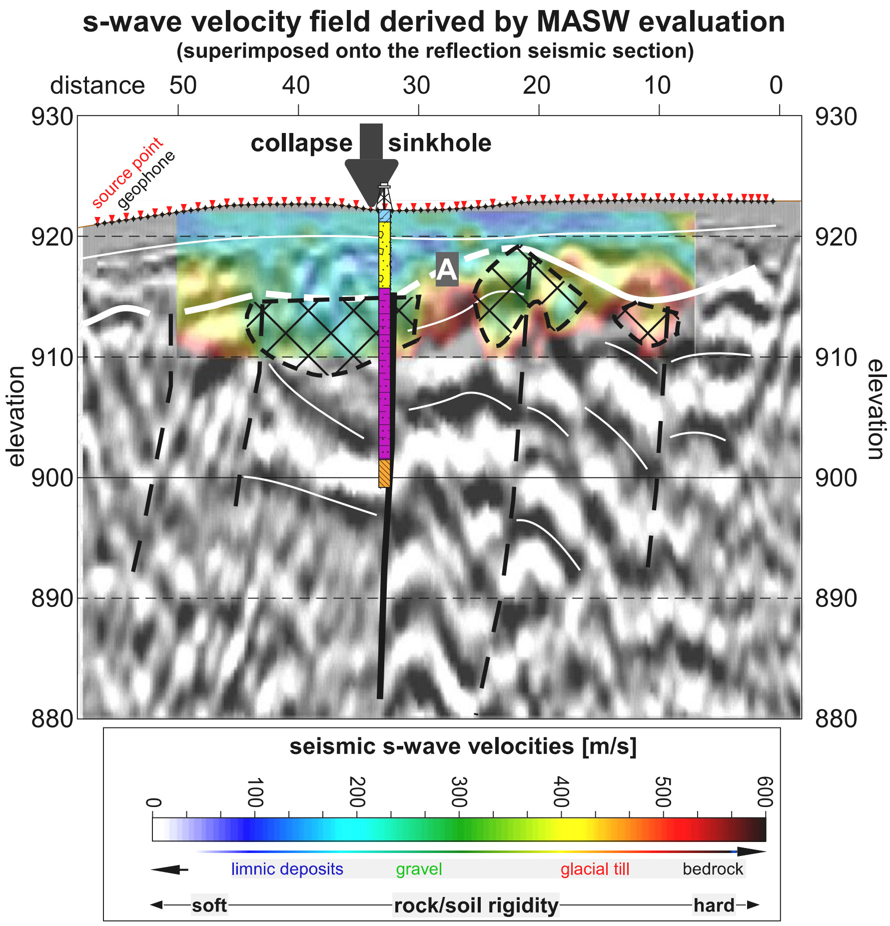

Figure 5. The s-wave velocity field, although mappable to a depth of approx. 12 m only, is in good agreement with the geological interpretation of the hybrid seismic section in Fig. 4. It clearly shows the significantly reduced soil / rock rigidity at the location of the collapse sinkhole. It also pictures the reduced rock strength associated with the faults at 9 m, 20 m and 43 m distance.

The data pictured in Fig. 2 – 5 were acquired with a geophone station spacing of 60 cm, and shot point separations between 0.6 cm and 1.2 m. The near surface structures in the uppermost 20 m are highly complex, being a lithological mixture of top soil and various glacial deposits overlying leached metamorphic rock material.

A well drilled to a depth of 24 m at the location of the collapse sinkhole confirmed the poor rock quality as documented by the seismic data. Apart from mapping the subsurface structures around the collapse sinkhole, the survey's objective also was the detection of additional weakness zones at the site.

Another seismic traject, line 2, intersecting line 1 (above) at the collapse sink-hole, is pictured in Fig. 6 with a clear indication of another ground instability calling for preventive measures.

