GEODYNAMIC MONITORING OF MOSCOW KREMLIN

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ABSTRACT:

The Moscow Kremlin plays a very important part among the UNESCO monuments of architecture because it is a symbol of the statehood of Russia. It can explain its historical and cultural importance. The article discusses different aspects of networks for geodynamic processes monitoring through examining reference marks stability in the historic complex of the Moscow Kremlin, investigation of buildings, making 2D maps and 3D models. While collecting data on geodynamic deformation, different technologies are used such as classical geodetic networks, automatic deformation monitoring systems, remote sensing and photogrammetry, laser scanning. Mathematical approaches to preparing different measurement information, stability analysis of the Kremlin monuments and general multilevel approaches to the concepts elaborated are considered.

1. INTRODUCTION

The Moscow Kremlin is a symbol of the Russian statehood, one of the largest architectural ensembles, included on the UNESCO's world heritage list, a treasury of Russian national historical relics. Preservation of sites like that for the present and coming generations is the most important task for our society.

In recent years, the issue of the Moscow City territory geodynamic stability and the problems of the megalopolis in preserving historical objects as parts of our cultural heritage have been widely discussed in popular and scientific publications.

The first work on monitoring deformations of the Moscow Kremlin monuments started in the middle of the 1930s, its aim was to study the deformations of the monuments foundations, collect and generalize data for predicting the deformation processes. On the basis of the measurement information gathered some steps in stability strengthening of the Kremlin monuments were planned and carried out for their preservation. The main technology used was leveling of the reference marks placed in the interior and external walls and floor of the buildings. A great deal of information has been kept till our days, including that of leveling deep benchmarks. Unfortunately, over the last more than 70 years, some of these marks were lost. That is why the problem of presenting in detail how the deformation processes have been developing for each of the Kremlin monuments is difficult though very important.

2. HISTORY OF THE SITE

The Moscow Kremlin was founded in 1156 by Yuri the Long Arm, Grand Duke of Suzdal. A fortress with an eight-meter high rampart and a thick for those times wooden wall reaching 3 m in height and 1200 m in length was erected on Borovitsky Hill. The Kremlin grew larger and more powerful together with the town. In 1339-40 under Ivan Kalita (Money-bag), strong defensive fortifications were built, then the residence of the Grand Duke and white limestone churches.

In 1367-68, Grand Duke Dmitry Ivanovich, being afraid of a new Mongol invasion, walled the fortress and built a few towers, situated approximately 60 m away from the old oaken fortifications. The area of the Kremlin reached its present dimensions.

In the second part of the 15th century, Grand Duke Ivan III began great construction work in the capital. The Kremlin was reconstructed in the first place. Skilled West European architects like Antonio Gilardi, Marco Ruffo, Pietro-Antonio Solari, Alvise da Carcano designed reconstruction plans of the Duke's and the Metropolitan's residences. The Kremlin saw-toothed walls as they appear now (more than 2 km long and 5-19 m high) were built in 1485-95. At the same time, 18 small and big towers, the Assumption Cathedral (1475-79), the Annunciation Cathedral (1484-89), the Tsar's Stone Palace with the Palace of the Facets (1487-91) were built, and the foundations of the Archangel's Cathedral, the burial vault of Russian tsars and grand princes, were laid (1505).

The bases of the Kremlin monuments are oak piles (1.2-1.8 m long) driven into the soil. The monuments which stood many centuries would have stood further but in the middle and at the end of the 20th century the hydrological regime of the Moscow Kremlin territory changed. That was the reason for hastening the pile decay, it becoming non-uniform, which resulted in intensification of the deformation processes of the buildings and constructions.

