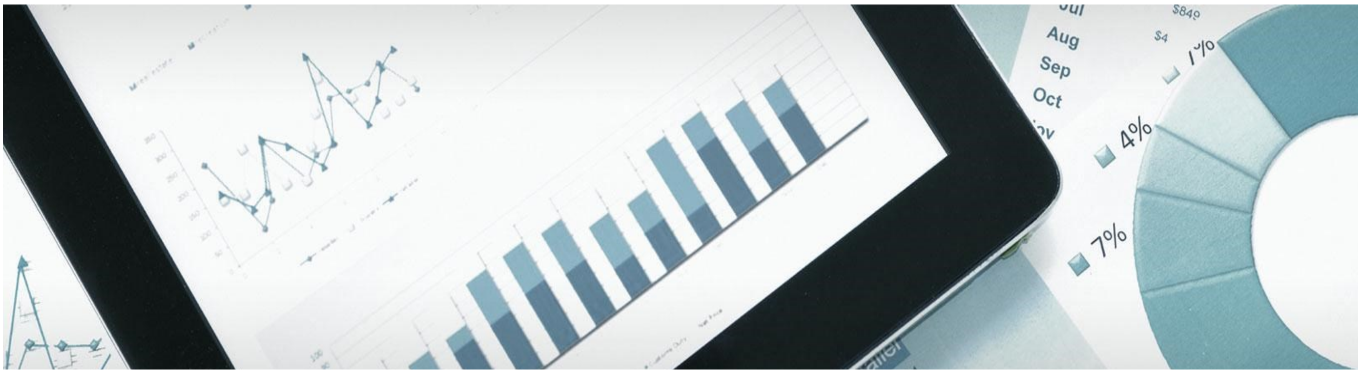
Using the cluster analysis for the statistical study of vibro-seismic waves for a more accurate estimation of their arrival times.



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ABSTRACT

The vibro-seismic monitoring of the Earth's is a sufficiently efficient tool for studying the corresponding background layers for the geotechnical engineering. The base of such studies is the instants of waves arrival times which are picked out from the records of vibro-seismic waves. However, the corresponding records represent the interference of different waves including the noise ones which are added in the course of the seismic waves propagation. Therefore, the task is estimating these instants in such complicated conditions.

Generally, periodic (harmonic and FM) signals are used as the seismic waves models. Therefore, the harmonic and the spectral analysis are the most wide spread for deciding the above task. We propose to use a distinct model and to interpret records of seismic waves as time series. This paper describes the way of the plural estimation of the instants of waves arrival times on the basis of the cluster analysis by attracting the method of statistical trials and the user's interactive interaction with the computer. The way is useful to increase the accuracy of the above estimations values. The process will be illustrated with actual data from the area of the mud volcano on Mt. Shugo of Taman Province.

KEYWORDS :

vibro-seismic monitoring, periodic signals, cluster analysis, instant of wave arrival time, method of statistical trials, interactive interaction "user – computer"

I. INTRODUCTION

Before considering the nature of estimating the wave arrival times, it is worthwhile to present the essential points of the methodology of vibro-seismic research as an independent field of geophysical studies.

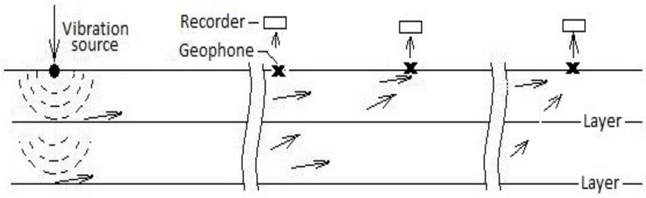

Figure 1. The scheme of the Earth's vibro-seismic monitoring.

The capability of vibrosounding of the Earth is considered in Nikolaev (1975). The Earth's Vibro-seismic monitoring includes the two parts:

I. (1) Excitation (generation) of waves of a determined frequencies band into the Earth by attracting physical sources, (2) recording the fluctuations of the Earth's corpuscles by using the geophones which are installed at some distances from a source of waves as demonstrates Fig. 1;

II. (1) Studying the records data and estimating the instants of wave arrival times, (2) tracing the layers (creating a model of the Earth's layers) and making the conclusions concerning the specificity of the Earth's structure in the region of monitoring.

Studying the recorded data and estimating the instants of wave arrival times is the content of the paper because other parts of the Earth's vibro-seismic monitoring are other fields of research and needs a separate attention.

As for detection of an instant of wave arrival time, it can be informally formulated as the instant of time which marks the beginning of the presence of a periodic signal on the input of recorder. However, the recorded signals are sufficiently complicated because of their distortions in the course of propagation. Therefore, the task of estimating the above instants needs a considerable attention.

As a rule, researchers use the harmonic or the spectral analysis because seismic waves are interpreted as periodic signals (harmonic and FM). However, with an appropriate approach one cannot decide the dilemma "time-frequency" (the spectrum components are listed in the domain, where the time scale is absent).

