Application of NDT-Methods to Discover Design-Engineering Properties of Old Retaining Walls Made of Natural Stonework

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Abstract
For the rating of the design-engineering properties of old retaining walls made of natural stonework knowledge of the wall thickness, the shape of the cross section of the wall and the masonry bond and transverse bracing is necessary. This information cannot be gained by a visual survey. Non-destructive testing methods may provide the information without destroying the structure. During the last two years a research project has been carried out with the goal to find out suitable non-destructive testing methods for the topic described above. Inspections had been carried out with Ground Penetration Radar as well as the Impact Echo method and the Spectral Analysis of Surface Waves method. The prime result of the study is that there exists not a single method which is able to solve the tasks described above in the exact same manner. Instead one has to choose a NDT-method according to the type of masonry the retaining wall is made of.

Keywords: Old retaining walls, Natural stone masonry, Ground Penetration Radar (GPR), Impact Echo (IE), Spectral Analysis of Surface Waves (SASW)

1. Introduction

During the last 11 years a rating system has been developed at the Lucerne University of Applied Sciences and Arts for the assessment of old retaining walls made of natural stonework. Up to now this rating system has been applied successfully in several projects. The goal of this rating system is to assess the as-is state of old retaining walls as well as their constructiveness.
Unfortunately, in many cases there is no information available about the design and construction details of walls with an age of about 100 years. So, significant data for an assessment of the constructiveness of those constructions is missing. Therefore a research project has been carried out to evaluate the possible contribution of nondestructive testing for the investigation of the constructiveness of such walls. In this project different methods have been used with acoustic and electromagnetic waves. Data were acquired with those different methods on a test wall with a length of approximately 5 m and a height of 1.8 m. In addition, data were acquired on an existing old retaining wall on a Swiss pass road.

2. Design-engineering properties and structural safety

2.1 Wall thickness, ratio of slenderness and cross-section design

To assess the structural safety of a retaining wall, knowledge about the constructiveness is essential. A significant constructive parameter is the ratio of slenderness of a retaining wall. That is the ratio of the wall thickness at the bottom to the height of the wall. Schwing [1] had studied 25 old retaining walls, most of them with a ratio of slenderness in the range of 0.15 to 0.25. All of those retaining walls showed deformation and at most of them repair work had been necessary during the years. A study on retaining walls in Hong Kong [2] showed, that retaining walls made of natural stonework had been very often affected by damage or even a collapse occurred, if the ratio of slenderness was less than 0.33. On the other hand, retaining walls with a ratio of slenderness larger than 0.33 in most cases stayed stable (Fig. 2).

![Graph showing relationship between wall height, wall thickness at the bottom, and structural safety.](image)

Figure 2. Relationship of height H, wall thickness at the bottom B of retaining walls made of natural stonework and their structural safety, according to [2] (modified graph).

The influence of the cross-section design of a retaining wall and the inclination of the masonry’s bed joints on the structural safety had been studied by Burgoyne in 1834. Four retaining walls, every with a height and length of 20 feet, but with a different cross-section design, had been constructed. The construction was done in such a way that the wall thickness at medium level was 3 feet 4 inch for all 4 retaining walls. But during the backfill process, two of the walls failed (Fig. 3). Harkness et al. [3] showed by numerical calculations that for the cross-section design A in Fig. 3 the horizontal component of the earth pressure will be obtain a minimum compared with the other cross-section designs and therefore cross-section design A results in a maximum of structural safety in comparison to the other cross-section designs.
According to the studies shown above, it can be stated, that structural safety problems very often occur at retaining walls made of natural stonework with a ratio of slenderness less than 0.3. While the height of the construction in general can be measured with only little errors, because the embedment depth of those old structures is small, the wall thickness at the bottom can only be determined by drilling, opening of the wall or with the help of nondestructive test methods.