Such an endangered zone is indicated by the velocity anomaly associated with the Y-shaped fault pattern at elevations between 900 m and 913 m on this line between 48 m and 30 m distance. The subsurface structures in the endangered zone are further characterized by seismic line 3 (Fig. 8).

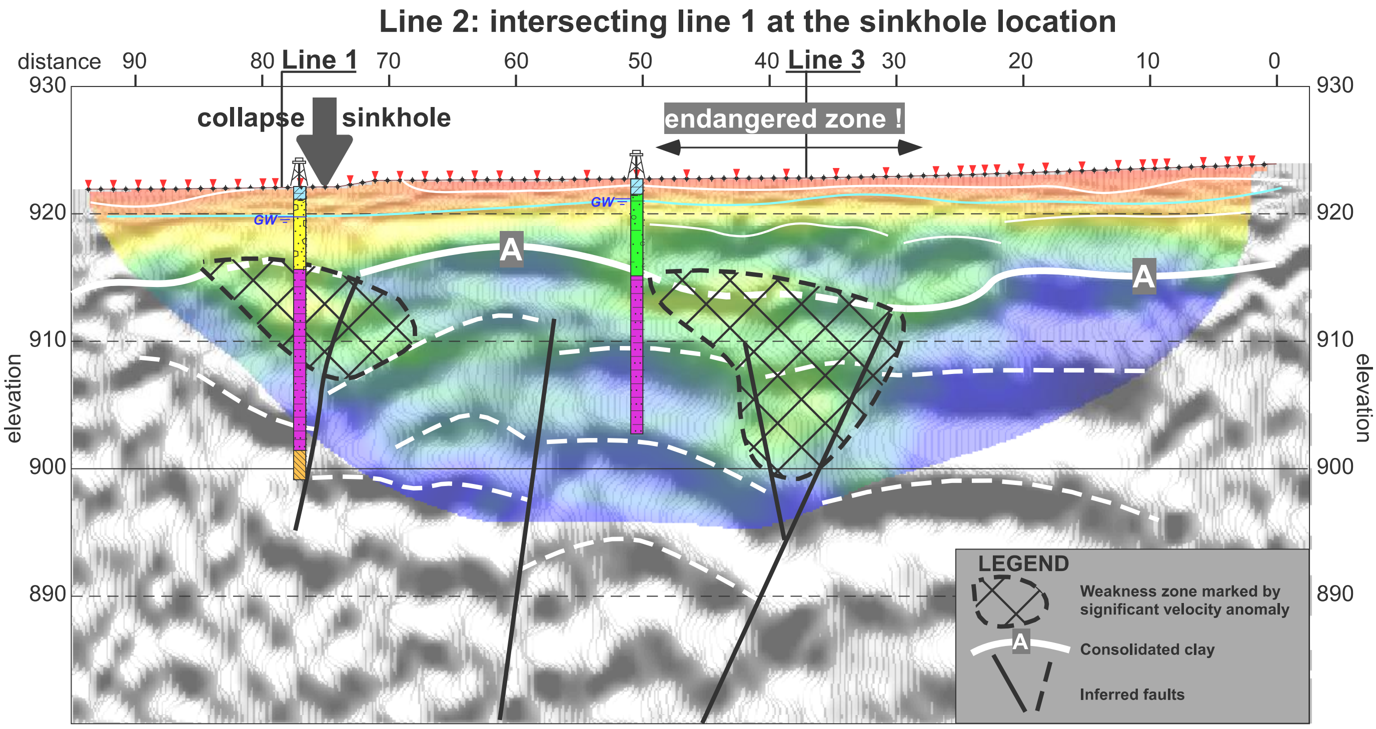

Figure 6. Interpreted hybrid seismic section of line 2 (see situation map in Fig. 7 below). This line was recorded using a geophone spacing and a source point distance of both 80 cm.

