ABSOLUTE MOVEMENTS OF LARGE DAMS ANALYSIS BY REGRESSION METHOD UTILIZATION

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UDK: 528.02:528.481
DOI: 10.14415/konferencijaGFS2018.074

Summary: *Determination of large dams' absolute movement is of crucial importance for assessment of their state and behaviour. Absolute movement of large dams is meaning change of their position in space and time as well as the change of its geometry of their parts. Absolute movements of large dams are determined by geodetic methods and conclusions about its movements in space and time are based on movement of benchmark and points marks by which dam it is approximated, i.e. the conclusions about movements in space and time are based on the position of set of discrete points in certain interval of time. On the base of long time geodetic monitoring of certain large dam it is possible to find the patterns of its behaviour in space and time. This paper attempts to investigate the behaviour of large dam by regression method utilization.*

Keywords: *Statistical analysis, deformation analysis, geodetic measurements*

1. INTRODUCTION

Determination of point's movement which represent large dams' state and behaviour is of importance for decision making about taking adequate actions for prevention of undesired events. Because of big number of different influences which affect large dams, which also are very complex structures, determination of their position change is of crucial importance for comparison of their factual and designed state. Deviation between factual state and design of large dam represents the level of danger on which it is exposed to. As large dams together with accumulations formed behind them are a danger for downstream area, the concepts of risk and hazard are developed in order to indicate the level of potential damages which could occur In case of unwanted event such as dam failure.

Absolute movement of points which represents an object structure are determined by geodetic methods and they point out the movement in space and time. The concept of

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absolute movements is introduced in order to make difference to relative movements which represents the changes of certain parameters related to previous measurement, or related to mathematical or physical condition. Relative movements represent only local movements of separated points.
Determination of absolute movements of objects' points is very complex problem which was in past decades an issue of numerous scientific research, articles and discussions. The result of scientific research in area of absolute movements of points and changes of objects' geometry is establishment of scientific area called "deformation analysis of geodetic network" [1]. A big number of methods developed for deformation analysis of geodetic networks as well as permanent development in this area point out the complexity of phenomenon as well as the further possibilities for development of that research. The fact that deformation analysis of geodetic networks is an issue of literature and professional practice is the consequence of its importance as well as its complexity in theory and practice. Determination of causality of position and/or height changes of certain benchmarks-points which represent the changes of large dams in space and change of their geometry are significant and necessary data for reliable conclusions about level of concordance between designed and actual geometry and position of large dam.
Polynomial regression [2] could be used for determination of absolute movements of points dependent on time while the determination of different influences on absolute movements could be analysed by linear multidimensional regression [2].

2. ABSOLUTE MOVEMENTS OF POINTS

According to literature [3] absolute movements are the movements related to the reference (control) points and which shall be stable (which not change their position) in space and time for the given geographical location. It means that, if the movement of broader area exists, all control and points on object are moved for the equal values. Relative movements represent behaviour of object and changes of mutual position between points located on object. Absolute movements represent the changes of position of object related to geodetic network i.e. to the stable points of geodetic network while relative movements represent the changes of objects' geometry. On the base of absolute movements of points it is possible to determine if object is moving (changes its position in space and time) or it is deforming (i.e. mutual relation between points which represent the object changes).

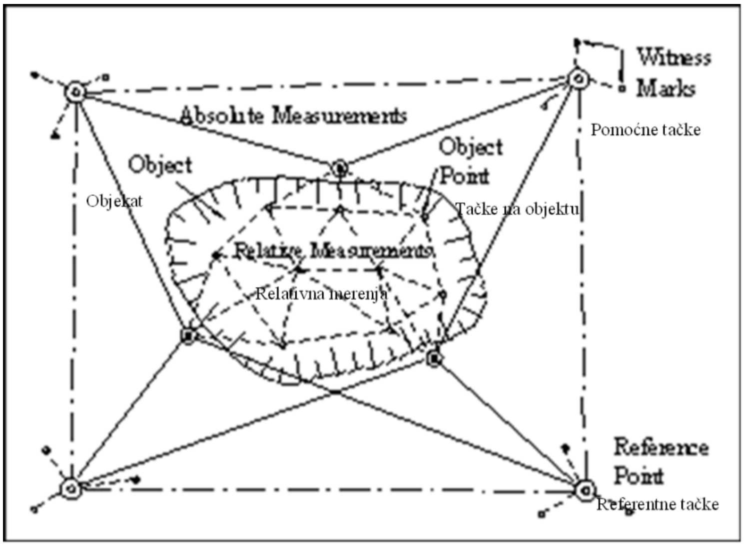


Fig.1. surveying points on object and their relationship with geodetic control network [3]