2.2 Masonry bond and transverse bracing

Other essential factors for the structural safety of retaining walls made of natural stonework are the type of masonry bond and the transverse bracing. The importance of an adequate number of header bricks and a sufficient depth of such stones has already described in the nineteen-thirties and nineteen-forties in guidelines in Switzerland [4]. According to these guidelines every third stone should be a header brick and the distance between two headers should be less than 1.8 m. Additional the depth of a header brick should be at least 1.5 the height of the brick plus 15 cm and the brick should protrude the other stones by at least 15 cm.

While the type of masonry bond can directly be determined visual, the place and number of header bricks in natural stonework cannot be determined in general by a visual survey. Also drilling is not an adequate method to find out the number and distribution of header bricks in a wall, nor the depth of the stones. Nondestructive test methods may help to solve this problem.

3. The rating system

Setting up a list of criteria alone does not represent a rating for retaining walls made of natural stonework. Several criteria have to be weighted and put into a relation to each other. This procedure is called rating. A system has been established for the assessment of old retaining walls made of natural stonework, which takes into account three topics:

- constructiveness of the retaining wall
- as-is state of the retaining wall
- as-is state of the “environment”.

The rating for the constructiveness of the retaining wall is named $q_{MK}$ and includes parameters like the ratio of slenderness and the implementation of the transverse bracing. The rating for the as-is state of the retaining wall is named $q_{Mz}$ and it takes into account every kind of damage which may occur to the structure itself as well as at the construction elements stones and mortar.
The third rating is called $q_{TGz}$. This rating summarizes the existence for example of plant roots, slope instability, water logging and so on.

The ratings $q_{MK}$, $q_{MZ}$ and $q_{TGz}$ may vary between 0 and 1. A value between 0.8 and 1 is assigned for good constructiveness respective good as-is state of the retaining wall. A value less than 0.5 on the other hand describes a poor condition of the retaining wall. A detailed description of the “Lucerne Rating System” for retaining walls made of natural stonework can be found in [5].

4. Objects of investigation

To test several NDT-methods at a construction of a well-known composition, a test wall has been constructed at the Lucerne University of Applied Sciences and Arts (Fig. 4a). The type of the masonry bond was chosen to be similar to that one of old retaining walls of natural stonework. The test wall has a length of approximately 5 m and was divided into three sections. One third was constructed as drystone masonry, one third was done with mortar and in the last section the joints have been filled with sand, which simulates a very weathered mortar (Fig. 5). To do measurements at a different wall thickness also a tripartition in the height of the construction has been implemented (Fig. 4b). Furthermore 2 cavities have been placed inside the masonry (Fig. 4b).

The results obtained with the NDT-methods at the test wall had to be verified at an existing old retaining wall. For this in-situ measurements had been done in Canton Uri, Switzerland, at a retaining wall which is called Eggental. Because this wall showed a significant bulge, retreating work of the damaged part of the wall was designated and so, there was also a possibility to check the results of the inspections carried out before the retreating work.
Fig. 6a shows the retaining wall Eggental at the time the inspections had been done. The bulge is clearly seen in this picture. Fig. 6b is an impression of the retreating work at the retaining wall Eggental.

The damaged part of the retaining wall Eggental was made of drystone masonry. The size of the stones in the masonry varies very much and the masonry bond is irregular. This combination of structural deficits very often results in bulging and at the end in a collapse of the wall.

5. NDT-methods

The following methods had been tested for their suitability on masonry made of natural stonework within the project:

- Impact-Echo method, IE (p-waves)
- Ultrasonic Pulse Test, UPT (s-waves)
- Spectral Analysis of Surface Waves, SASW (Rayleigh waves)
- Ground Penetrating Radar, GPR (electromagnetic waves).

Some of the results with GPR, IE and SASW are shown below. With the used methods very different results had been achieved as a function of the type of masonry bond. The measurements with the Ultrasonic Pulse System showed poor results and were abandoned.

