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Operational reliability of geodetic control points

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Abstract: Methods of reliability engineering allow to anticipate an efficiency both geodetic network and single control points throughout the period of its operating. A reliability assessment of a predicted survey object behaviour produces data useful in optimisation of survey scope, timetable and accuracy. The essentials of reliability approach and procedures of finding of operational reliability characteristics have been presented in the paper. The presented characteristics include: the failure rate function $\lambda(t)$, the reliability function $R(t)$ and the random object life $F(t)$. Methods applied in reliability engineering viz. method of complete probability and method of evaluation of raw and parallel reliable structures have been adopted for survey purposes. Besides the standard ones original methods are also presented in the paper. Their concept lies on finding of stability functions and reliability characteristics indicated by means of statistical tests referring to density probability of predicted displacements. Although the presented theory is of general character the main application is focused on levelling networks.

Keywords: Operational reliability, geodetic control

1. Introduction

A reliability engineering theory provides effective tools for the evaluation and designing of technical structures. The main purpose of reliability analysis is to anticipate a system efficiency in the interval $< t_0, t_N >$, where t_0 is the time of the beginning of planned object operation. According to engineering reliability theory an operational reliability is defined by a probability that an object fulfils technical requirements. The requirements are specified variously. Reliability analysis is usually referred to as a mean time to failure (Bartoszewicz et al., 1982). Also a time period in which specified requirements are met by the object can be considered. Random features of variables are estimated by probability measures.

The role of the time in reliability engineering is substantial. It differs reliability approach in technical structures analysis from geodetic problems. The geodetic reliability analysis refers to the completed survey process, and moment t_0 pointed in the definition of the operation reliability in the case of geodetic analysis refers to the last observation. If $U(t)$ is the condition of geodetic structure, then the probability that maintenance requirements will be fulfilled in each time t_N, may only be equal to the structure's condition at the time t_0, i.e.

$$P\{U(t_N)\} \leqslant P\{U(t_0)\} \tag{1}$$

From the reliability engineering point of view the geodetic analysis is of "historical" type. Let's notice that kinematic models, which take into consideration a time variable, are also analysed after completion of survey process.

The difference between geodetic and operational reliability analysis of the survey structure is justified by rational evidences. Survey structures are not typical technical objects. The latter ones due to the lack of alternative are described by probabilistic models, which generalize the features of objects. Most of the models of survey structures are described reliably by means of equation system and covariance matrix. It is obvious that the evaluation of the results based on the theory of errors is much more effective than the reliability approach. The obvious result of this is just the different interpretation of reliability. Geodetic reliability analysis is focused on detecting blunders, their localizations and dispersion by adjustment procedures. Localization of them is important both from research and practical point of view as it allows to improve the designing of the survey control (Prószyński and Kwaśniak, 2002). From the theoretical point of view results of this analysis are correct, however, only in the beginning of the exploitation period. Only due to lack of alternative the assumption that the network is also considered stable later on is needed.

The practical purpose of the reliability analysis is to predict a rate of the "using up" of the object in a strictly determined operation period. As engineering practice shows, the problem of unstability of control points is significant as up to date measurements are carried out too rarely. As a rule levelling networks are updated (re-surveyed) only in a few decades intervals. Identification measurements which are carried out to find most stable benchmarks solve practical problem but only on a local scale as they refer to small part of a network.

The base of reliability analysis are studies of regularities in the behaviour of an object. It needs the recognitioning of two problems. Firstly, if the process of deformations shows any regularities, secondly – how to describe them by means of a prediction model? The method of prediction of a process can be – according to the author – assumed as the criterion of the operational reliability problem. Three types of problems may be pointed out:

- the determination of the reliability function by investigating the risk function;
- the method of the complete probability;
- the analysis of the probability density of the predicted displacements.