Implicit assumption for absolute deformation determination is that enough stable reference points exists i.e. points which do not change their position in space and time. This assumption, even when exists does not provide identification of stable points automatically. Identification of stable reference points is burdened by inevitable errors of measurements and which spread through the process of data processing influencing results of adjustment. Under assumption that all measurement results which contain gross errors were eliminated and reference points did not changed position in space and time coordinates of reference points shall be the same in two different series of measurements. But in practice it is hardly to expect that it will be the case. The reasons for differences between coordinates of the same stable points could be caused by different reasons. For example the complex of conditions [4] during the measurement could be different (probability that conditions for measurements in two different series of measurements is equal is to small), the plan of measurements could be changed as a consequence of different measurements burdened by gross errors, different systematic errors under the sensitivity of model for gross errors detection and other possibilities. The basic problem which causes complexity of deformation analysis is the fact that it is not always possible to determine the cause of coordinate differences of same points in two different series of measurements.
The causes of inequality of coordinates of reference points in two different series of measurements could be caused by:

- Different complex of conditions during measurements in two different epochs;
- Real changes of position of reference points;
- The influence of undiscovered gross errors in results of measurements;
- Change of measurement plan (caused by different reasons including eliminated measurements which contain gross errors in two different series) and
- Combination of mentioned reasons.

The similar statistical hypotheses could be formulated in case of equality of reference points' coordinates in two different series of measurements. It means that equality of reference points' coordinates could appear even in case that reference points between two series of measurements have changed their coordinates but the combinations of before mentioned reasons lead to the equality of coordinates. The probability of this case is relatively small but this possibility shall not be excluded in process of deformation analysis. When stable reference points were identified it is possible to determine absolute changes of objects' point's positions.
Analysis of absolute movements of points requires, along with value of movements, and values of root mean square errors of it or standard deviations of movements to testing statistical hypothesis about equality of one dimension in two series of measurements. Statistical hypotheses testing about equality of dimension in two different series of measurements is realized by calculating statistics which follows certain distribution of data [4]. If the number of freedom is finite then the Students' statistics shall be used, otherwise (when standard deviations are known or the number of degrees of freedom is big) the normal distribution is suitable. In some cases when number of degrees of freedom is big and the more stringent criteria are preferable it is possible to use normal distribution instead. Test statistics reads:

$$t = \frac{d}{m_d} = \frac{|X_n - X_0|}{\sqrt{m_{X_n}^2 + m_{X_0}^2}} \sim t_{1-\alpha}(f)$$

where:

- t – statistics;
- d – difference of dimension in two different series of measurements;
- m_d – root mean square error of analysed dimension;
- X_0, X_n – analysed dimension in null and n-th epoch of measurement respectively;
- $m_{X_0}^2, m_{X_n}^2$ – mean square errors of analysed dimension in null and n-th epoch of measurement respectively and
- $t_{1-\alpha}(f)$ – quintile of Students' distribution for level of significance α and degrees of freedom f.

During the geodetic network for deformation analysis design it is needed to strive to minimize root mean square of dimensions (coordinates and/or heights) and to maximize the degrees of freedom. This is especially important for large dams' analysis because of immanent risk and hazard.

3. REGRESSION METHOD

Regression method is suitable for analysis of objects' behaviour in time because its utilization could explain certain influences i.e. identification of individual influences on certain variable is possible. In case of large dams it is especially interesting question about trends in changes of coordinates and/or heights which represents its movements and if it is possible to explain its causality related to other independent factors.

