Determination of P – wave arrival time of acoustic events

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The new approach to the P-wave arrival time determination based on acoustic emission data from loading experiments is tested. The algorithm used in this paper is built on the STA/LTA function computed by a convolution that speeds up the computation process very much. The picking process makes use of shifting of temporary onset until certain conditions are fulfill and as a main decision criterion on the threshold exceeding of the STA/LTA derivation function is used. The P-wave onset time is determined in a selected interval that corresponds to the theoretical propagation of elastic wave in the rock sample. Results obtained by our algorithm were correlated with data acquired manually and a high order statistic software as well.

Key words: *Onset detection, Automatic picker, Acoustic emission, Loading experiments, STA/LTA*

Introduction

The evaluation of stability of underground engineering structures is one of significant tasks of geomechanics. For the development and verification of effective methods of assessing the deformation characteristics, it is advisable to carry out their research under laboratory conditions, which enable us to simulate the process of stress state growth up to the level of their own strength. As to the rocks, representing a heterogeneous discontinuous medium with primary cracks and places of different mechanical strength, the distribution of the stress field is inhomogeneous with higher local values especially in the vicinity of so-called “stress concentrators”. During the loading of rock specimens, the local strength will be exceeded in these places and brittle ruptures will be created, which leads to the elastic wave emission. These points of brittle ruptures are sources (foci) of elastic wave radiation ranging from acoustic to ultrasonic frequencies. Events like these are referred to as the “acoustic emission” (AE). The observation of the acoustic emission process is based on the monitoring via a geophone net, located on the surface of the studied rock specimen. The location of acoustic foci and the monitoring of their migration during loading until a final destruction of the rock specimen provides a significant information about foci clustering within the areas of predisposed places of future final rupture. Acoustic emissions and the location of their foci was studied by Lockner (1993), Lockner and Byerlee (1977), Vilhelm et al. (2008), Veverka J., Rudajev V. (2004). The accuracy of the location depends on the knowledge of the velocity model as well as on the accuracy of determining the P – wave onset time. Therefore, the accuracy of determining the time of the onset is very important and often poses a difficult problem.

This paper is concerned with the determination of the time of the first arrivals of P – waves important for localizing acoustic events occurring during the rock specimens loading. This topic is also involved in many publications, based on different principles. The methods most frequently used for the P – wave time determination are, for example: the STA/LTA ratio (short-term average/long-term average) by Allen, R. (1982), Baer, M., Kradolfer, U. (1987), SNR (signal-to-noise ratio) by Zuolin Chen (2005), HOS (high - order statistics) by Lokajicek, T., Klima, K. (2006), and the AIC criterion (Akaike Information Criterion) by Sedlak et al. (2009).

Background of the Pick – Tester (PT) Method

In general, it always stands good that signal is transformed to a characteristic function (CF) which creates the signal envelope. The time of the first arrival is then determined on this envelope by using specified criteria.

The procedure presented in this paper is based on the STA/LTA principle (Allen, 1982). The characteristic function is computed using the following equation

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$$CF(i) = y(i)^2 + K\big(y(i) - y(i-1)\big)^2$$

where y is the input signal and the second part of the equation is its derivative. K is the weight constant, which reflects the sampling frequency and the noise characteristic of the seismic receiver,

$$K(i) = \frac{\sum_{i=1}^{n} |y(i)|}{\sum_{i=1}^{n} |y(i) - y(i-1)|} \quad ,$$

where *n* is the number of signal samples. The STA/LTA ratio was chosen as the detector. It is the average of the CF amplitude in the short- (long-) time window. The calculation of the real STA and LTA values then yields an average of the values of the characteristic function in a time window of a certain length. These windows have shifted subsequently along the characteristic function. For this operation, it is necessary to use cyclic algorithms repeated depending on the quantity of the data (number of traces), when the first arrival time is determined. All algorithms were realized in the Matlab software. Therefore, this software is not optimized for using cyclic operations; the convolution was used for computing the STA and LTA functions.