Two first methods which are typical for engineering reliability (Migdalski, 1992; Wieczysty, 2001) have been adapted for the geodetic purposes in the presented paper. The third method that has been proposed by the author essentially differs from two first ones. It exemplifies an interdisciplinary approach as the basis of that method is a prediction of displacements.

At the presented conception the object of reliability analysis is assumed as a set of vertical or horizontal network points. In the result of analysis an operational reliability of each set element is determined. In the second stage the produced results can be analysed to determine an operational reliability of limited number of points. For example, if a few network points are chosen as a reference system, the resultant reliability can be found using the reliability structure analysis as it is shown further down in the paper.

The result of reliability analysis depends on statistical homogeneity of set elements. It refers to metrological and environmental features. The first one depends on survey accuracy, the latter one characterizes the area where the survey object is localized. In the engineering problem the object of reliability analysis will be defined by points of horizontal or vertical control network, reference points etc. The reliability analysis considers neither method of measurement nor geometrical features of geodetic structure.

The problem of operational reliability in the presented scope and approach is not known in geodetic literature. The outline of operational reliability approach was published by the author (Wolski, 2002). Following the conception of operational reliability the results of measurements of vertical network of Cracow have been analysed in the paper (Toś and Wolski, 2005). In the presented paper theoretical basis of the reliability approach has been completed by results of up-to-date experience. But it should also be emphasized that the application of operational reliability approach suits well the vertical measurements. Application to other surveys is limited by difficulties in gathering of necessary data. A preliminary analysis shows that the method can be applied for the analysis of stability of horizontal control points in the border mining area. Procedures of reliability approach are identical independently of the kind of survey control network.

2. Reliability probabilistic model and reliability function

The main purpose of reliability analysis may be described as a practical question: what part of objects will be in the state of usability in the determined future. The problem is described by means of the mathematical model, first of all by a reliability function $R(t)$ called also a survival function. The $R(t)$ function determines a probability of surviving the period $\langle 0, t \rangle$. The beginning of that period is a moment of delivery of object to operating. The $R(t)$ function determines a random stability value of an object. It is found as complement to a unit

$$R(t) = P\{t_N \geqslant t\} = 1 - P\{t_N < t\} \quad \text{for} \quad t \geqslant 0 \tag{2}$$

$$R(t) = 1 - F(t) \tag{3}$$

where t_N is an object life time, and $F(t)$ is the cumulative function of random object life.

Failure rate function (or hazard function) $\lambda(t)$ is strictly related with the functions $R(t)$, $F(t)$. The failure rate function shows the probability that the object will be in failure condition in the time t. The function $\lambda(t)$ by definition (Migdalski, 1992) is

$$\lambda(t) = -\frac{d}{dt}[\ln R(t)] \tag{4}$$

and after rearranging can also be given as

$$\lambda(t) = \frac{1}{R(t)} \frac{d[1 - R(t)]}{dt} \tag{5}$$

The failure rate function $\lambda(t)$ may be determined from the failure probability function $f(t)$

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{6}$$

where

$$f(t) = \frac{d}{dt}[F(t)] \tag{7}$$

To solve the reliability problem the one of three above mentioned functions, i.e. $R(t)$, $F(t)$ and $\lambda(t)$ have to be determined. The functions can be well determined only by empiric investigations which verify other similar objects. But in typical reliability problems the failure rate function $\lambda(t)$ is usually assumed as similar to other cases from engineering practice. Furthermore it is very often assumed arbitrarily. For example, assuming $\lambda(t) = a$, according to (4) one gets

$$a = -\frac{d}{dt}[\ln R(t)]$$

what gives

$$R(t) = e^{-at} \tag{8}$$

The value of a is determined as a number of defects found in the assumed time interval. In the case of levelling network it will be the part of total benchmarks number, which in a defined time unit loses requirements of an operational capacity. Data necessary to analyse deformations of control structures are gained from periodically repeated surveys. The measurements must be performed in proper statistical conditions and must fulfil conditions referring to number and features of examined population, period of agents impacting negatively at stability of survey geometrical structure. In statistical investigations carried out for reliability analysis it is usually assumed, that displacement process of control points is of random character with a determined trend and dispersion. Let's notice that completed measurements of geodetic networks are carried out very rare. Usually only two points of diagram are known: the initial and final ones, an intermediate measurement is given very rare.