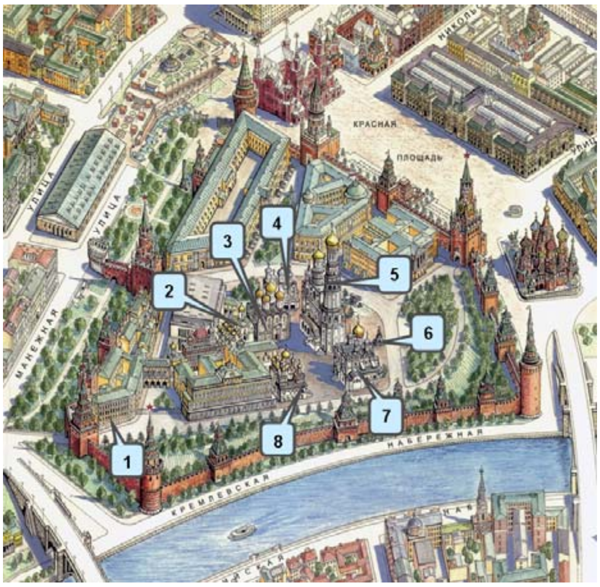

Figure 1. The Moscow Kremlin State Historical and Cultural Museum-Preserve (1 - the Kremlin Armoury, 2 - the Church of Laying Our Lady's Holy Robe, 3 - the Assumption Cathedral, 4 - the Patriarch's Palace and the Twelve Apostles' Church, 5 - Ivan the Great Bell Tower Complex, 6 - the Tsar Bell, 7 - the Archangel's Cathedral, 8 - the Annunciation Cathedral)

3. BASIC WORK ON ARRANGING GEODYNAMIC MONITORING

3.1. Monitoring policy design

Two conceptual premises made the methodological basis for geodynamic monitoring of deformation processes.

1. A three-level approach to the task solution, which means that the task is analyzed:
   - at the level of the whole city;
   - at the level of the Kremlin territory;
   - at the level of every single object.

In order to understand clearly local processes one has to analyze the information of different levels. From comparing and discovering common changes one can draw more precise conclusions about local deformations.

2. A comprehensive approach to the task solution, which means that a fundamental analysis of processes can be ensured with the help of generalization of various data obtained by different technical means. These are data from aerial photographing, GPS/GLONASS surveys, traditional levels and tachymeter's, laser scanning systems, digital cameras, as well as geological data and construction investigation data.

Before starting the monitoring of the Kremlin monuments, our specialists began to work in four directions:

- they collected and generalized surveys carried out earlier, including registration and certification of the marks and benchmarks;
- conducted a mathematical analysis of surveys performed earlier /1/;
- estimated the Kremlin territory as a part of the Moscow City territory, with all its geodynamic, geological, anthropogenic and other factors influencing the stability of man-made constructions /2/;
- developed and started to put into life the monitoring technology employing modern geodetic instrumental and software achievements.

Such a comprehensive approach made it possible to take into consideration all the surveys made earlier and regard the Kremlin as a constituent part of a large megalopolis with all its problems. At the same time there were not forgotten new technologies, improving instruments fleet and mathematical tools allowing one to generalize better different, superficially non-connected data in order to build a model of the deformation processes development.

3.2. Data gathering and registration of leveling network marks

Besides the time factor causing natural aging, the Kremlin monuments are also influenced by external factors such as surface and underground construction work in immediate proximity. A correlation analysis of the data collected, which establishes the dependence of spatial location changes of the Kremlin objects on external factors, will make it possible to not only fix the changes but also to predict future changes if something is built near the monuments.

In view of this, the first step of monitoring was a fundamental analysis of the materials on the technology of the surveys made earlier, on measuring height and planimetric control marks, on construction work carried out nearby. At the beginning, an analysis and registration of all height marks placed in the interior and external walls and floors of the buildings were a very important step. More than 20% of all marks investigated were deemed unfit for further use and had to be reestablished. All marks (including the new ones) were certified, their passports having the description of their location, condition, catalogues with the elevation history data beginning from the time of their establishing, compulsory photos. While reestablishing marks, their material had to be selected carefully not to make it active chemically in the buildings' walls and be durable at the same time.

3.3. Generalization and analysis of previous surveys materials

In analyzing the observation results and building up a dynamic model of the deformation processes development the following strategy of data processing was suggested:

- an analysis of observation results was made for each mark separately in order to find gross errors and exclude bad results caused generally by man-made changes in the mark position;
- with a lack of bad results or after their exclusion, the normalcy of observation data distribution was estimated, which confirmed the presence or absence of systematic shifts;
- with presence of systematic shifts, shift timing was estimated;
- after height shift timing, correlation dependencies were constructed for each mark, which revealed the deformation processes development and their causing factors, as well as their mapping was made.