The convolution is defined by the equation $y(t) = \int_{-\infty}^{\infty} s_1(t-\tau)s_2(\tau)d\tau$ and is noted as $y(t) = s_1(t) * s_2(t)$, where s_1 is the rectangular signal with the length STA or LTA and s_2 is the acoustic (ultrasonic) signal. The signal s_2 is a discrete series of numbers and the convolution equation can then be expressed in the following form; $y(k) = \sum_j s_1(k-j)s_2(j)$; $k - j > 0$. Replacing the cyclic algorithms by the convolution accelerates the calculation. Consequently, the criteria for determining the times of the first arrivals enter the computation process. Figure 1 shows a simplified block diagram of particular steps of this process.

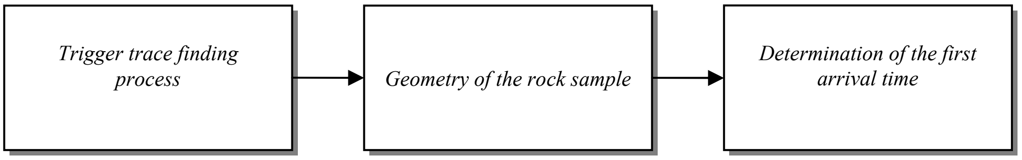

Fig. 1. Block diagram of the arrival time assessment.

During our loading experiments, the acoustic emission data were recorded by an 8-channel piezoceramic system. For this reason, the first step of the computation process is to find the trace on which the acoustic event was first registered. Based on this fact, it is possible to apply considerations of rock specimen geometry and then to determine the P–wave time arrival. The whole process is based on the values and shape of the STA/LTA ratio function, whereas the length of the LTA window is 100 points (10 μs) and the length of the STA window is 10 points (1 μs).

In the following, the criteria of determining the arrival time will be described in a more detail.

Step 1 – STA/LTA level determination

The first step is the dynamical determination of the STA/LTA level. When this level is exceeded, the raw arrival time is assessed. For this purpose the median of the maxima of all eight traces is computed. The STA/LTA level is then established as 15 % of the median value. Two extreme cases can occur:

Strong event – The STA/LTA level is higher than the smallest maximum of any STA/LTA function. In this case the decision level is established as the smallest value of maxima of the STA/LTA function.

Weak event – The STA/LTA level of 15 % of the median is not high enough so that the decision level is established by a predefined empirical value.

The value of the level then reflects the magnitude of the registered AE event.

Step 2 – STA/LTA derivation and its peaks

In this step, the STA/LTA function is derived (hereinafter called "Derivation") and its maximum is determined again. Consequently, the level of the Derivation is determined for every trace. In this case, the decision level is established as 1/3 of the Derivation maximum.

Step 3 – P – wave pick allocated to the main or local maximum of Derivation

Points whose amplitudes of the STA/LTA and Derivation functions exceed their levels determine the peaks which indicate a certain increase of the signal.

Next in the process, only the peaks of the Derivation whose maxima are higher than or equal to a half of the main maximum are considered. According to the number of peaks which satisfy this criterion, the following cases can be identified:

a. Only one peak found; raw P – wave pick is placed to the point of Derivation maximum,
b. More than one peak found and at once STA/LTA ratio in the place of the local maximum of previous peak is higher or equal to STA/LTA level and at once distance between last two peaks is shorter than 100 samples (10 μs); raw P – wave pick is placed to the point of the local Derivation maximum of the previous peak (Fig. 2c),
c. None of the previous cases applies; raw P – wave pick is placed to the point of the main Derivation maximum.

Using this procedure we assessed the raw P – wave picks, which are placed to a certain Derivative maximum.

Step 4 – Trigger trace determination

All these steps (Steps 1 – 3) lead up to the best possible determination of the trace, where the signal was recorded as the first, so-called, trigger trace. Once the trigger trace is known, the parameters of the specimen geometry can be applied in the computation.