The analysis starts with finding of a value (8). The value a is used to determine the failure rate function $\lambda(t)$. There is no alternative for assumption $\lambda(t)$ = const if initial and final measurements are only given. The value a can be determined as a mean value of sampling population but according to the author an assumption of distribution quantile seems to be better solution. In Table 1 some examples of reliability $R(t)$ and density $f(t)$ functions have been derived assuming failure rate function $\lambda(t)$.

Table 1. Functions $\lambda(t)$, $R(t)$, $F(t)$ for different models of operational reliability

Failure rate function $\lambda(t)$	Reliability function $R(t)$	Density function $f(t)$
a	e^{-at}	$a \cdot e^{-at}$
$a\ t$	$e^{-\frac{1}{2}at^2}$	$a \cdot t \cdot e^{-\frac{1}{2}at^2}$
$a\ t^2$	$e^{-\frac{1}{3}at^3}$	$a \cdot t^2 \cdot e^{-\frac{1}{3}at^3}$
$\frac{a}{t}$	$e^{-a \ln t}$	$\frac{a}{t} e^{-a \ln t}$

In the case of stability analysis of levelling control points the reliability function $R(t)$ contains two kinds of influence. The source of the first one is an impact of environmental conditions. The environmental agents are both of systematic and random character (Wolski, 2006). The second effect is observed as destructions and damages of benchmarks (Gajderowicz, 2005; Wolski, 2006; Derezińska, 2007). The values determined by means of $R(t)$ allow to anticipate deformations which exclude usability of object. It covers the problem of updating the order of levelling network after the determined period of operating. It means that using of the operational reliability measure could effectively replace the present arbitrary standard rule.

3. Reliability of object structure

Assuming that analysed object (control network) is composed of n established marks and each of the points is of determined reliability R_i, then the resultant reliability R_u can be determined using structural analysis of a given reliability system. Two structures of the system are considered as the basis of reliability analysis: row and parallel ones. For example, the levelling control is better modelled by the parallel structure. According to general definition of reliability one accepts that the object fulfils requirements if at least k from n its elements are good (Migdalski, 1992). A reliability of such system can be determined by equation

$$R_u = 1 - \prod_{i=1}^{n} (1 - R_i) \tag{9}$$

where R_i is a reliability of i-control point. The system is identified as non uniform. It is considered as uniform if each element fulfils the condition $R_i = R$. This assumption rearranges (9) to

$$R_u = 1 - (1 - R)^n \qquad (10)$$

To determine the value R statistical surveys have to be carried out. The investigations of levelling network in the Cracow area mentioned in Sections 1 and 2 exemplify them very well (Toś and Wolski, 2005).

Other structures used in reliability engineering, viz. raw structures or mixed structures, i.e. raw-parallel, are of less meaning for the presented problem. In the case of raw structure, if $k = n$ an object is efficient provided all its elements are efficient ones. A reliability of such object is determined by multiplying of partial reliability characteristics

$$R_{n/n} = \prod_{i=1}^{n} R_i \qquad (11)$$

while in the case of raw- parallel system it is given as

$$R = \prod_{i=1}^{n} \left[1 - \prod_{i=1}^{m} \left(1 - R_{ij} \right) \right] \qquad (12)$$

where R_{ij} is a reliability of i-element in j-set (Migdalski, 1992).