The large number of independent factors exists which represents the behaviour of large dams and they often are not completely known. Under assumption that those influences have not constant intensity in space and time and that the certain influences could be unknown, immediately follows that movements could not be completely covered by utilized analysis. In case of large dams the independent factors are: the period of dam exploitation, temperature of water and air, the height of water upstream and downstream of dam and other physical influences (uplift pressure, leaking etc.). Response (dependent) variable is a change of points' position (coordinate and/or height) in space and time. The regression model points out the connection between certain independent variables and changes of points' position which represents the behaviour of large dam in space and time.
Mathematical model of linear regression is given as follows:

$$Y_i = \theta_0 + \sum_{j=1}^{n} \theta_j x_j \tag{1}$$

where:

- Y_i – absolute movements of points which represent behaviour of large dam in epoch i related to null epoch;
- θ_j – parameter j ;
- n – number of independent variables and
- x_j – j-th independent variable i.e. the value of independent variable in epoch i.

As the number of measurements is greater than number of independent variables the solution of equation system (1) is obtained by utilizing the method of least squares. In case of $n = 1$ the one dimensional linear regression is obtained.
Nonlinear regression also could be used for analysis of large dams' absolute movements because it is expected that movements in the beginning of their exploitation are greater than in in later phase when the stabilization of soil and of the movements is expected and consequently the movements shall be smaller. These assumptions do not have to be exact but it could be the base for statistical hypotheses formulation.
Model of nonlinear regression could be defined in different ways but in this research only polynomial regression was utilized whose form is given by following formula:

$$Y_i = a_0 + \sum_{j=1}^{n} a_j t^j \tag{2}$$

where:

- t – interval of time (in years) from the null epoch of measurements;
- a_j $(j = 0,1,\dots,n)$ – unknown coefficients and
- n – number of polynomials' terms.

4. CASE STUDY

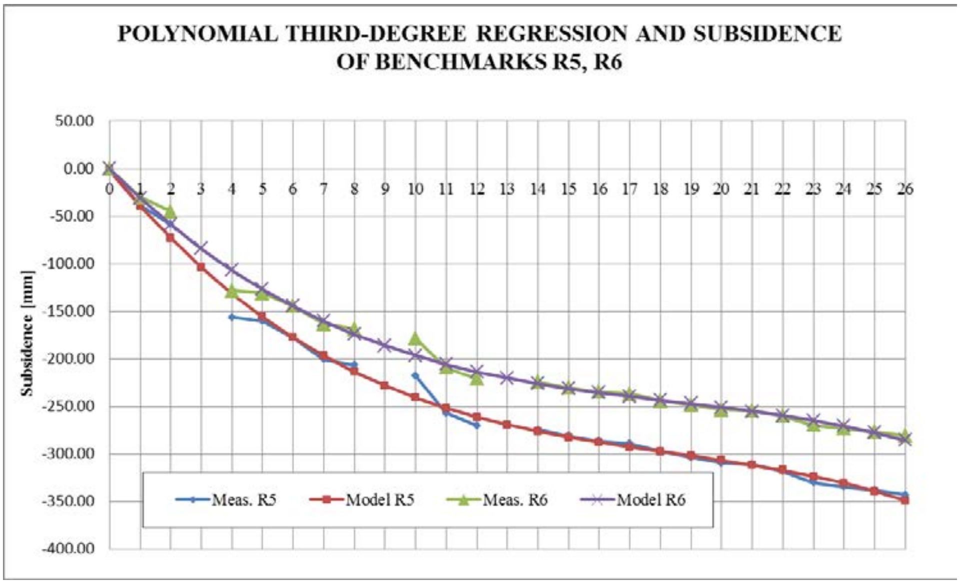
For case study are chosen two benchmarks on the seawall of "Zavoj" earth filled dam.

This case is specific because benchmarks belongs to the part of the dam which is not deeply founded (it is practically supported only by crest of the dam) and does not jeopardize dam stability. On the other side the movements in vertical direction are relatively high which provides obviousness of analysis. In case when the movements are small the additional analysis are needed for determination of absolute movements. This problem appears because of measurements errors as well as the errors of coefficients which in regression model could be greater than the absolute movements.
The benchmarks have been monitored since year 1989 and for this analysis the measurements during 26 years are used. In this period only 3 measurements are missing. Figure 1 shows the satelite image of "Zavoj" dam with position of benchmarks.