Step 5 – Determination of the theoretical signal propagation time in the rock specimen

With a view to the mutual distance of sensors, we can compute the theoretical propagation time of elastic waves in the rock specimen and determine the travel-time limits, in which the signal has to reach the sensor. Using the 8-channel system, we obtain 28 mutual sensor distances from the following equation:

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}\quad , i = j = 1 \ldots 8,\ i \neq j,$$

We then compute the theoretical time of propagation from the reference (trigger) sensor (S_R) to the other sensors (S_i) using the equation $t_{S_R S_k} = \frac{r_{Ri}}{v}$, *i=1, 2,...7,* where $t_{SRSK} = t_{SR} - t_{SK}$ and v is the P – wave velocity in the rock specimen. This formula is, in general, valid in an isotropic medium. Hence, since most rocks are more or less anisotropic, the previous formula needs to be modified with respect to the real value of rock anisotropy. The problem of anisotropy is discussed in more detail for example in Petružálek et al. 2007. With regard to the anisotropy, we can express the previous equation in the following form:

$$t_{S_R S_k} = \frac{r_{Ri}}{v} P$$

where P is the parameter of the anisotropic velocity ellipsoid represented by a 3 x 3 matrix of semi-axis vectors of this ellipsoid. We thus obtain the theoretical propagation times for every sensor and can determine the time interval (Fig. 2c - red part of STA/LTA) on every trace, for which the relation $t_{S_k} < (t_{S_R S_k} + t_{S_R}) \cdot 1{,}2$, where t_{Sk} is the time measured at the *k-th* sensor and t_{SR} is the arrival time at the reference sensor, is valid. The lower value of the time interval is limited by the arrival time on the trigger trace. The real time of the signal has to be looked for in the interval defined by these rules. Of course, we need to know the velocity model of the specimen under examination perfectly. This model is obtained from the ultrasound radiation. During the loading, the parameters of the velocity model can vary; hence the coefficient 1.2 was applied in the previous relation. This coefficient was determined empirically.

Step 6 – Possible pick shift

In this part of the algorithm, the shape of the STA/LTA function will be analyzed and the pick can be possibly shifted to the previous peak. This step is applied in situations when the signal is rising very slightly. If this situation occurs, it is possible that the main Derivation maximum is not at the first peak but on any following peak of STA/LTA. If any peak of STA/LTA exists before the point of the Derivation maximum, and the mutual distance of these two peaks is less than 25 samples (2.5 μs), it is recognized by the procedure in this step and the pick is shifted to the previous STA/LTA peak (Fig. 2c). Repeating of this shifting procedure depends on the number of relevant STA/LTA peaks.

Steps 7 – Final pick determination

In the last step, we analyze the shape of the real signal in the vicinity of the temporary raw pick and, if necessary, the pick is again shifted to one of the characteristic points of the signal (maximum, minimum or plateau) and the final P – wave arrival time is determined.

Figure 2 shows the individual steps of the algorithm mentioned above for a better understanding.

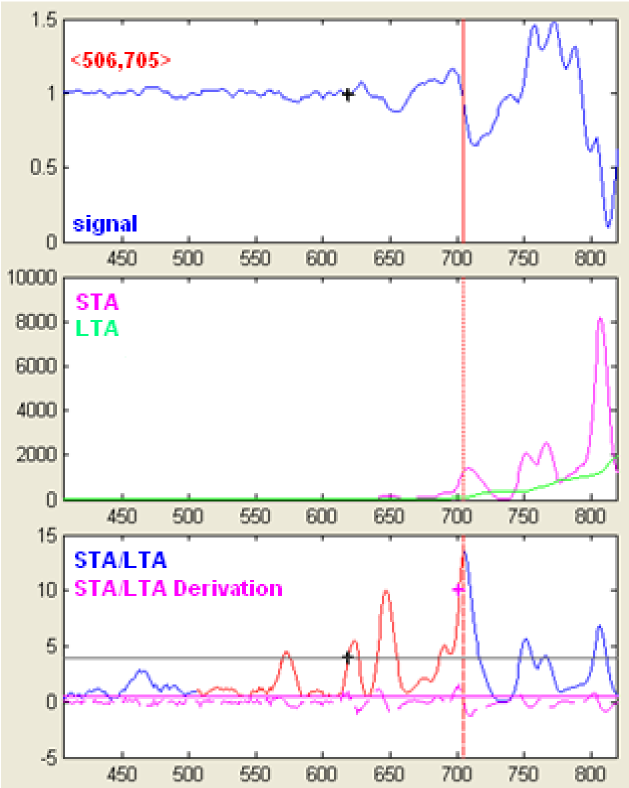

Fig. 2 Procedure explanation (A – recorded signal, B – STA and LTA functions, C – STA/LTA and its Derivation; x-axis units [samples]