The raw structure can be used at modelling of each agents at resultant operational reliability, if the separate influence of random-systematic errors caused by environmental agents have to be integrated with the characteristics of usability of control points. According to the author "the usability" combines two conditions: the point is available for taking surveying observations, and secondly: the point cannot be damaged. The values of elements of the considered model of operational capacity may be estimated on the basis of results of measurements published in surveying literature. Gajderowicz presenting results of periodical measurement of the 1st order Polish Vertical Control Network determines those values on the level of about 20% and 5% in the period of 30 years (Gajderowicz, 2005). The similar values have been determined in the case of levelling networks in Cracow (Toś and Wolski, 2005). The failure rates are much worse in the case if a network is established in the area dominated by expansion soils. Such investigations carried out in the Bydgoszcz area show that the damage characteristic reaches a level of 35% in the period of 30 years (Dereziñska and Kujawski, 2007).

4. Evaluation of operation reliability by means of complete probability

The evaluation of operational probability is noted in zero-one binary code. The investigation of operational probability is carried out according to two different programs. According to the first one the sampling population is examined and results are generalized to all survey results. That approach produces characteristics of limited credibility due to different and complicated conditions of points stability. The better and more detailed estimations of operational probability characteristics give the method of the complete probability. The procedure takes into consideration probabilities of appearance of different classified conditions (Wieczysty, 2001). If probability of displacements within the limits permitted to sign as $p(B)$, and by $p(A)$ the probability of appearance of A_i – condition, then the conditional probability, where the event B depends from the state A_i is by definition determined from the formula

$$P\,(B/A) = \frac{P\,(B \cap A)}{P\,(A)} \tag{13}$$

and the probability of operating of the whole system is determined as follows

$$P\,(B) = \sum_{i=1}^{n} P\,(A_i) \cdot P\,(B/A_i) \tag{14}$$

where conditions A_1, A_2, ..., A_n determine influences of environmental agents. The appearance of permitted displacements in the conditions A_i has been signed by $p(B/A_i)$. The probability $p(B/A_i)$ can be used as a criterion of serviceability of control structure. It is the probability of displacements permitted, when the control network fulfils the criterion of operational capacity. The best way to assess the probability $p(A_i)$ is the examination of proper sampling population and to find

$$p(A_i) = \frac{g_i}{\sum\limits_{i=1}^{n} g_i} \tag{15}$$

The estimation of $p(A_i)$ probabilities is difficult due to the scope of geotechnical and civil engineering studies which should be taken to collect necessary data. Firstly, engineering documentations are dispersed in many archives, secondly and more important is that studies of history of changes in environmental conditions should cover long periods, even a few tens of years.

5. Operational reliability characteristics found by means of statistic tests of density of predicted displacement probability

From the engineering point of view the usability of levelling benchmarks is the problem of unstability of construction foundation in which survey marks are fixed. The problem of benchmarks behaviour in the time of predicted exploitation can be treated as the interdisciplinary one and analysed by methods used in soil mechanics and foundation analysis. Unfortunately this way of predicting deformations and displacements occurs to be extremely complicated. The engineering specificity of the deformation problem appears from the fact that period of the investigations have to be very long, whereas the displacements analysed are very small. Furthermore, displacements which are evaluated as very small by civil engineers are of crucial meaning from the geodetic point of view. Geotechnical models do not describe correctly the process of displacements in multi – years period. The main barrier of this is the lack of data of load history and changes in soil parameters. That is why there is no alternative for empiric approach and assuming statistic model of displacement process.

The choice of prediction method depends on data available. In the extreme cases the process of displacements can be described either by means of geodetic data only or mentioned above physical models of soil. In practice as a real one the methods combining different data and approach can be adopted. Three main types of prediction problem base on:

- geodetic data – Problem A;
- both geodetic and geotechnical data – Problem B;
- physical features of soil – Problem C.

According to the author' proposal the deformations and displacements can be described by means of "stability function" being the correlation model of soil deformation. In the result of application of the model and procedures the set of displacements $\{H_l\}_g$ is found referring to the period of prediction.