The assessment criterion of the maximum term in the series of observations was chosen out of a great number of criteria (Charlier's, Chauvin's criteria, assessment criterion of the maximum term in observation series, Dickson's criterion and others) in order to check the results and eliminate gross errors. The analysis carried out allowed the marks whose position had been changed due to man-made factors not to be processed.

With a lack of errors the results were checked for normal distribution. The X-criterion, Kolmogorov's criterion as well as asymmetry and kurtosis were applied to do it. Eventually, the asymmetry and kurtosis coefficients were used, which permitted the observation series available to be assessed really accurately. An abnormal distribution of the results indicated the presence of a variable bias causing a data aggregation centre shift. To determine the shift Abbe's criterion was applied as it allows one to detect the presence of a variable bias in the observation results, caused by one of the factors influencing them. In our case, such a factor was time factor.

Then the relationships between the measurement results and time were found. The relationship can be expressed by different mathematical functions both straight-line and curvilinear ones. It was practically impossible to select a unified formula reflecting deformation processes even for a single object because of the heterogeneity of vertical shifts of marks.

General subsidence was revealed actually in each Kremlin monument, a lot of them having local abnormal areas correlated with the time of surface and underground construction work nearby. In some objects, however, local changes dominated at a certain time period as compared with common height changes of the marks of the whole complex. The appearance of local deformation areas within one object territory is the main reason for disturbance of the object's integrity and therefore for its destruction.

Figure 3 represents summarized examples of the observations of one of the cathedrals under consideration, the Archangel's Cathedral (Figure 2), throughout the 1988-98 time periods. It shows a general insignificant tendency of the cathedral to subsidence as a whole and a significant subsidence of its eastern part throughout the period at the same time.

Figure 2. The Archangel's Cathedral

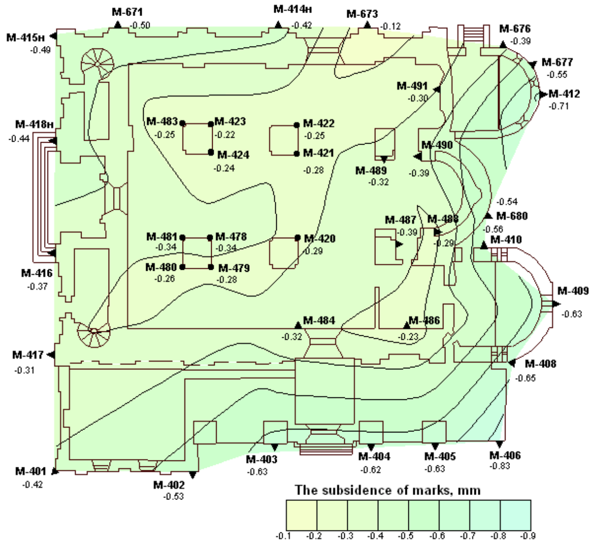

Figure 3. The subsidence of marks in the Archangel's Cathedral throughout the 1988-98 period

3.4. Analysis of the stability of the Kremlin territory as a local area of the city

The next step was an estimation of the stability of the Kremlin territory as a local area of the megalopolis. The city, including its central part, is growing very quickly. The underground component of both the city as a whole and its central part is also developing. Surface and underground construction work is one of the most important factors affecting the stability of the city's territory. In view of that, a battery of investigations was conducted to determine the possible influence of the city on the territory occupied by the Moscow Kremlin.

In the course of them:

- the state of the deformed buildings was examined (Figure 4). The most critical situation turned out to be in the central part of Moscow City where a majority of cultural and architectural monuments are situated;
- engineering-geological, hydrogeological structures, anthropogenic and karstic conditions of the city were studied (Figure 5);
- from the above data, a geodynamic satellite network was established that consisted of 36 stations located in the main anthropogenic areas (Figure 6);
- 8 sessions of satellite observations were carried out at the stations of the geodynamic network, twice a year from 1996 till 1999. They allowed the stability of the Moscow Region to be estimated both horizontally and vertically;
- from the repeated measurements, a cartogram of the vertical ground movements in the city and in the Kremlin territory was drawn (Figure 7), it confirming a general subsidence of the City center and planimetric movements of the stations situated in the Kremlin towards the Moskva River.