- Grey horizontal line – STA/LTA level calculated according to the Step 1 (Fig. 2c)
- Purple horizontal line - Derivation level calculated according to the Step 2 (Fig. 2c)
- According to the Derivation function we find the raw P – wave pick whereas we assume that the arrival time does not occur after the main Derivation maximum (purple cross) calculated according to the Step 3 (Fig. 2c).
- Red part of STA/LTA calculated according to the Step 5 (Fig. 2c)
- The figure indicates that the Derivation maximum (purple cross) is the incorrect determination of the arrival time. For this reason, the shape of the STA/LTA function is analyzed (Step 6). This function has larger peaks in comparison with the Derivation function. As peaks of the STA/LTA function, we consider only peaks whose amplitudes are higher than the estimated STA/LTA level (grey line). If the distance between two neighboring peaks is less than 25 samples (2,5 μs), the P – wave pick shifts to the place where the previous peak crosses the STA/LTA level;
- Black cross calculated according to the Step 7

Results and discussion

The algorithm of Pick-Tester (PT) program is tested on a data file, obtained during the loading of a migmatite rock specimen. The 950 AE events (7600 traces) were chosen from the data recorded during this experiment. The P- wave arrival times were manually picked from these traces. These data served as a model data file to develop the algorithm for the automated arrival time determination in the PT program.

The P – wave arrival time difference is the main criterion for the resultant evaluation. The quality of the picks will be evaluated by comparing the times manually determined by a human operator. We assume these picks to be correct. Another criterion is a comparison with times obtained using the HOS method (Lokajíček, Klíma, 2006). The correctness of the picks determination is reflected in the location residuum of the individual AE events.

In the following figure 3, one can see a general view of the user interface of the Pick-Tester program. This figure shows the comparison of P – wave arrival times determined by different methods. In the main graph (left side), there are 8 records of one AE event. The manual pick on each signal is marked in the red color, the HOS pick in blue and the PT pick in black. The green cross indicates the trigger trace. The right-hand side of the figure shows a detail of the selected trace (upper graph), its STA and LTA functions (middle graph) and the STA/LTA function with its Derivation function (bottom graph). In the upper part of the interface are situated control buttons which can be used to set the length of the STA and LTA windows and allow the movement in the data sets.