The A-problem. The results of geodetic measurements of displacements are given only. The sets: initial $\{H_i\}_0$ and final $\{H_i\}_k$ should refer to the period of ten at least, but optimally 20–30 years. The measurement may cover all benchmarks of the analysed network or a part of it. The set $\{p_j\}_k$ of displacements of benchmarks in the period between t_0 and t_k is found by formulae

$$\{p_j\}_k = \{H_j\}_k - \{H_i\}_0 \tag{16}$$

where $\{H_i\}_0$ is a result of initial measurement in time t_0, and $\{H_j\}_k$ is a result of levelling in time t_k. The set of predicted elevations $\{H_l\}_g$ is determined using the stability function by extrapolation of the data. In the extrapolation problem two other variables should also be taken into consideration:
σ_k – standard deviation of displacements found for the set $\{p_j\}_k$ of n_k in number,
t_g – time of predicted measurement $t_g > t_k$.

The B-problem. Two kinds of data are given: results of geodetic measurements and physical (environmental) features of soil. The stability function is of the form

$$p_i = \sum_{j=1}^{m} w_{j,i} \cdot k_j \quad (i = 1, 2, ..., n) \tag{17}$$

The coefficients $w_{j,i}$ determine influences of analysed agents at the point $P_i(X_i, Y_i)$. They give environmental characteristics of analysed area. The values of $w_{j,i}$ are assumed arbitrarily on the basis of other experiences. The coefficients $w_{j,i}$ determined on the basis of the author's own experience have been given in (Wolski, 2006). In (17) the values of k_j ($j = 1, 2, ..., m$) are obtained from the given vertical displacements and environmental characteristics $w_{j,i}$ using least squares adjustment procedure. The B-problem differs significantly from the previously considered A-problem. In the B-problem the environmental characteristics $w_{j,i}$ as well as stability functions p_i are accredited to fixed points $P_i(X_i, Y_i)$.

The C-problem. The results of geotechnical investigations are given and also a number of measured displacements. But sometimes it may happen that there is no geodetic data on displacements of benchmarks. In such cases the predicted values of displacements which one need for reliablility analysis may be taken only with the use of the correlation method by comparison with other area of similar environmental conditions.

Data referring to displacements used in the procedure of finding the stability functions have to fulfil general conditions of sampling population. They are as follows:

- settlement process of structures (buildings) should be in a final stage; the building should be at least a few dozen years old;
- buildings observed should be of similar type of construction, especially concerning the foundation;
- network points should be dispersed all over the studied area.

The credibility of analysis is higher if the dispersions of analysed variables are recognized. It is possible (and necessary) only in the case of surveying structures. The standards errors of analysed data sets $\{p_j\}_k$ and $\{p_j\}_g$ can be found either by definition or from the variance of stability function p_i.

All practical displacements prediction tasks are solved at assumption that the gradient of displacements is constant in the analysed period $\langle t_0, t_g \rangle$. It is assumed that the set of predicted displacements $\{p_j\}_g$, as well as the set of measured displacements can be modelled by normal distribution $N\{p_{g,m}, \sigma_g\}$.

Characteristics of operational reliability are determined by means of statistic tests t-Student and F-Fisher. The reliability characteristics are indicated by verification of statistic hypothesis that mean values and variances do not differ essentially and they derive from the same parent population. Following the t-Student procedure the variable T_0 and reliability characteristic q_T are found

$$q_T = P\{|T| = T_0\}$$

According to F-Fisher test procedure the value of significance level q_F is found. The final reliability characteristic v assumed at the assumption

$$v = \min(q_s), \ s = T, \ F$$

shows that the two compared samples do not derive from the same parent population at the probability of $1 - v$. The bigger v the better is the operational reliability characteristics of analysed network.

6. Remarks and conclusions

The operational reliability extends the scope of theoretical and practical issues of projecting surveying with aspects of no-failure operation, operational capacity and predicted technical efficiency of geodetic structures. Prediction of technical efficiency of control surveys is a new issue in geodetic literature.