Figure 1. Large dam "Zavoj" with position of benchmarks

Response variable is the change of benchmarks height related to null epoch of measurements. As the root mean square errors in every epoch of measurements is significantly smaller than benchmarks' height changes and they are similar in all epoch of measurements it is assumed that the height changes are real and that accuracy of benchmarks height are equal in all series of measurements.
On diagram 1 the changes of benchmarks height in time obtained by measurements as well as the model obtained by third-degree polynomial are shown. Analysis of data about subsidence of benchmarks in time is utilized by polynomial regression of first, second and third-degree. The least deviations are obtained by third-degree polynomial regression and it is utilized for coefficient $a_j\,(j = 0, 1, 2, 3)$ determination.
Number of degrees of freedom in this analysis is $f = 20$ and the root mean square error is $m_0 = 9.17$ for benchmark R5 and $m_0 = 7.72$ for benchmark R6. Statistical hypotheses testing about equality of root mean square errors of models for those two benchmarks results by acceptance of null hypotheses i.e. reasons for acceptance of hypothesis of different root means square errors of analysed benchmarks , on the base of results of geodetic measurements, do not exists.

Diagram 1. Benchmarks subsidence obtained by measurements and by third-degree polynomial regression



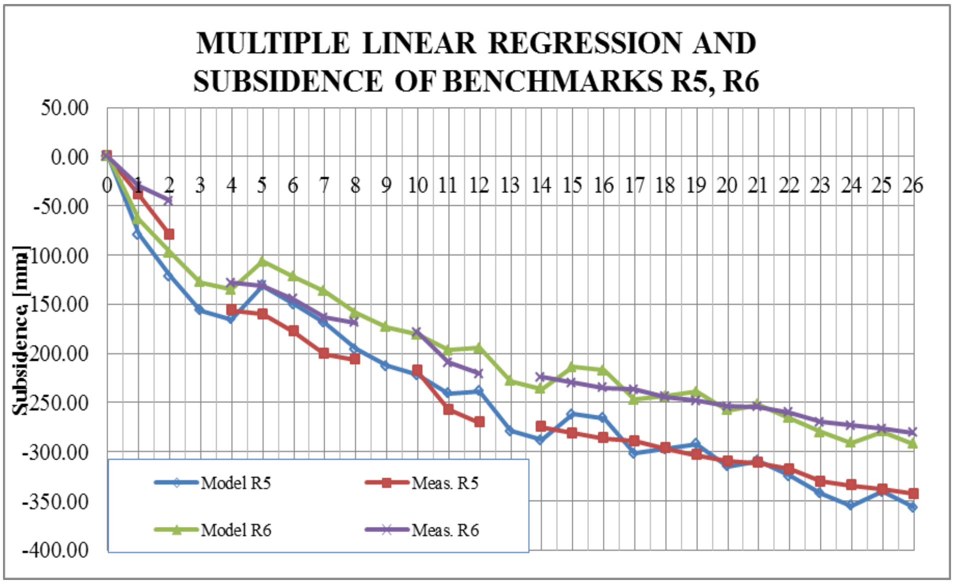
For multiple linear regression models the following independent variables were used:

- Time interval from the null epoch of geodetic measurement given in years;
- Minimal air temperature during the measurements;
- Maximal air temperature during the measurements;
- Minimal level of water in accumulation during the measurement and
- Maximal level of water in accumulation during the measurement.

Because of bigger number of independent variables and the same number of response variables the number of degrees of freedom is $f = 18$ and the root mean square errors in model are $m_0 = 25.64$ for benchmark R5 and $m_0 = 22.96$ for benchmark R6. Statistical hypotheses testing about equality of root mean squares results by acceptance of null hypothesis i.e. the reasons for acceptance hypothesis about different values of root mean squares errors with time, based on geodetic measurements, do not exist.
Analysing mean root square errors in model of third degree regression and multiple linear regression according to root mean square errors of models, because of their significant differences, it is obvious that polynomial model of regression gives better approximation for benchmarks behaviour in time than multiple linear regression. The reasons for those deviations could be explained by the different influences on benchmarks' movement which were not included in model of multiple linear regressions. On the other side the polynomial regression does not include various different influences on the benchmarks' subsidence (except time interval) which means that it does explain the movements only by time interval which is not enough for complex analysis of large dams behaviour and reliable estimation of their state. The improvement of analysis by

multiple linear regression models could be done by including additional parameters (influences) which affect the behaviour of dam in area covered by benchmarks during geodetic measurements. Diagram 2 shows the changes of benchmarks' changes obtained by measurements and model of multiple linear regressions.