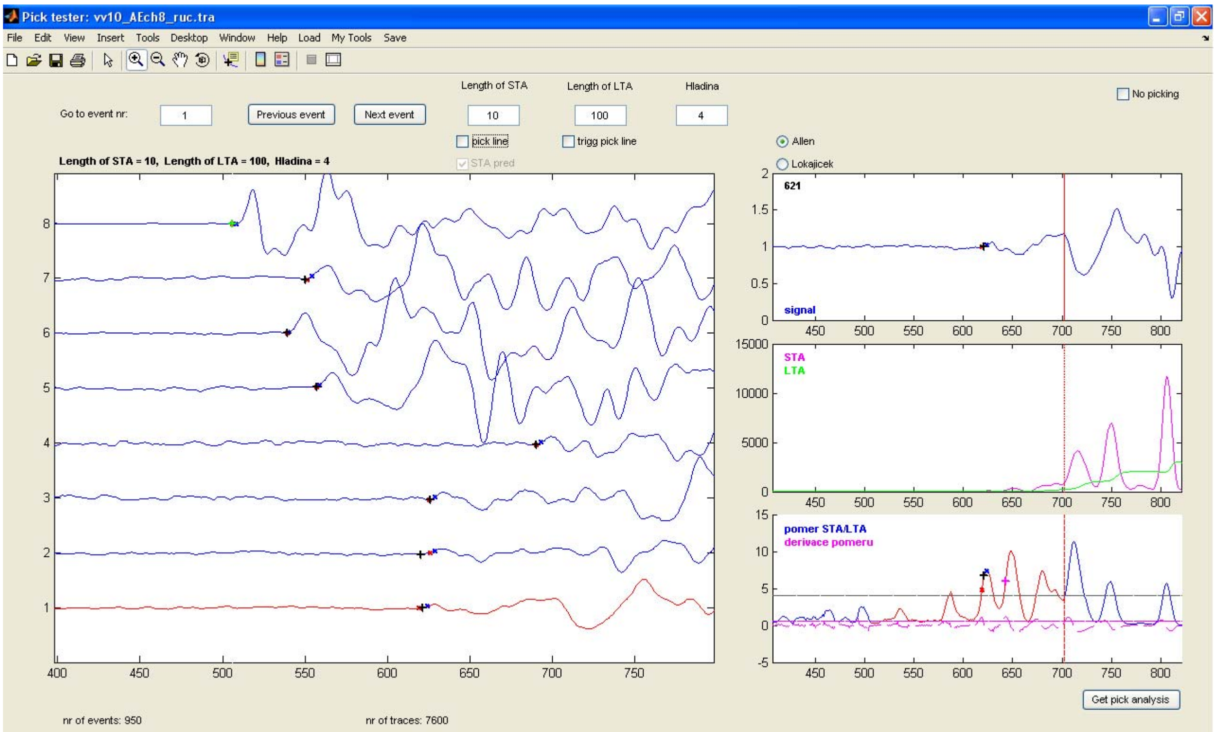

Fig. 3. Preview of picking program Pick-tester.

Figure 4 shows the results of the whole data set (950 AE events ~ 7600 traces). Histograms in this figure represent the absolute value of the arrival time difference determined manually, by the HOS software and by the PT program. The measure of the "x" axis is in the samples; 1 sample ~ 0.1 μs (sampling frequency 10 MHz).

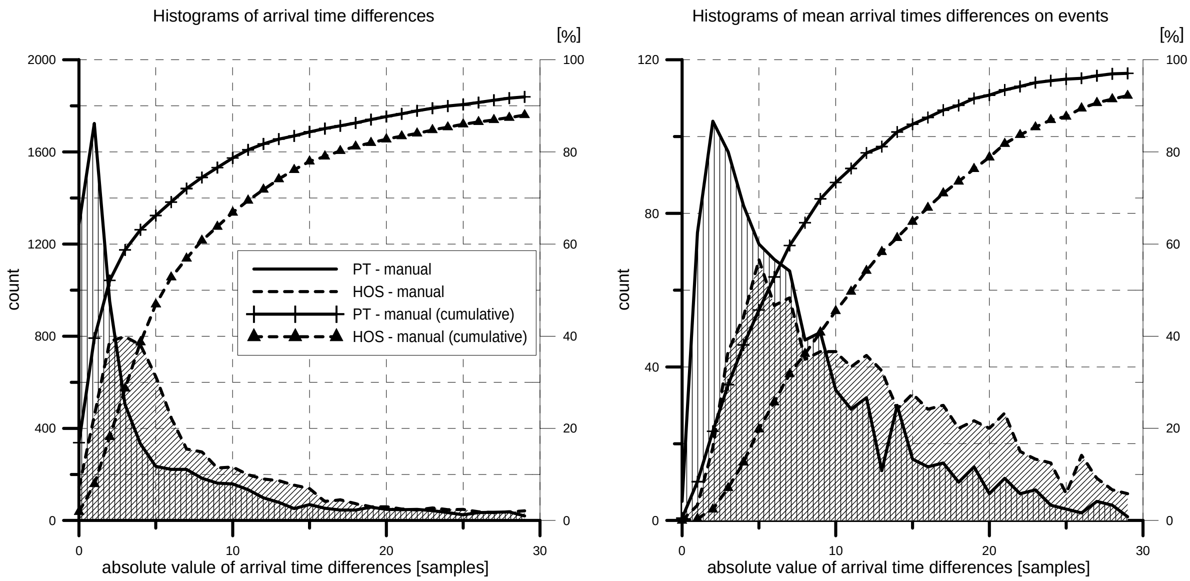

Fig. 4. Histograms of absolute values of arrival time differences assessed by HOS software, PT and manual; x-axis units [samples], legend is valid for both graphs.

The histograms in Fig. 4a represent the absolute value of the time difference individually for each signal. The histograms in Fig. 4b represent the absolute value of the mean time difference for 8 records of one AE event. The cumulative curves indicate that the PT picks agree better with the manual picks (78.7 % picks with 10 samples error) than the HOS method picks (only 66.8 % picks with 10 samples error).