The presented procedures of analysis allow to predict a time of a credible operation of an object. As non-arbitrary methods they provide objective evaluations of survey networks quality. They can be applied for analysis of a scope of updating control surveys as well as at identification of most stable parts in geodetic network both in current and future operation.

The integration of surveying, geotechnical and environmental problems is crucial in the presented approach. Unfortunately it is an extremely difficult task due to necessity of acquisition of numerous data. That is why it can be completed only in rare cases. But on the other hand it is the only way to find the answer for the questions which have not been taken up till now in geodesy. Only on the basis of the operational reliability approach it is possible to predict periods of operation efficiency and validity of survey controls, specifying scopes of updating surveys as well as finding points which in future at the realisation of survey task will fulfil the demands of stability in determined time interval.

The possibility of widespread of reliability approach and application of presented solution faces, however, the difficult barriers in the stage of data acquisition. In this context the GPS technology may play an important role as the method of levelling (Baryła et al., 2007). Proper power of set will allow to determine the failure rate function $\lambda(t)$ according to procedures assumed by engineering reliability and on that basis to form and solve reliability problems both for single points and a whole network.

The results of analysis can be concluded, as follows:

- A reliability problem of geodetic control is not a typical application of reliability engineering. That is why geodetic applications need some modifications especially in the scope of data collecting.
- Problem of evaluation of operational reliability of survey object is efficiently described by the reliability function $R(t)$, random object life $F(t)$, complete probability of the system and probability density function of predicted deformations.
- The reliability approach is a useful tool for the purpose of quality and condition evaluation of the examined network, optimisation of updating measurements and optimisation of monitoring program of soil and structure deformation. According to technical regulations decisions referring to the change of the order of network is presently taken up automatically and refer to the whole network independently of stability conditions.
- Data acquisition is the first stage in the operational reliability algorithm. The data allows to build a model of predicted behaviour of the analysed process. That is why the systematic collecting of archival materials referring not only survey results but also other technical documentations is so important. An efficient use of database depends on processing procedures which describe the system according to necessity of reliability analysis.
- Although the presented operational reliability approach is of general character, it covers the problems of levelling network analysis best.

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Niezawodność eksploatacyjna punktów osnowy geodezyjnej

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Streszczenie

Metody inżynierii niezawodności umożliwiają ocenę jakości osnów i pojedynczych punktów geodezyjnych w okresie ich użytkowania. Niezawodnościowa analiza zachowania się obiektu geodezyjnego w okresie przyszłej eksploatacji dostarcza danych przydatnych w optymalizacji zakresu, harmonogramu

oraz dokładności planowanych pomiarów. W artykule przedstawiono podstawy podejścia niezawodnościowego i procedury wyznaczania wskaźników niezawodności eksploatacyjnej. Charakterystyki niezawodności eksploatacyjnej przedstawione w artykule obejmują funkcję intensywności uszkodzeń $\lambda(t)$, funkcję niezawodności $R(t)$ i funkcję losowej trwałości obiektu $F(t)$. Metody stosowane w inżynierii niezawodności, w tym ocenę niezawodności eksploatacyjnej metodą prawdopodobieństwa zupełnego oraz metodę oceny niezawodności złożonych struktur zaadoptowano dla potrzeb problemu pomiarowego. Poza standardowymi metodami inżynierii niezawodności w artykule przedstawiono także oryginalne procedury. Ich podstawę stanowią funkcje stabilności i wskaźniki niezawodności eksploatacyjnej wyznaczane metodą testów statystycznych na podstawie gęstości prawdopodobieństwa przemieszczeń prognozowanych. Jakkolwiek zaprezentowana teoria niezawodności eksploatacyjnej ma ogólny charakter, to najlepiej wpisuje się w problematykę pomiarów wysokościowych.