5.1 Ascertainment of the wall thickness and the wall cross-section

5.1.1 Ground Penetrating Radar

GPR was used according to the specifications given in [6] and based on own experience [7]. With the GPR the position of the rear side of the test wall was detected, but only if there was a sufficient contrast in the electromagnetic parameters of masonry and backfill. Fig. 7 shows the results of radar measurements before and after doing the backfill at the test wall. While in the sections A and C the rear side of the test wall can be easily identified before the backfilling was done (Fig. 7, top), this was hard to do when the backfill had been placed (Fig. 7, bottom).
On the other hand there are a lot of reflections produced by single masonry stones. So even if the rear side of the wall cannot be detected directly, the area filled with masonry can be identified and this will give an idea about a minimum wall thickness and the shape of the cross-section.

The measurement with GPR at section B, masonry with mortar, showed some surprising results. Even though this part of the test wall made with mortar is the most solid-state part of the complete test wall, the reflections in this area are only very poor or even missing (Fig. 8). The reason for this result is probably bound on the use of lime mortar.

The lime mortar conforms to the specification to be as close as possible to the historic construction method, but this kind of mortar has also the nature to adsorb humidity, which may increase the electric conductivity. But with an increase of the electric conductivity, a higher damping goes along and therefore a lower penetration depth for the GPR.
Figure 8. Results of Ground Penetration Radar (GPR) measurements at the test wall in a horizontal section. Only very low signals can be recognized in part B of the test wall. The measurement was done with a 400 MHz antenna at the bottom of the construction before doing the backfill.

Figure 9. Results of measurement with Ground Penetrating Radar (GPR) at three vertical sections of the retaining wall Eggental. The measurement was done with a 900 MHz antenna.
At the retaining wall Eggental a 900 MHz antenna has been used to determine the wall thickness. Measurement has been done along vertical profiles. Three of these profiles are shown in Fig. 9. The profiles represent a measurement height of 3 m and the penetration depth is shown up to 2 m. A continuous reflection, which may be produced by the rear side of the construction, is not recognizable. But at the upper third of the profiles according to the reflections, there should be a wall thickness of about 65 cm to 80 cm. This agrees very well with measurement of the wall thickness done in that area during the retreating work. But in the middle part of the profiles at 10.5 m and 11.5 m reflections can be seen as deep as to 2 m. This could not be verified by measurement of the wall thickness during the retreating work. In fact the measurement of wall thickness during the retreating work showed a thickness of about 1 m to 1.2 m in that area. So the reflections shown in the deeper part of the profiles are a result of the intensive jointed rock behind the retaining wall (Fig. 10).

5.1.2 Spectral Analysis of Surface Waves
The wall thickness of the test wall could neither be determined in the case of drystone masonry, section A, nor in the case of masonry with joints filled with sand, section C, by measurement methods using acoustic waves.

Measurement according to the SASW method had been done at the upper third of section B of the test wall. Fig. 11 shows the test set-up. The distance D between the 2 accelerometers A1 and A2 has been chosen to 0.88 m which is approximately 1.5 the wall thickness at this part of the wall. S1 and S2 are source points. As seismic sources different ball hammers have been used. The distance between S1 and the accelerometer A2 was 0.52 m, the distance between S2 and the accelerometer A2 was 0.75 m.

Figure 9. Intensive jointed rock behind the retaining wall.

Figure 11. Test set-up for the SASW-measurement at the test wall.
For measurement with distance A2 – S1 equal to 0.52 m the complete set-up was placed in section B, masonry with mortar. Fig. 12 shows the experimental dispersion curve of the Rayleigh waves. According to this experimental dispersion curve the wall thickness can be determined to be approximately 0.6 m, which corresponds very well to the real wall thickness in that area.

![Experimental dispersion curve of the Rayleigh waves as a result of the SASW-measurement at the test wall (A2 – S1 = 0.52 m). The wall thickness can be estimated to 0.6 m approximately.](image)

On the other hand for a distance A2 – S2 of 0.75 m or larger, part of the set-up has to be placed in the area with drystone masonry or masonry with joints filled with sand. In such a case no analyzable signals could be measured at the accelerometers.