In some cases, as in Baziw (2007) and Torrence and Camp (1998), methods of the wavelet analysis and transformation are of interest to researchers. In these published works, the time localization of the signal frequency components can be found. Resulting from the development of the window technologies of the Fourier analysis, the wavelet analysis retains their specifics: the resolution depends on the "width" of the wavelet function. Narrowly localized in time, the wavelet function has a good time resolution but a bad frequency resolution and vice versa. At the same time, there is no commonly accepted method for choosing the basis function and a set of scales. A wavelet could also be interpreted as a band filter with a known response function, and the selection of the filter spectrum requires that the background spectrum should be known. This implies that, here, a special analysis must be used in each specific case. Essentially, such an approach is the development of the window Fourier analysis.

Second, generally, researchers attract methods of studying statistical properties of signals to be of interest as time series. Here, we should note: recognition of such instants of time in which signal statistical properties are change, appropriate estimations, as are attained in Nikiforov (2000). Because of the distortion of vibro-seismic records by noise, filtering such signals is used in some cases for increasing their quality. One of such kinds of the processing of the above signals is the convolution of recorded data with a sounding signal. In such a case, the estimation of a maximum of the envelope can help in determining the instant of the wave arrival time, as proposed in Glinskii and Znak (1998). At the same time, attracting the weighted order filters also allows an increase in the quality of periodic signals and allocating the specific frequency on the time axis.

Despite the availability of various techniques of the formal estimation of the instant of wave arrival time, involving the geophysicist-interpreter as an active participant in the process of solving the above problem is useful in practical cases, i.e., an interactive estimation of the instant of the wave arrival time of a periodic signals is desirable.

In our case, periodic signals will be treated as time series, and the cluster analysis will be used as the base of their studying. The statement of the corresponding task was presented in Znak and Grachev (2009) and was used as base of the studying of periodic signals in Znak (2010), Znak (2017), and Znak (2009). The approach of interest allows one to estimate both the instant of the wave arrival time as proposed in Znak (2009), and the signal duration time as is demonstrated in Znak (2010) and Znak (2011) .

Owing to the distortion of a signal in the course of its propagation, any estimation of the instant of the wave arrival time can be interpreted as a random one. By virtue of the above circumstance, it is offered to give attention to all characteristic points of a "clusters heap" which can potentially represent the estimation of searching. Involving the method of statistical trials allows one to expose a set of the corresponding points, on the one hand, and, on the other hand, attracting the interactive algorithm of the user/computer interaction, as is demonstrated in Znak (2015), that increases the probability of obtaining the qualitative estimations. Thus, the approach of plural estimations of arrival times of vibro-seismic waves is proposed.

II. THE BASIC DEFINITIONS OF TRANSFORMING PERIODIC SIGNALS TO CLUSTERS FORMATION

We will treat a model of a signal as a numerical sequence $X=\{x_1,\ldots, x_N\}$, which reflects the behavior of some real process recorded in a discrete time $t_1,\ldots, t_N$, where $t_i - t_N = \Delta t = cost$, $i=2,\ldots, N$. The values of the above sequence can have the form $x_i=x_i+\zeta_i$ in the case with the presence of noise, where ζ_i is the value of noise.

The key mapping function of transforming a periodic signal to a clusters formation image is formalized in Znak and Grachev (2009) as follows:

$$\sigma_k(L) = \sqrt{\sum_{j\in L}(x_j - M_k(L))^2}\,/L \quad \ldots\ldots\ldots\ldots(1)$$

where the sliding basis of the estimation L is odd, x is the signal value, $k=(L\text{-}1)/2,\ldots, N\text{–}(L\text{–}1)/2$.

Let us assume that in the general case, the dispersions σ_k are representatives of a signal at the instants of the time t_k to be considered as integers. We will utilize the uppermost dispersion value $\hat{\sigma}$, $0 \le \sigma_k \le \hat{\sigma}$. Further, the notion of a dispersion value will be used along with the notion "threshold" (h_l). Thus, we juxtapose a grid $Q = h_l \times t_k$ with our signal. Further, we will assume that each node of the grid represents the event $q_k(h) \in \{0, 1\}$:

$$q_k(h) = \begin{cases} 1, \text{if } \sigma_k \ge h, \\ 0, \text{if } \sigma_k < h, \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$k=(L-1)/2,\ldots, N-(L-1)/2,\ h=1,\ldots, \hat{\sigma}$.

The respective subset $Q_{r(h)} \subset Q$ of the adjacent instants such that $\forall q \in Q_{r(h)}$: $q=1$ will be called a cluster with the cardinal number

$$\beta_{r(j)}(h) = \sum_{q \in Q_{r(j)}} q,\ r = 1,\ldots,m(j);\ j = 1,\ldots,n(h) \quad \ldots\ldots(3)$$

localized at the time interval $\Delta t_{r(j)}(h)=t_1 \div t_{m(j)}(h)$ on the threshold h.