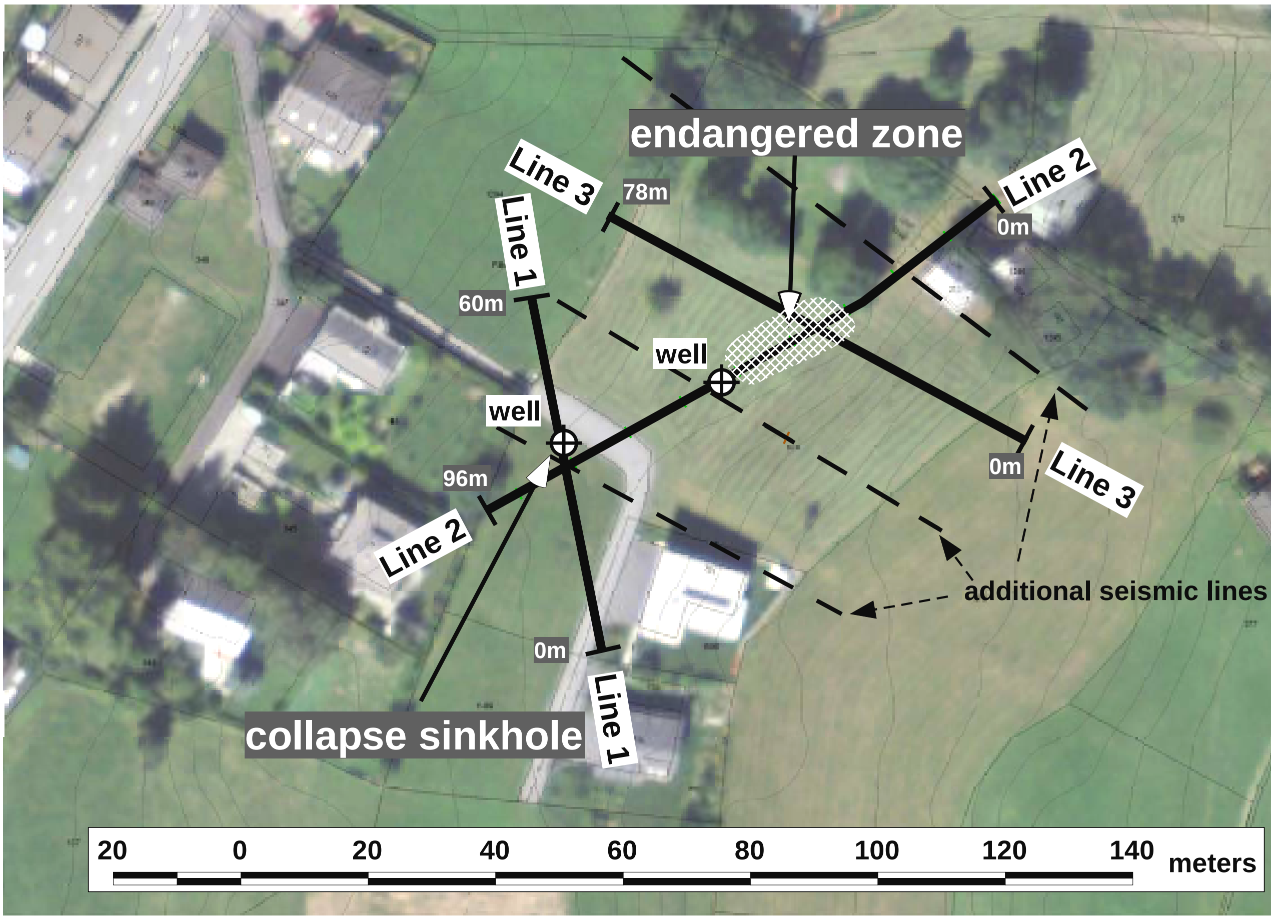

Figure 7. Situation map of the three hybrid seismic / MASW lines

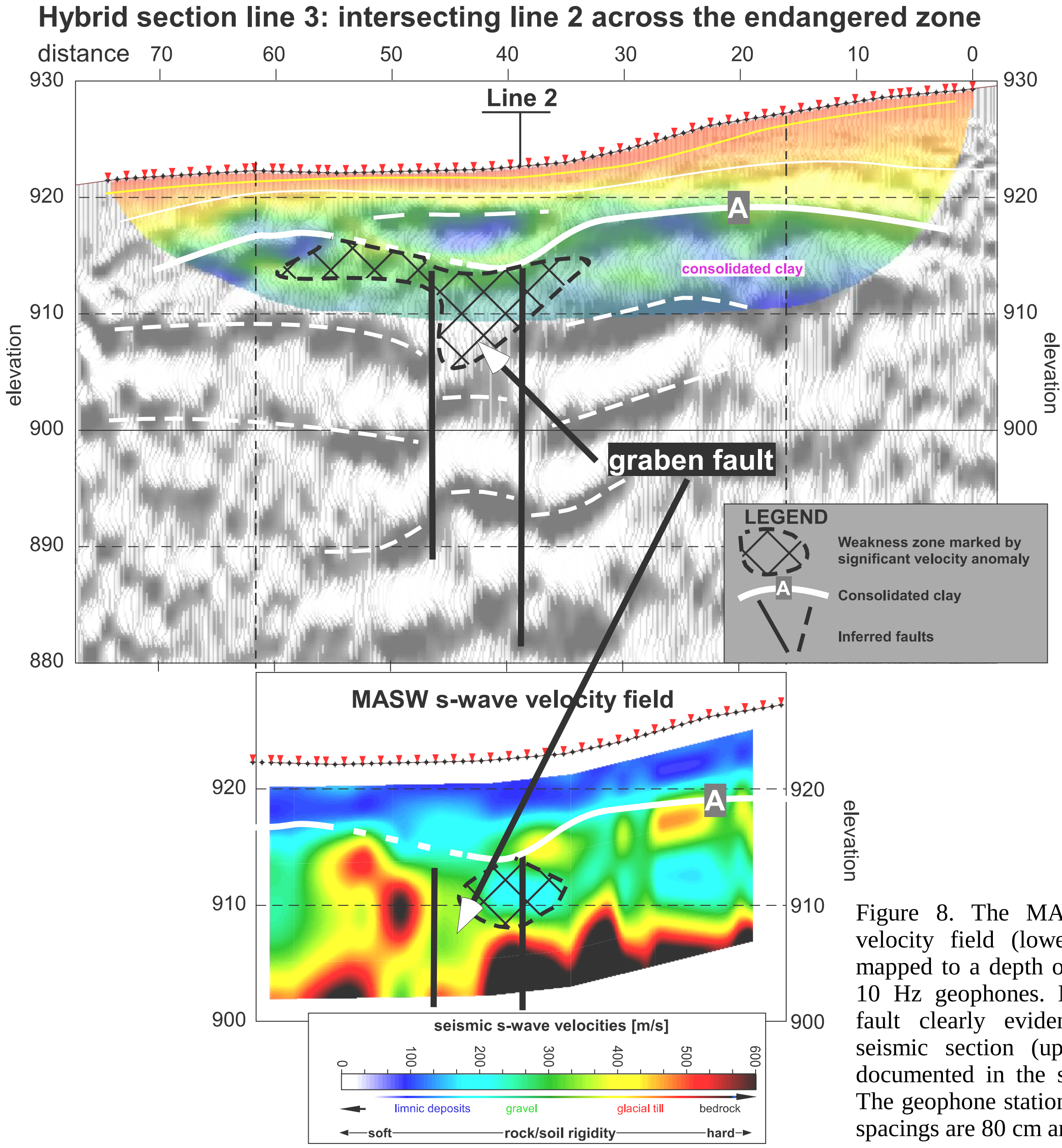

Figure 8. The MASW derived s-wave velocity field (lower picture) could be mapped to a depth of approx. 18 m using 10 Hz geophones. Note that the graben fault clearly evidenced on the hybrid seismic section (upper picture) is also documented in the s-wave velocity field. The geophone station and the source point spacings are 80 cm and 1.6 m respectively.