With increasing wall thickness also the lay-out of the SASW set-up has to be enlarged. But at the test wall this required to place accelerometer in a position in section A or section C. As described before in the sections A and C an analyzable signal was not received. Therefore measurement of the wall thickness at the bottom and at middle height of the test wall was not possible.

The part, which was designated for retreating work at the retaining wall Eggental, was made of drystone masonry, as shown in Fig. 6. Therefore the SASW method could be used in this part of the retaining wall only to determine the thickness of some larger stones. But at the right hand side of the part designated for retreating work, in the front view there is masonry visible with joints filled with mortar (Fig. 13a). So it was assumed that it should be possible to do SASW measurements here to determine the wall thickness.

![Retaining wall Eggental, section with joints filled with mortar at the front view, lay-out for the SASW-measurements is plotted in the picture, b) after opening the masonry, the joints show only mortar at the first few cm.](image)
Fig. 13a shows the set-up chosen for the SASW measurement. But even in this area, where the front view of the retaining wall shows joints filled with mortar, no analyzable signals have been received at the accelerometers. The retreating work disclosed that the joints had been filled only to a depth of a few centimeters (Fig. 13b). So also this part of the retaining wall Eggental has to be denominated as drystone masonry.

5.1.3 Impact-Echo

The impact-echo method is well known to determine the thickness of homogeneous concrete slabs. For a known p-wave velocity $v_p$ the slab thickness $d$ can be estimated with the resonance frequency $f$ of the slab using a simple formula [8]:

$$d = \frac{(0.96v_p)}{2f}$$  \hspace{1cm} (1)

For a homogeneous concrete slab the frequency spectrum shows a single dominant frequency peak, which easily can be identified. In the case of a retaining wall made of natural stonework the frequency spectrum contains a lot of peaks. These peaks are the resonance frequencies, which are produced by the stones as well as by the wall as a whole. Therefore the different frequency peaks first have to be assigned to the particular mode of a stone or to the mode of the wall. The method to assign frequency peaks to a mode of a masonry stone is described in detail in [10] resp. [11]. An example is given in chapter 5.2.

As a general rule it may be stated, that the wall thickness is larger than the longest dimension of a masonry stone. Therefore the peak belonging to the wall thickness must have a lower frequency than the resonance frequencies of the masonry stones. In Fig. 14 b) the wall frequency at the masonry stone BV-O has been identified as $f = 1.46$ kHz. With a p-wave velocity $v_p = 5000$ m/s the wall thickness was estimated with formula (1) to $d = 1.64$ m. This value is approximately 43% larger than the real wall thickness, which is 1.15 m at the measurement point BV-O.

Two parameters affect the result for the wall thickness in formula (1). These two parameters are the wall frequency $f$ and the p-wave velocity $v_p$. In the example above the step size of the frequency was 0.488 kHz. Therefore the effective wall frequency will be in the interval $(1.46 \pm 0.244)$ kHz. The other parameter $v_p$ was estimated due to direct sound transmission measurement before doing the backfilling. At the stone BV-O this measurement yielded to $v_p = 5000$ m/s. But measurement at other positions showed a variation of the p-wave velocity for the masonry between 4100 m/s and 5500 m/s as a function of mortar percentage. The p-wave velocity of the rock was found to be in the interval 5600 m/s to 5950 m/s for comparison.
Table 1 shows the results of the estimated wall thickness with IE at several places in section B of the test wall in comparison to the real wall thickness. There seems to be a tendency to overestimate the wall thickness, but in most cases the wall thickness could be estimated with a deviation less than 20%. A similar result has been found for section C, masonry with joints filled with sand. Here the wall thickness could be estimated with a deviation less than 30% in most cases. The p-wave velocities presented in table 1 are those, which had been measured by direct sound transmission measurement.