Let two clusters of the two neighboring thresholds $Q_{s(l)}(h+1)$, $Q_{r(j)}(h)$ be such that they are intersected at some time instants $\exists r,s$: $\Delta t_{r(j)}(h)$ & $\Delta t_{s(l)}(h+1) \neq 0$. The pooling of such clusters will be called a cluster family; $r_j(h)=\{1\ldots, m\}_j$, $j=\{1,\ldots n\}_h$, $s_l(h+1)=\{1,\ldots, n\}_l(h+1)$. Let a cluster $Q_{s(l)}(h+1)$ be called a child of the cluster $Q_{r(j)}(h)$, while the latter be called a parent of the cluster $Q_{s(l)}(h+1)$. The corresponding cardinal number of this family is

$$b_{r(h)} = \beta_{r(h)} + \sum_{s=1}^{n(h+1)} \beta_{s(h+1)} \quad \ldots\ldots\ldots\ldots\ldots(4)$$

Let all the clusters of a corresponding image be selected by some way. It should be noted that there exist such clusters that they obey one of the following conditions:

5a) $t_1 \le L$,
5b) $t_{m(h)} \ge N-(L-1)/2$ …….. (5)
5c) $t_1 \le L \wedge t_{m(h)} \ge N-(L-1)/2$,

where $\wedge$ is the disjunction (And) symbol. Such clusters will be called uninformative (undesirable) ones and will not be used by any way as well as the threshold h will be called an uninformative one if condition 5c is valid.

At the same time, each complete (perfect) family should have the uppermost boundary (edge) which is presented by such a cluster that it has no "child", while the same family should have the lowest boundary (edge) which is presented by such a cluster that has no informative parent. Let such a family be called a cluster clan and be denoted as $\hat{\Delta}$. A possible clan formation of the corresponding image is presented in Fig. 2

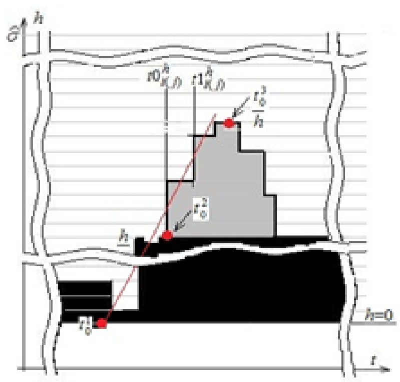

Figure 2. An example of the cluster clan as a fragment of a dispersion distribution image.

An important property of a clan is such that it has a single lowest cluster, while some of them can have more than one upper cluster which belongs to the same threshold. Let the threshold of the upper cluster of the clan be denoted as $\overline{h}$, and the threshold of the lowest cluster be denoted as $\underline{h}$. Naturally, the condition $\exists r$: $\overline{h}_r = \hat{\sigma}$ should be satisfied. In this case, the least informative threshold will be denoted as $\breve{\sigma}$.

Let a periodic signal be transformed to an image by using the dispersion estimation (1) and then be jointly scanned with building a set of N_{clan} clans.

One can study different peculiarities of a signal and use them for estimating its specific features. More often, the cardinal numbers of the i^{th} clan ($i=1,\ldots, N_{\text{clan}}$) are used, which are defined as follows:

$$B_i = \sum_{\underline{h}_i}^{\overline{h}_i} \left(\sum_{r=1}^{n(h)} b_{r(h)} (\Delta t_{r(h)} \subset \Delta t_{\underline{h}}) \right). \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Thus, the cardinal number of the i^{th} clan is obtained by the consecutive summation (layer after layer) of all the cardinal numbers of such clusters which are projected (implicated on to the time interval) onto the cluster of the lowest threshold and are included into the corresponding thresholds, beginning from the upper one.

The value obtained by formula (6) reflects the importance of the corresponding clan, or, in other words, presents the signal energy value localized on the time interval $\Delta t_{\underline{h}}$. Then the relation

$$P_i = B_i \Big/ \sum_{i=1}^{N_{\text{Clan}}} B_i \quad \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

III. THE ALGORITHM AND DECISION PROCCEDURES OF STUDYING THE CLUSTERS FORMATION

It is worthwhile to become clear about the basic conditions of analyzing the clusters heap obtained after transforming a periodic signal.

The starting points of building the clusters families are noted in conditions (5), i.e., excluding uninformative clusters from the subsequent analysis should be executed. The process of the cluster analysis can be presented as a sequence of the following steps: transforming a periodic signal to an image by using estimation (1) and scanning the image of dispersion estimations on a certain sliding basis L → picking out the cluster sequences by using the step function (2) → constructing the cluster clans by using the fact of their intersections at certain time instances → estimating probabilities of clans using definition (7) and → picking out their locus on the time axis. Here, the denotation → makes sense "a jump to the next step". Fig. 3 presents a sequence of the procedures of the corresponding algorithm.