4 PRACTICAL DATA PROCESSING ASPECTS

4.1 *Seismic refraction tomography evaluation*

The factors with the highest influence on the quality of the first break picking procedure are a) the complexity of the geological structures and b) the degree of uncertainty of the refraction arrivals due poor signal to noise ratio.

It is recommended to use a software which allows the projection of the first arrival time picks from adjacent field records for subsurface consistent arrival time picking. It is also to be ascertained from the display of the total of arrival the time picks that no intersection of time - distance curves occurs.

4.2 *Reflection seismic data processing*

Standard processing techniques are adequate for reflection seismic data evaluation.

Special attention is to be paid to the accuracy of the velocity functions used for the NMO correction, and the more so for the time-depth conversion process. With poor reflectivity data in the near surface depth range, it is indispensible to use the refraction tomography results for deriving a simplified interval velocity model, which after application of the inverse Dix function, can be used as NMO velocity function.

4.3 *MASW data evaluation*

Successful MASW data processing requires a fair amount of experience and routine, as its outcome is tainted much more by subjective judgement than is the case with seismic reflection data processing and refraction tomography inversion.

It is strongly recommended to evaluate two separate data sets, each containing shot records in only one shooting direction (PLUS records), the other with records in the opposite direction (MINUS records):

X----------o-o-o-o-...-o-o-o
(→ increasing station numbers: PLUS record)

o-o-o-…-o-o-o----------X
(← decreasing station numbers: MINUS record)

with: X = shot position
o = receiver station
- = unit distance (between receivers

A major difficulty attributable to complex geological structuring and/or to a poor signal-to-noise ratio is that structural variations are not accurately reflected in the phase velocity - frequency graphs of neighbouring shot records, which would lead to a consistent image of the velocity field in the vicinity of certain structures. Continuous comparison of the selected dispersion curves with the curves from adjacent records and appropriate editing is indispensible.

In addition, structural irregularities in the subsurface produce PLUS and MINUS s-wave velocity fields of differing, often contradictory appearances. In order to reconcile these dissimilarities, numerous reciprocal cross reference consultations between the PLUS and MINUS results are needed for the determination of the dispersion curves at a specific location on the seismic line.

In circumstances of an extremely irregular geological setting, a satisfactory compromise often is difficult to find, which necessitates the calibration of the interpretation with the help of the results of hybrid seismic surveying.

To the author's knowledge there seems to be, unfortunately, no commercially available MASW evaluation software on the market with the capability of handling and presenting data recorded along seismic lines in a non-flat terrain with irregular topography.

5 CONCLUSIONS & RECOMMENDATIONS

- Data sets for high resolution reflection seismic profiling, diving wave refraction tomography and MASW can be acquired jointly by applying an adapted roll-along recording technique using one single spread only, which results in a significant reduction of the costs for the data acquisition in the field.
- The data acquisition parameters are to be optimized for obtaining adequate data redundancy in terms of a high spatial data density. To this end, the recording instrumentation is recommended to be of a modular type featuring a minimum of 150 - 250 data channels.
- The joint presentation of the results of all three seismic methods ensures a high degree of interpretation accuracy due to the fact that the results of each method can be calibrated by the outcomes of the other methods.
- MASW data are highly sensitive to minor structural variations in the subsurface. Picking subsurface consistent dispersion curves requires extensive cross-correlation and plausibility checks with curves from adjacent shot records and also from the records with opposite shooting directions at one and the same location. The interpretation of the MASW derived shear-wave velocity field is recommended to be calibrated by suitable information from bore holes, SPT, hybrid seismic surveying or other geophysical methods.
- Hybrid seismic surveying combined with MASW s-wave velocity field derivation are instrumental both for diagnostic purposes and for planning preventive measures in areas with suspected ground instabilities.

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