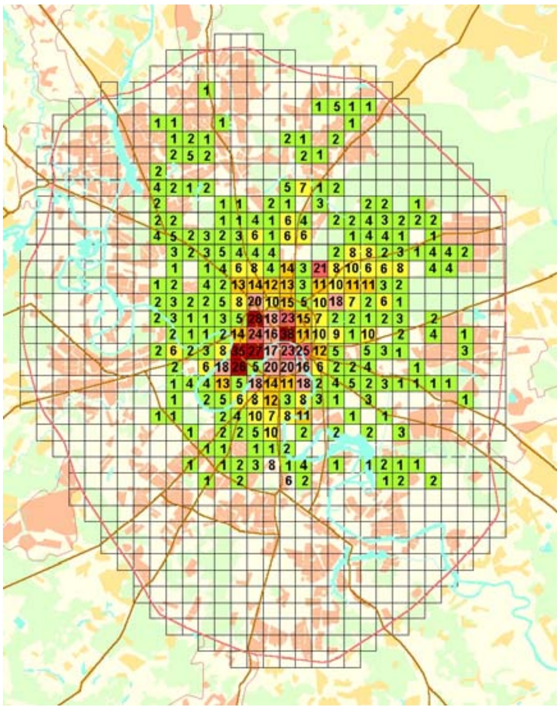

Figure 4. The quantity of deformed buildings in the central part of Moscow City as of early 1996