Table 1. Comparison of wall thickness estimated by IE and real wall thickness

<table>
<thead>
<tr>
<th>Test point No.</th>
<th>(v_{p,MW}) [m/s]</th>
<th>(f) [Hz]</th>
<th>(d_{estimated}) [m]</th>
<th>(d_{real}) [m]</th>
<th>deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BV-S</td>
<td>5500</td>
<td>2930</td>
<td>0.90</td>
<td>0.60</td>
<td>150%</td>
</tr>
<tr>
<td>BV-U</td>
<td>5250</td>
<td>2930</td>
<td>0.86</td>
<td>0.60</td>
<td>143%</td>
</tr>
<tr>
<td>BV-A</td>
<td>4850</td>
<td>3420</td>
<td>0.68</td>
<td>0.60</td>
<td>113%</td>
</tr>
<tr>
<td>BV-T</td>
<td>4500</td>
<td>3420</td>
<td>0.74</td>
<td>0.62</td>
<td>119%</td>
</tr>
<tr>
<td>BV-D</td>
<td>4500</td>
<td>1950</td>
<td>0.63</td>
<td>0.62</td>
<td>102%</td>
</tr>
<tr>
<td>BV-N</td>
<td>5000</td>
<td>1460</td>
<td>1.23</td>
<td>1.15</td>
<td>107%</td>
</tr>
<tr>
<td>BV-O</td>
<td>5000</td>
<td>1460</td>
<td>1.64</td>
<td>1.15</td>
<td>143%</td>
</tr>
<tr>
<td>BV-R</td>
<td>4500</td>
<td>1950</td>
<td>1.11</td>
<td>1.20</td>
<td>92%</td>
</tr>
</tbody>
</table>

At the retaining wall Eggental 21 IE tests had been executed in the area shown in Fig. 15 a). Although this part of wall Eggental is made of drystone masonry as shown above, it was possible to determine a wall frequency in 10 of the 21 IE data sets. For those 10 data sets it was possible to estimate the wall thickness. Wave velocity \(v_p = 3900\) m/s was used, which is the mean value of the p-wave velocity determined at the masonry stones. Using formula (1), this results in a wall thickness between 0.78 m and 1.06 m for the 10 data sets. Measurement during the retreating work showed a wall thickness of the Eggenthal retaining wall between 0.9 m and 1.05 m (Fig. 13 b). So in this case, even though the wall consist of drystone masonry, it was possible to determine the wall thickness and the derived values agree very well with the direct measured wall thickness. On the other hand it was only possible to determine a wall frequency for about half of the measurements done. Additional, peaks larger than the wall frequency appear in the spectra at a lower frequency (e.g. 0.68 kHz in Fig. 15 b, wall frequency: 1.81 kHz). These peaks may represent other wave types than p-waves and this has to be clarified in further studies.

Figure 15. a) Locations of impact echo measurements Egg_S11 to Egg_S31 at the test wall Eggental, b) mean value spectra of IE measurements at masonry stone Egg_S14, the wall frequency is at 1.81 kHz.
5.2 Transverse bracing

To get information about the number and the position of the header bricks in the masonry, the depth of the individual stones has to be determined. But old retaining walls made of natural stonework may have a large dimension (see Fig.1). So it is not possible to explore every single stone in a wall. Therefore one has to define a characteristic area of the wall, which will be surveyed. This characteristic area should have a dimension, which secure that 2 or 3 headers are existent in vertical as well as in horizontal direction, if the wall was constructed according to the guidelines [4]. So such an area may stretch across 6 to 9 stones in horizontal as well as in vertical direction.

Inspections were carried out with the GPR and the IE method. The SASW method is not suitable for the detection of stone depth because of the large extension of the set-up.

5.2.1 Ground Penetrating Radar

For the GPR inspections a 1.5 GHz antenna was used. The antenna was fixed at a stone while doing the measurement. Fig. 16 shows some of the results received at stones of the retaining wall Eggental. The blue lines are showing the stone depth determined by the GPR. During the retreating work there was a chance to measure the dimensions of some of the stones. In Fig. 16 the yellow lines show this measured stone dimension. If there is a large deviation in the geometry of a stone, as for example for stone Egg_S32, two yellow lines had been drawn representing the minimum and the maximum length.