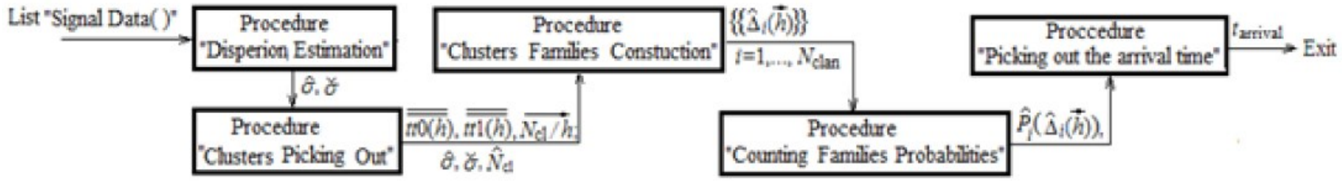

Figure 3. The flow-chart of the algorithm of studying periodic signal clusters.

In this case, a set of output procedures data is denoted as follows:

$\hat{\sigma}$ is the uppermost dispersion value;

$\breve{\sigma}$ is the dispersion value of the lowest informative threshold;

$\overrightarrow{N_{\mathrm{cl}}/h} = \{N\mathrm{cl}(h)\}$ is the data sequence, where $N\mathrm{cl}(h)$ is the number of clusters localized on the corresponding threshold, h=1,…, $\hat{\sigma}$;

$\overline{\overline{tt0}}(h) = \{\{\vec{t0}\}^{h}_{i(j)}\}$ and $\overline{\overline{tt1}}(h) = \{\{\vec{t1}\}^{h}_{i(j)}\}$, $h = 1,\ldots,\hat{\sigma}; i = 1,\ldots,m(j); j = 1,\ldots, N\mathrm{cl}(h)$ are the two sequences of the subsequences of the start and the finish points ($t_{1(j)}(h_j) \div t_{n(j)}(h_j) = \Delta t_{i(j)}(h_j)$) of the clusters that are nested on the corresponding threshold, respectively;

$\hat{N}_{\mathrm{cl}}$ is the full number of clans ($\hat{N}_{\mathrm{cl}} = \sum_{h=\breve{\sigma}}^{\hat{\sigma}} N\mathrm{cl}(h)$);

$\hat{P}_i$ is the maximum likelihood value ($i \in 1,\ldots, N_{\mathrm{clan}}$);

$\Delta t_{i(j)}(\underline{h}_j) = t_{1(j)}(\underline{h}_j) \div t_{n(j)}(\underline{h}_j)$; $j \in 1,\ldots, N_{\mathrm{clan}}$ is the location of the j^{th} clan on the time axis.

The key procedure of studying the clusters formation is Clusters Families Construction considered in Znak (2017). Its flow-chart is represented in Fig. 4.

We will give some explanations about specific features and notations of this procedure in addition to the inner variables because they are defined by its logic and are distinguished only by the corresponding data sequences and separate data of importance:

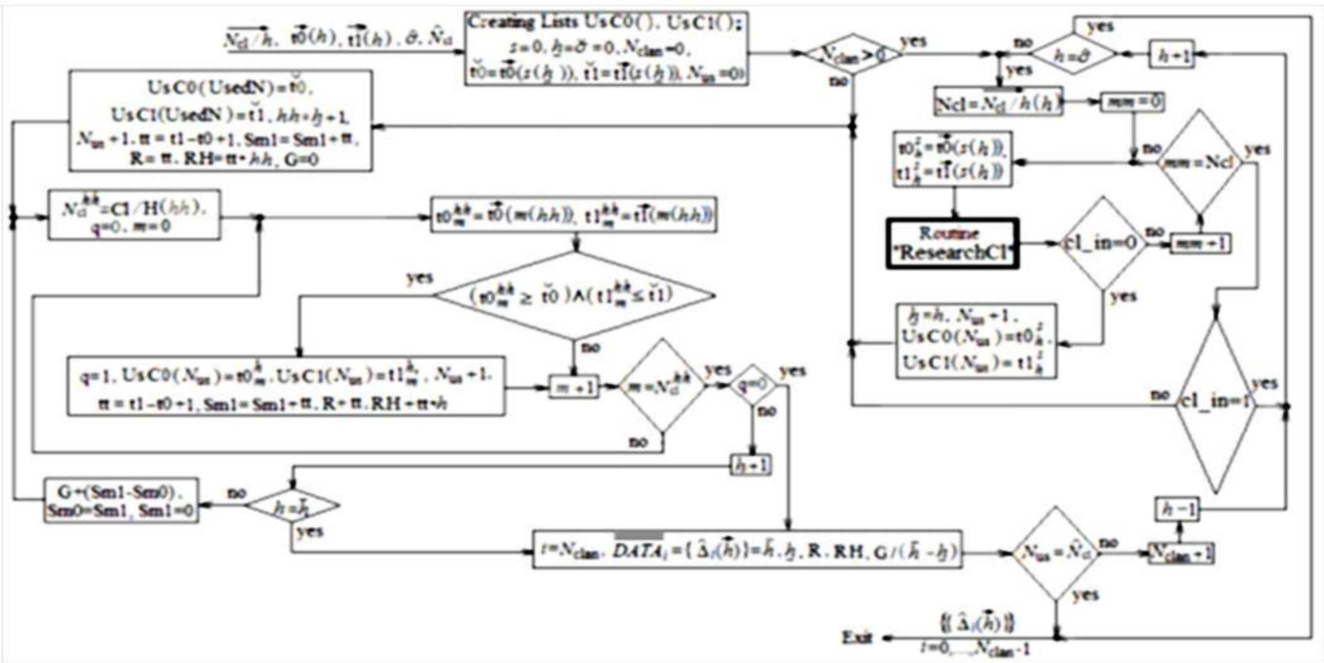

Figure 4: The flow-chart of the procedure of constructing the cluster families.

" $\mathrm{Data}_{\mathrm{clan}(i)}$"; i=1,…, N_{clan} is the sequence of lists of values that are needed for estimating parameters and characteristics of the corresponding clans. Each list includes the arguments (numerical values), which are intended for subsequent calculation of the corresponding parameters and characteristics of a signal (such as $\overline{h}_r$, $\underline{h}_r$, the cardinal number, and so on).

The process of carrying out the clusters formation analysis of the dispersion distribution of periodic signals is sufficiently complicated because in its basis lies the formal-logic analysis of the corresponding image. Here, we will note that the procedure "constructing cluster clans" includes the two stages: a) selecting the lowest cluster of the next (by turn) clan; b) selecting the clusters from the uppermost one to the lowest one under condition of their intersection in time with the lowest cluster: threshold by threshold. At the same time, the routine "ReseachCl" checks the presence of the current cluster $\Delta t_{i(j)}(h_j)$ (its start/finish instants of time) among the already inventoried clusters: a jump to the next cluster $\Delta t_{i+1(j)}(h_j)$ should be made by the procedure if the output of the routine is "True"; otherwise, the current cluster is inventoried for the current clan and is included into the list of inventoried clusters.

IV. MODES OF ESTIMATING CHARACTERISTICS OF PERIODIC SIGNALS USING THE CLUSTER ANALYSIS

Let all the cluster clans be enumerated and a set of the corresponding clans the corresponding clans.

Let all the cluster clans be enumerated and a set of the corresponding clans $\{\{\hat{\Delta}_i(\overrightarrow{h})\}$; i=1,…, $N_{\text{clan}}\}$ be obtained. The following initial assumptions and the key conditions of selecting the most representative clan were made in Znak (2017):

1) The process of signal recording begins at the time instant t_1=0 before the signal arrival, i.e., T_0>0, where T_0 is the instant of the wave arrival time.
2) A signal on the dispersion estimator input is $y=s+\xi$, where s is the source signal and ξ is the additive noise. Let $t_1 \div t_N$ be a signal recording period, and ΔT be a signal existence period. Then, the following conclusion is a consequence of such an assumption: the probability of localizing the upper cluster of the clan $k(\overline{h} \vee \hat{\sigma})$ on ΔT is proportional to the ratio t_N /ΔT and to the signal-to-noise ratio, i.e., $P(\overline{h}, \hat{\sigma} \in \Delta T) \sim t_N / \Delta T \;\&\; s/\xi = f(t_N / \Delta T, s/\xi)$ (each separate case needs its own analysis).

Here, the conditions of selecting the most representative clan, unlike the above case, are reduced to selecting such a cluster clan $\Delta t_i(\underline{h}_l)$, which would fulfil the following conditions:

$$\begin{aligned} & t_i(h_l) > L/2, \\ & t_n(h_l) < N - L/2, \\ & P_i(h_l) = \max, \\ & \Delta t_i(\overline{\overline{h_l}}) \in \Delta t_i(\underline{h_l}), \\ & 1 \geq i \leq N\text{clan}, \\ & h_l \in 1,\ldots,\hat{\sigma}. \end{aligned} \qquad \text{…………………(7)}$$

The time boundaries of the lowest cluster of such a clan can be considered as borders which reflect the period of existence of a real signal.

The time boundaries of the lowest cluster of such a clan can be considered as borders which reflect the period of existence of a real signal.

However, the interest of our research is the most precise estimation of such an instant of time of any clan that can be used as an instant of the wave arrival time of a periodic signal. Let the clan depicted in Fig. 2 be such a representative domain which includes the above instant.

One of the possible techniques to estimate the wave arrival time instant is presented in Znak (2009). The base of the above technique is the approximation of the left boundary (uniformity) by a straight line. The intersection of this line with the threshold h=0 can be understood as the instant of the wave arrival time. In Fig. 2, such an estimation is denoted as t_0^1.

The second possible technique is using the instant t_1 of the lowest cluster $\Delta t_{r(j)}(\underline{h})=t_1 \div t_{m(j)}(\underline{h})$ of a corresponding clan. In Fig. 2 such an estimation is denoted as t_0^2.