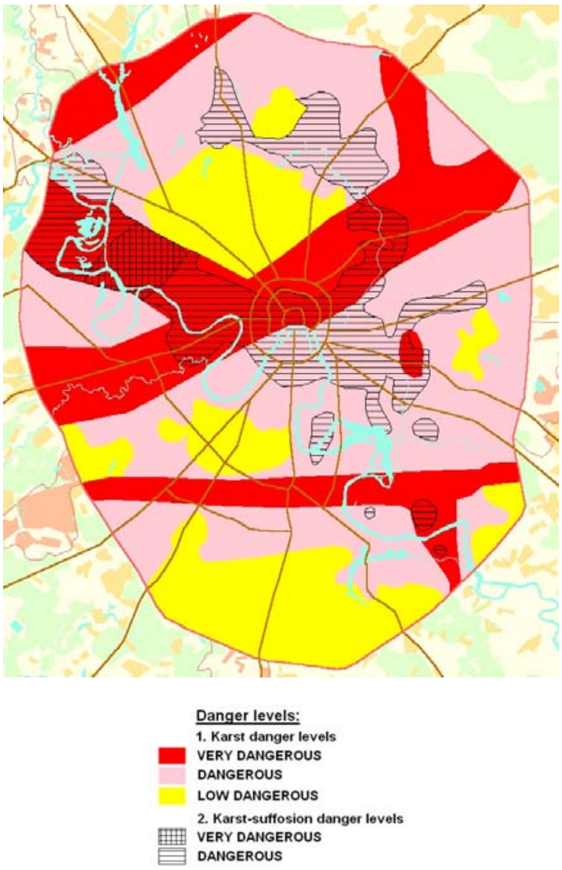

Figure 5. The City hydrology and karst structure

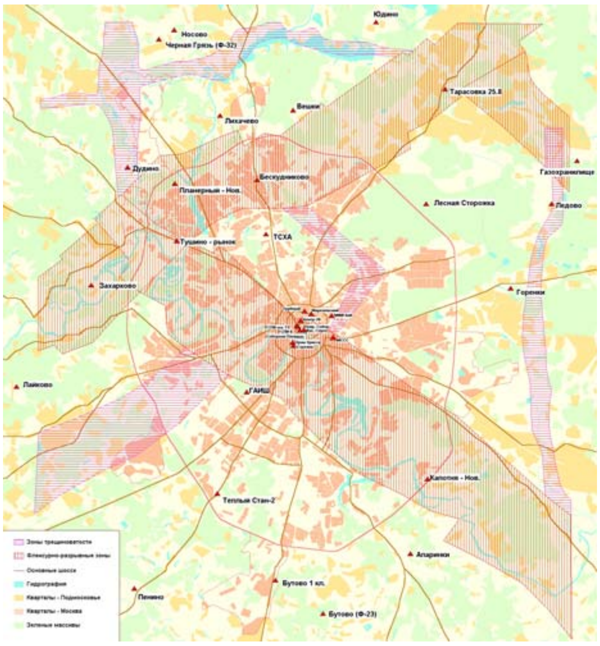

Figure 6. The geodynamic faults and the Geodynamic network stations

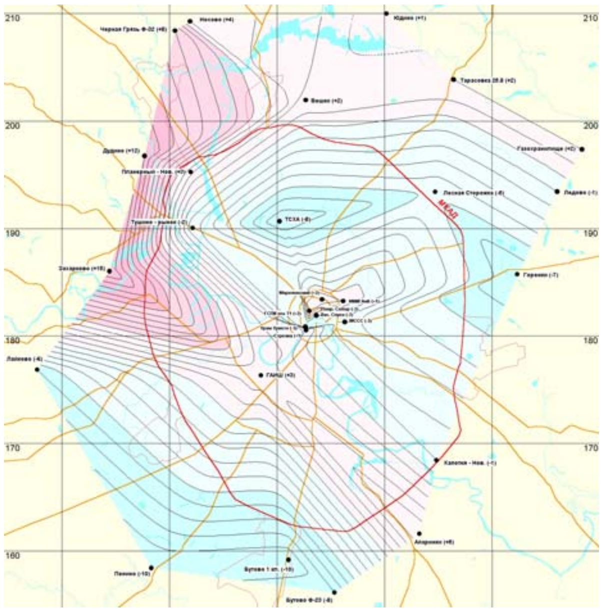

Figure 7. Vertical deformations of the City geodynamic network (the 1996-98 period observations)

The Kremlin occupies the terrace slope of the Moskva River. The geological basis for the Cathedral Square and the main architectural monuments around it is made of the following types of soil:

- fill-up soil from 2 to 6 m thick;
- ancient alluvial sands of intermediate density, from 1.4 to 8 m thick;
- drift clay from 1 to 4 m thick;
- morainal fluvioglacial sands up to 13 m thick.

The morainal water-bearing horizon was exposed at a depth from 8.5 to 9.2 m. A second water-bearing horizon was exposed at a depth of 18.5 m. Besides, geological surveys of different years established that the drift clay top is heterogeneous, and there are separate saucer-shaped depressions where underground water is collected. The presence of underground water in the foundation of the monuments of architecture plays a double role:

- firstly, it leads to a rise in the humidity of their foundation and wall brickwork, which influences negatively the preservation of a stone foundation;
- secondly, it ensures preservation of a wooden foundation if it is embedded deeply.

The work done in the late 1990s permitted one to preliminarily establish the deformation causes, and it became the basis for a reconstruction work package of the foundations of many objects. The main deformation causes revealed through analyzing the data obtained were the following:

- the presence of fill-up soil under the foundations. The Kremlin territory was leveled out with fill-up soil, of 10-15 m thick in some places. Building on the fill-up soil was the reason for great construction deformations during the first years of their service. The foundations subsidence was uneven. Then subsidence rates stabilized;
- the presence of holes left by decayed wooden piles near the foundation beds. All historical monuments around the Cathedral Square are built on wooden short-pile foundations, with the constant water plane lower than the pile feet. That was why the wooden piles started to decay slowly but evenly during their service.
- the change in the hydrological regime over the territory of the Cathedral Square in the last years, which accelerated the pile decay process. Those wooden piles can still be found in the foundations of some buildings (Ivan the Great Bell Tower). The decay process resulted in activation of the deformation processes. Having established that Moscow City as a whole was quite a stable region in terms of geodynamic processes and that the Kremlin should be considered as a local area with the dominating anthropogenic factor characterizing its stability, the researchers developed and began to implement a project of its monitoring, consistent with modern technological procedures, equipment and software.