One advantage of the PT method is its computation speed. Computation of the dataset used, i.e. 7600 signals, takes only 75 seconds.

Another parameter that can be used to evaluate the accuracy of the automated picks is the location residuum of the AE events. The location algorithm is based on a simple and reliable grid search method. The modified location method with the L1 norm was used, i.e. the minimum sum of the power of time differences is replaced by the minimum sum of the absolute values of time residues. By comparing the residual times of the manual, HOS and PT picks, one can find how accurate the individual kinds of picks are. The comparison is shown in Fig 5.

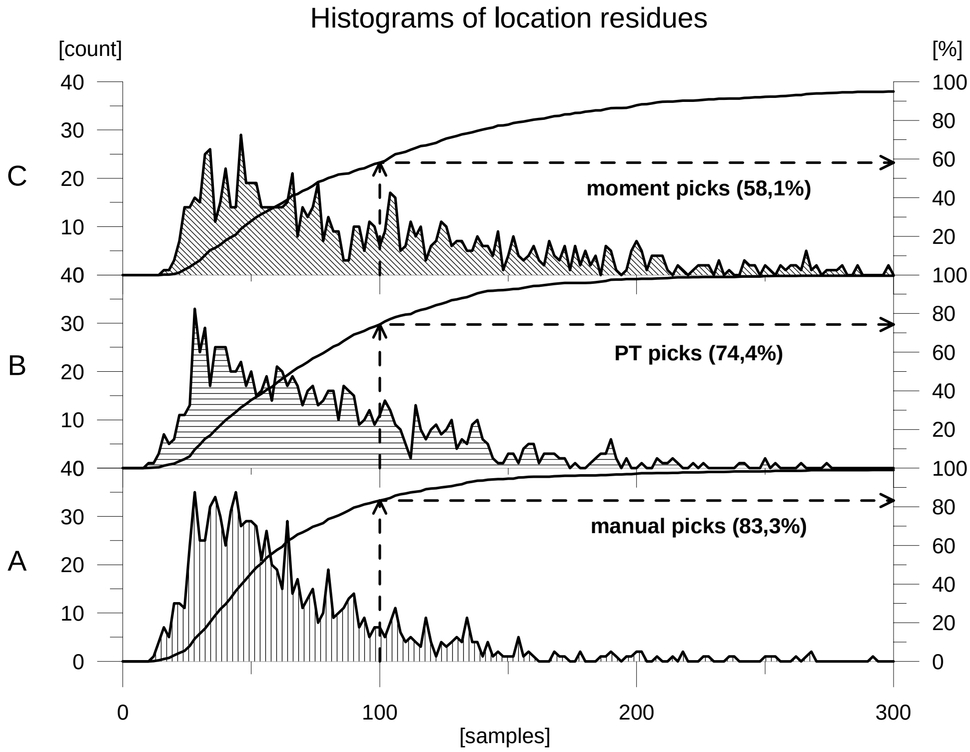

Fig. 4. Histograms of location residues of manual (A), PT (B) and HOS (C) picks.

The residues computed from the manual picks are shown in Fig. 5A, the HOS (moment) residues in Fig. 5C and the PT residues in Fig. 5B. The comparison of location residues displays a similarly successful sequence as in the case of the time difference comparison. If the value of 100 samples (10 µs) is taken to be the criterion of the pick's quality, the manual picks fit this criterion in 83.3 % of the cases, the PT picks in 74.4 % and, finally, the HOS picks fit only in 58.1 % of all AE events.

Conclusions

In this paper, a new derived method for determining the P-wave time arrivals is presented, and its application is demonstrated on the acoustic signals occurring during the rock specimen loading. This method of automated picking by the Pick-Tester program allows to analyse large volumes of data in a relative short time. The accuracy of the automated picks is in a very good agreement with the manually determined picks. The time values determined by both methods differ by less than 1 µs in 78 % cases. The final locations of the AE events display a similar agreement. However, manual processing of such large data files is very time-consuming and practically unworkable. It has been found that the approach used in the Pick-Tester program yields better results than the high-order statistics (HOS) method which is able to work automatically as well.

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