Finally, one can use the median point of the upper cluster $\Delta t_{r(j)}(\overline{h})=t_1 \div t_{m(j)}(\overline{h})$ of a corresponding clan. In Fig. 2, such an estimation is denoted as t_0^3. This technique of estimating the instant of the wave arrival time is the analog to that considered in Glinskii and Znak (1998).

V. THE ALGORITHM OF INTERACTIVE STUDY OF A SIGNAL AND ESTIMATING ITS TEMPORAL CHARACTERISTICS BY ATTRACTING THE METHOD OF STATSTICAL TRIALS

Keeping in mind that the dispersion estimation $\sigma_k(L)$ is represented by formula (1), the sliding basis of the estimation L can be used as a variable parameter of statistical trials. Then, the result of the above procedure "constructing the cluster clans" is a certain number of such objects. That is, some conglomerate of sets of estimations of the instants of the wave arrival times can be attained in the course of statistical trials of the search for cluster formations.

The corresponding interactive algorithm of searching the instants of wave arrival times is presented by the flow-chart depicted in Fig. 5.

It is possible that any estimations obtained do not satisfy the user despite the presence of a conglomerate of sets of clans. Therefore, estimations obtained include the value of all averaged estimations (arithmetical mean) and the statistics of the variation rows also defined by the procentile value, α (in essence, the statistical average if α=0.5). Finally, the user is offered to independently choose estimations for calculating the average.

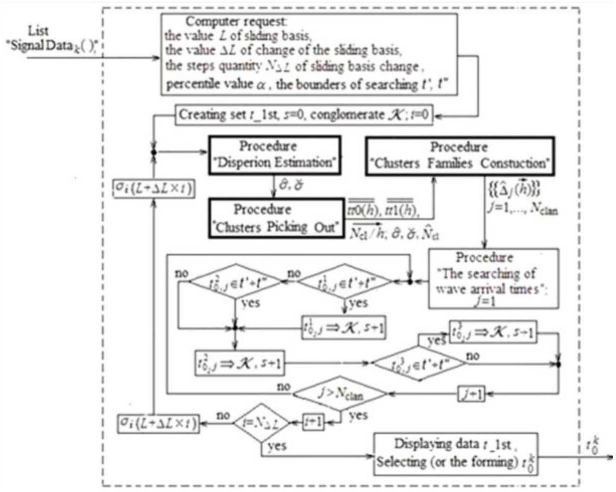

Figure 5. The flow-chart of the interactive algorithm of statistical trials of cluster formations and their study in the course of estimating the wave arrival times instants.

VI. SPECIFICITY OF STUDYING THE REAL DATA OF FIELD EXPERIMENTS; RESULTS OBTAINED

Because data recorded in the course of the Earth's vibro-seismic monitoring are sufficiently corrupted by different noises, some attention will be devoted to the possibilities of the improving the quality of periodic signals before the considering estimating its characteristics.

First of all, we will mention publications Znak, 2005, Znak (2011). We will note also the convolution of vibro-seismic data with the sounding signal besides the above mentioned propositions. In essence, the convolution is the linear concordant filtration. At the same time, we can to note that the behavior of the convolution data are somewhat similar to the behavior of the data of Vertical Seismic Profiling (VSP). In other words, VSP is Downhole Seismic Testing. Fig. 6 demonstrates this circumstance by examples of a record of the VSP (a) and an convolution of vibro-seismic data with the sounding signal (b).

We will use the convolution of vibro-seismic data with the sounding signal in the subsequent research.

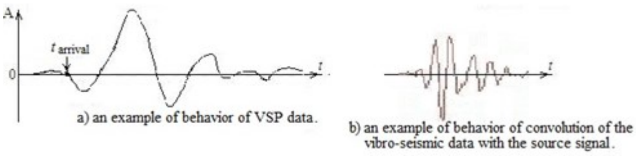

Figure 6. An example of the records of the vertical seismic profiling and convolution of vibro-seismic data with the sounding signal.

The approach proposed is tested by means of attracting real data recorded in the course of monitoring (in 2005) of the mud volcano on Mt. Shugo of Taman Province (results of the field experiments are currently accessible at the web_site http://opg.sscc.ru). As an example of utilizing the approach we can mention the use of the cluster analysis of periodic signals and studying its time position by the approximation technique of the left boundary as in Znak (2009) (t_0^1, see Section II). The above example is demonstrated by Fig. 7 where there are represented (from top to bottom) the source seismic record, the result of filtration by the order filters, and the approximation of the left boundary of the cluster family by a straight line.

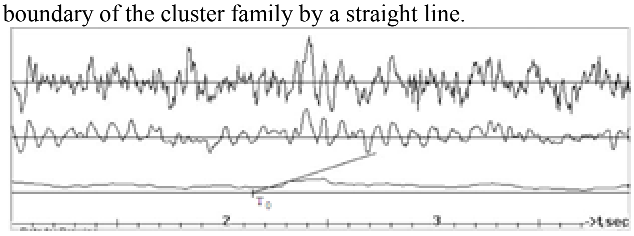

Figure 7. An example of the estimation of the wave arrival time instant of the noise periodic signal.