4. LASER SCANNING AND PHOTOGRAMMETRY

In addition to the above-listed surveys, three-dimensional laser scanning and close range photogrammetric surveying of the Palace of the Facets were carried out. These kinds of work were a further development of the traditional technology for geodynamic monitoring and assured a comprehensive approach to it. Laser scanning point clouds are supposed to be a source of accurate data in repeated scanning to detect deformations for each construction element. The first paper discussing this kind of technology has already been published /3/.

Along with this task, the following top-priority objectives were selected:

- to create by the combined method from laser scanning and photogrammetric data two-dimensional measurement drawings for restoration work;
- to create a three-dimensional model by the combined method.

The application of the combined method was necessitated by the requirements to get high accuracy and detail results. Many authors compare the technological potential of laser scanning with that of close range photogrammetric surveying. Laser scanning equipment and its software have been developed considerably. Combination of scanning and digital metric photographing has become universally recognized. But the potential capabilities of this combination have not been implemented in full so far. Photogrammetric programs make it possible to import laser scanning point clouds by limiting their number. Import of triangulation surfaces formed from points of laser scanning is not provided for in photogrammetric programs. Construction of such surfaces from points of laser scanning by means of photogrammetric software is incorrect because this process does not take into account the scanner positions in cross-scanning the architectural details and stucco of the object. But a capability to create an orthophotoplan by the simplified method does exist in programs meant for laser scanning point processing (Cyclone, LupoScan) but it is impossible to use it in practice to obtain highly accurate results.

In our work, Leica ScanStation 2 was used for getting laser scanning data, and a 28 mm lens Kodak Professional DCS ProSLR/n digital camera was for close range photogrammetric surveying.

The combined method in our case was that the main elements of the object’s construction were represented by three-dimensional space vectors in producing two-dimensional drawings by Cyclone Software. Points of laser scanning for the areas where stucco was (portals, columns) were imported by PHOTOMOD photogrammetric program. In order to construct stucco surfaces correctly, the main break lines of the stucco were plotted with stereoscopic photogrammetric restitution in addition to laser scanning points. The surface constructed from combined data was checked up and corrected in stereo. Orthophotoplans were produced from digital photos on the basis of the accurate surface constructed.

At the next stage, in order to produce drawings along specified cross sections mosaics were prepared by MicroStation Program, they consisting of the orthophotoplans, the main break lines of the stucco (got in stereo) and lines of the main construction elements (got in Cyclone); vectorization of the stucco work was done further, and eventually the finalized drawing was produced (Figure 8).

Figure 8. A plan view of a stucco fragment

A three-dimensional model of the Palace of the Facets was built from three-dimensional laser scanning and close range photogrammetric surveying data for the presentation (Figure 9).

Figure 9. A 3D model of the Palace of the Facets

5. CONCLUSION

The work package carried out and, first of all, the analysis of the earlier surveys made it possible to reveal the main reasons for deformation processes over the Moscow Kremlin territory; thanks to the results obtained:

- mark reconstruction work was performed in the main Kremlin monuments of architecture;
- the leveling marks network placed in the internal and external walls of the monuments was re-established in them as a united proving ground;
- the GeoMos-system (Leica, Switzerland) was introduced to monitor the verticality and stability of the monuments;
- the GOKA-system (Karlsruhe University, Germany) is being introduced for estimating the Kremlin monuments stability;
- laser scanning and metric camera surveying of the Palace of the Facets were executed;
- from the laser scanning and metric camera surveying data, measurement drawings and a three-dimensional model were produced, they together with source laser scanning data are going to become the main components for the deformation analysis of the Kremlin monuments.

As of today, the first materials have already been obtained that make it possible to estimate the stability of the monuments both as separate constructions and as the whole Moscow Kremlin architectural complex. The analysis of the deformation dynamics made has shown a general tendency to stabilization of the deformation marks subsidence for most cathedrals and monuments of the Moscow Kremlin and for their planimetric location.

All these have confirmed the correctness of the chosen strategy for the monitoring arrangements of the Moscow Kremlin monuments of architecture.

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