Diagram 2. Benchmarks subsidence obtained by measurements and by multiple linear regressions



Positive feature of regression method is that it could be used for estimate the large dam behaviour in the epoch in which the measurement was omitted. Omitting geodetic measurements in case of large dams is not recommended at all because of the immanent risk, hazard and unpredictable intensity and appearance of different influences (as earthquakes, floods etc.). But in case of known parameters (or a few of them) which are included in regression model it is possible to estimate values of response variable in the epochs in which the geodetic measurements were not provided.
Also it is possible to use regression method for prediction of large dam behaviour and to compare it with the results obtained by measurements. This method also shall be utilized in order to analysing the expected and real behaviour of large dam.

5. CONCLUSION

In this paper is shown the utilization of regression method for analysis of absolute vertical movements of benchmarks which represents the behaviour of large dam "Zavoj" on its crest. The example was chosen because of high accuracy of measurements and relatively high value of movements which represent only local behaviour of dam and do not jeopardize the global stability of dam because of shallow foundation. Results of analysis are that third degree polynomial regression gives a better approximation of benchmarks behaviours than multiple linear regressions. This might be a consequence of insufficient independent variables (influences on benchmarks behaviour) which explain the vertical movements of benchmarks during the geodetic measurements. The model might be improved by including additional independent variables (influences on benchmarks behaviour) during the geodetic measurements.

Importance of regression methods for absolute movements of benchmark analysis is that by its utilization is possible to discover the model of benchmarks (which represent the behaviour of dam or its part) movements or could point out deficiencies of model and indicate the solutions through research of reasons of disagreement. One way for reduce differences of benchmarks movements between model and measurements is to include additional independent variables (influences) in model during the geodetic measurements.

The regression method also could be used for prediction of large dam behaviour and for timely preparing and taking actions in order to prevent unwanted behaviour of the large dam. Also the difference between expected and real behaviour of large dam could point to that certain risks exists.

Regression method could be treated as a very useful mathematical model for analysing behaviour of large dams but which shall utilized very carefully. Careful treatment of regression method is caused by its own deficiencies and the complexity of large dam and accumulations.

REFERENCES

[1] Mihailović, K., Aleksić, R.I.: Deformaciona analiza geodetskih mreža, Naučna knjiga, Beograd, 1994

[2] Perović, G.: Metod najmanjih kvadrata, Naučna knjiga, Beograd, 2005

[3] Klein, K.H., Heunecke, O.: Aims and Activites in German Standardization Respective Engineering Surveys, Quo Vadis – International Conference, FIG Working Week 2000, Proceedings, 21-26 May, Prague

[4] Perović, G.: Teorija grešaka merenja, Naučna knjiga, Beograd, 1989

ANALIZA APSOLUTNIH POMERANJA VELIKIH BRANA PRIMENOM REGRESIONE METODE

Rezime: *Određivanje apsolutnih pomeranja velikih brana je od kritičnog značaja za utvrđivanje njihovog stanja i ponašanja. Pod apsolutnim pomeranjima velikih brana podrazumeva se promena njihovog položaja u prostoru i vremenu kao i promena geometrijskih odnosa njenih delova. Apsolutna pomeranja velikih brana određuju se geodetskim metodama a zaključci o pomeranju donose se na osnovu promene položaja* *repera i tačaka kojima je brana aproksimirana, odnosno zaključci o položaju i ponašanju velikih brana u prostoru i vremenu donose se na osnovu položaja diskretnog skupa tačaka u određenom vremenskom periodu. Na osnovu dužeg perioda geodetskog osmatranja velike brane moguće je utvrditi određene obrasce u njenom ponašanju u prostoru i vremenu. Ovaj rad ima za cilj da istraži mogućnosti za analizu ponašanja velikih brana primenom regresione analitičke metode.*

Ključne reči: *Statistička analiza, deformaciona analiza, geodetska merenja*