![Figure 16. Depth of masonry stones measured by GPR and comparison with measured geometry data.](image)

For the most investigated stones a good agreement of GPR determined stone depth and measured geometry has been achieved. In some cases the stone depth has been overestimated by the GPR method. This may indicate that the radar velocity \( c = 0.12 \text{ m/ns} \) used in the analysis may be overassessed. Because the retaining wall Eggental is made of different rock material a variation in radar velocity is very probable.

In Fig. 17 the stone depth measured by GPR has been mapped with different colors for the different depth ranges. This visualization of the stone depth may help to identify easily header bricks in the masonry.
5.2.2 Impact-Echo

As already shown by Lin & Sansalone [9] the frequency spectra for a thick rectangular bar not only shows one dominant frequency but a series of frequencies. For bars, where one dimension is very much larger than the two other dimensions, Lin & Sansalone identified the resonance frequencies of the bar with the help of numerical calculations using the Finite Element Method (FEM). Their investigations result in a similar formula like formula (1):

$$f_1 = \frac{\beta v_p}{2H}$$

(2)

But now $\beta$ is no longer a constant. Lin & Sansalone stated that $\beta$ is a function of the ratio of the height $H$ to the width $B$ of the bar. Additionally they declared formula (2) is only valid, if the length of the bar is at least twice the size of the larger cross section dimension.

In an old retaining wall made of natural stonework the stones very often show a large variation in size. So the identification of the stones’ resonance frequencies with the help of FEM is therefore not a practicable solution. Additionally the limitation given by Lin & Sansalone, the length of the test specimen has to be at least twice the size of the larger cross section dimension, is usually not fulfilled for header bricks. So another solution had to be found for determining the stone depth in a wall with the IE method.

Kister [10] proposed to use the Helmholtz equation and its solution for a cuboid to identify the resonance frequencies in the IE spectra. The frequencies then can be calculated by the formula:

$$f(l, m, n) = \frac{v_p}{2} \cdot \sqrt{\frac{l^2 + m^2 + n^2}{l_x^2 + l_y^2 + l_z^2}}$$

(3)

$L_x$, $L_y$ and $L_z$ are the three dimensions of the test specimen, $l$, $m$ and $n$ are the harmonic numbers which may be 0, 1, 2, and so on. According to the solution of the Helmholtz equation for a cuboid, there are an infinite number of resonance frequencies. But in reality only a few of those resonance frequencies may be stimulated. Generally only the basic harmonics may be stimulated by an impact with a steel ball, i.e. modes with the harmonic numbers $l, m, n = 0, 1$ or 2.

If two of the dimensions of the test specimen are very large in comparison to the third one ($L_x, L_y >> L_z$), formula (3) may be reduced by approximation to:

$$f(n) = \frac{v_p}{2} \cdot \frac{n}{l_z}$$

(4)

For $n = 1$, this formula is very similar to that one given by Sansalone for a concrete slab (see formula (1)).

Kister ([11] resp. [10]) showed that there is a difference between the calculated resonance frequencies $f_c$ of a cuboid and the resonance frequencies $f_m$ measured by the IE method. Analyzing the data of Lin & Sansalone and doing IE measurements on concrete test specimen as well as on stones, it was found, that there is a relationship between calculated resonance frequencies $f_c$ and measured resonance frequencies $f_m$, which can be described by a linear equation (Fig. 18):

$$f_m = 0.937 \cdot f_c$$  \hspace{1cm} (5) \hspace{1cm}

![Figure 18. Calculated resonance frequencies $f_c$ versus measured resonance frequencies $f_m$.](image)

To determine the stone depth with the IE method it is assumed, that the shape of the stone is similar to a cuboid. At the front view of a retaining wall two of the three stone dimensions can be measured directly. The 3rd dimension, the stone depth, has to be determined by using the IE method and the solution of the Helmholtz equation for a cuboid.