As this example demonstrates, the visual selection of the region of the signal presence is sufficiently complicated in both cases (before and after filtering). Therefore, in our case , we used the convolution of data of vibro-seismic records Asg ^{j} with the data of the sounding signal Aop ^{j} (j=1,…, N). In the general case, such a transformation can be presented as follows

$$R_j = \left(\sum_{i=1}^{n} \mathrm{Asg}^{j+i} \times \mathrm{Aop}^{j+i}\right)/n,\ j = (n-1)/2,\ldots,N-(n-1)/2$$

The graphical dialogue interface, proposed in Znak (2011), was used as means of the communication of the user with a computer in the course of studying the data of the above transformations. Fig. 8 represents an example of displaying the estimations (t_1^0; t_2^0; t_3^0 shown in various colors) obtained in the course of studying the statistical trials of the clusters formations and which satisfy the condition of location in specified boundaries 1:876 ÷ 2:326 (string by string), the propositions of the computer to the user and, finally, selecting the user.

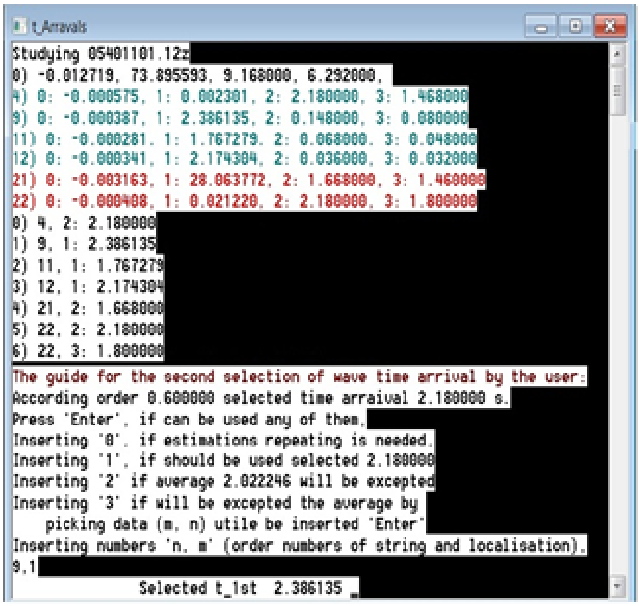

Figure 8. An example of displaying the estimations (t_0^0,..., t_0^3 shown in various colors depending on the value of the sliding basis L of the estimation $\sigma_k(L)$), the propositions of the computer to the user and, finally, the selection of the user.

Fig. 9 demonstrates an example of the source record (numbered as 05401101.12z), the result of the convolution and dispersion estimations with different dispersion estimations.

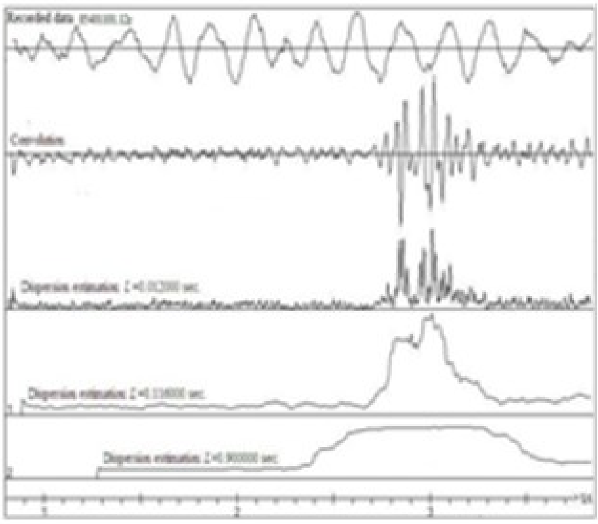

Figure 9. An example of the source record, the result of convolution and estimations of dispersion with sliding bases of estimation L=0.012 sec., L=0.116 sec., L=0.9 sec. (from top to bottom).

The estimations obtained in the course of studying the data after the monitoring of the mud volcano on Mt. Shugo are enumerated in Table 1.There are represented the data of three sessions of field experiments with the numbers 05400101, 05400601, and 05401101. At the same time, there was used the set of recording device with vertical orientation (z). The distance between the corresponding recording device and a source of vibrations is denoted as S, m., and the wave arrival time estimation is denoted as t_1 (sec.).

Table1. The list of the estimations obtained in the course of monitoring the mud volcano on Mt. Shugo.