As an example to show the method the stone MW+VM-S03 is used. The stone MW+VM-S03 is placed in the test wall at section B. Fig. 19 a) shows the geometry of the stone. It is obvious that the geometry of that stone does not correspond to an ideal cuboid. In the front view the stone has a height of approximately 32 cm. At the base the width of the stone is approximately 33 cm and at the top the width is reduced to approximately 29 cm. During the construction of the wall the stone depth was measured to be approximately 43 cm at the left and 48 cm at the right.

When the test wall was finished, 10 IE tests had been done at this stone. The frequency spectra resulting from those measurements are presented in Fig. 19 b). Four resonance frequencies of the stone MW+VM-S03 had been assigned with the help of equation (3) to the axial modes $(1, 0, 0), (0, 1, 0), (0, 0, 1), (2, 0, 0)$, one resonance frequency had been assigned to the oblique mode $(1, 1, 1)$. A best fit of the 5 pairs of values $(f_c, f_m)$ to the linear function was given for a stone geometry $L_x = 46 \text{ cm}, L_y = 32 \text{ cm}$ and $L_z = 29 \text{ cm}$ taking into account a p-wave velocity $v_p = 5750 \text{ m/s}$. So the stone depth $L_x = 46 \text{ cm}$ is exactly the mean value of the measured stone depth at the left and the measured stone depth at the right side of the stone MW+VM-S03.

In Fig. 19 b) there is an additional frequency peak at 2.44 kHz. This peak has been assigned to the wall thickness. With $v_p = 5000 \text{ m/s}$ for the masonry, the wall thickness can be calculated with formula (1) to 0.98 m. The real wall thickness at this place is 1.2 m. So the deviation is approximately 20%.
At the retaining wall Eggental IE tests had been done at the stones marked in Fig. 15 a). The stone depth of 20 of the 21 stones had been determined by the IE method. Fig. 21 shows the result in cm written at the stones. Three colors had been used to visualize the different depth intervals: ≥ 60 cm (red), 40 cm – < 60 cm (blue), < 40 cm (green). The analysis of the data shows that the requirement of a stone depth 1.5 the height of the stone plus 15 cm given by [4] is not fulfilled.
6. Conclusions

The test results show that the selection of a test method for old retaining walls made of natural stonework is highly dependent on the type of masonry of the retaining wall. So for drystone retaining walls the GPR will offer the best chance to obtain data concerning the wall thickness and the shape of the cross section. The joints filled with air do not represent a problem for the radar wave to travel through. In contrast, for the measurement procedures with acoustic waves, these air filled joints prevent or restrict very hard the transport of wave energy. Nevertheless at the retaining wall Eggental it was possible to estimate the wall thickness with a precision of about 20% with the IE method.

On the other hand at masonry with mortar the GPR may not always lead to sufficient results as shown at the test wall. A too small contrast of the parameters of electric conductivity of masonry and backfill may prevent reflection from the rear side. Or a high electric conductivity generated by lime mortar and/or water in the joints may lead to higher damping and this also will prevent reflections from the rear side. Here sometimes methods using acoustic waves, like the SASW method or the IE method may produce better results, especially if the material placed behind the wall has significantly lower wave velocities than the masonry.

For the GPR the type of antenna is essential for a successful measurement. With a high frequency antenna one will have a high resolution but the penetration depth will be small. So the antenna has to be chosen according to the assumed wall thickness and sometimes more than one antenna has to be used to get a sufficient result.

Also for the methods with acoustic waves it often will be necessary to do more than one measurement. So subject to the wall thickness several sources have to be used to get sufficient results. Or, for example with the SASW method, several lay-outs have to be tested.

Two different IE equipments had been tested with diverging test results. While the one equipment produced frequency spectra, which could be used without problems to identify the different modes, the other equipment produced frequency spectra where low frequencies had been suppressed and the resolution was very poor. Additional a large difference in the handling of the accelerometers of the two systems has been realized.
The position of header stones in masonry and their stone depth can be detected by the GPR as well as with the IE method. But today the course of action for the IE method is not a standard procedure, so a part of the analysis has to be done “by hand”. For the GPR there are standardized evaluation programs available. Therefore the GPR has an advantage in comparison to the IE method with reference to the performance.

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