05400101	S m.; t_1	05400601	S m.; t 1 s.	05401101	S m.; t_1 s.
01z	500; 0:248	01z	1670; 0:846	01z	3500; 1:811
02z	516:5;	02z	1686:5; 0:870	02z	3516:5; 1:874
03z	533; 0:292	03z	1703; 0:893	03z	3533; 1:882
04z	549:5;	04z	1719:5; 0:910	04z	3549:5; 1:957
05z	566; 0:331	05z	1736; 0:926	05z	3566; 1:972
06z	582:5;	06z	1752:5 0:954	06z	3582:5; 1:981
07z	599; 0:368	07z	1769; 0:960	07z	3599; 1:996
08z	615:5;	08z	1785:5; 0:970	08z	Absent
09z	Absent	09z	Absent	09z	3632; 2:01
10z	648:5;	10z	1818:5; 0:1:004	10z	3648:5; 2:02
11z	665; 0:441	11z	1835; 1:014	11z	3665; 2:02
12z	681:5;	12z	1851; 1:030	12z	3681:5; 2:026

The example of some estimations of locus of arrivals times on development of convolutions depicted in Fig. 10.

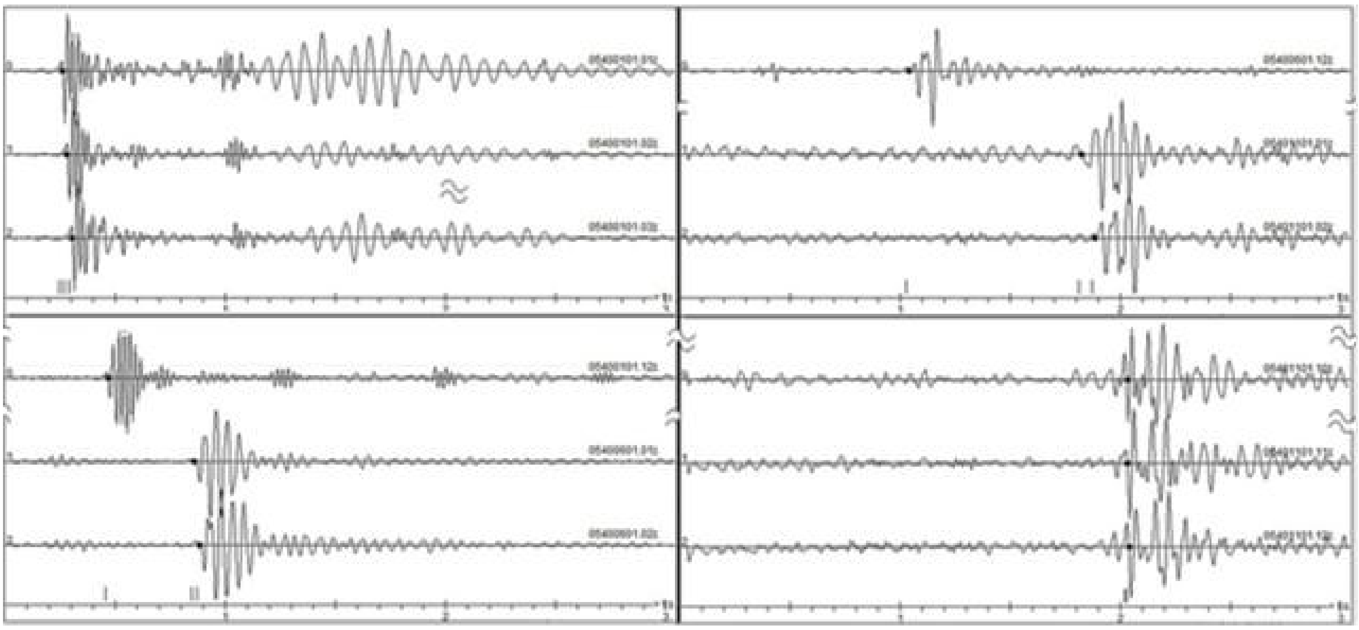

Figure 10. The example of the estimations of locus of arrivals times on development of convolutions.

VII. DISCUSSION

We can say that the estimations of the instants of wave arrival times and the results of analysis of the convolutions of vibro-seismic signals depend on the signal-to-noise ratio. Therefore, the method of statistical trials is rather a useful means of studying the noised periodic signals, and attracting the graphical dialogue interface is useful to maximize the user's efficiency. The other possibility of improving the accuracy of the above estimations is attracting the co-phased order filters, which were proposed in Znak (2011) and Znak (2005) to the preliminary signal processing. However, our main objective was restricted to the development of the method of the formalized estimation of the instants of the wave arrival times of periodic signals. Therefore, we are not concerned with the methods of improving the periodic signals, as it is a subject of separate investigation.

VIII. CONCLUSION

We have considered the approach of using the cluster analysis as a base of estimations of the instants of wave arrival times in the course of studying the data of vibro-seismic records. At the same time, the convolutions of vibro-seismic signals were used as objects of studying. The method of statistical trials was used as the main means of the above investigation along with attracting the graphical dialogue interface. There are proposed the algorithm and the decision procedures of studying the cluster formations. Finally, we have presented the results of processing the real data recorded in the course of monitoring of the mud volcano on Mt. Shugo of Taman Province.

IX. ACKNOWLEDGEMENT

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