DECISION-MAKING SUPPORT BASED ON VIRTUAL STATISTICAL MODELLING: CASE STUDY OF LARGE SUBWAY TUNNEL LAUNCHING

Zbyněk Keršner[1], Drahomír Novák[1], Jan L. Vítek[2], and Břetislav Teplý[1]

ABSTRACT

The paper describes decision-making support based on the statistical simulation of the launching of large concrete subway tunnels onto a river bed. Both the selected technology of construction and the virtual statistical treatment of the feasibility of launching are unique. The actual load on the tunnels during launching is extremely sensitive to the scatter of geometrical imperfections. Due to expected variability, balancing forces were considered over a certain range and then applied in reality. There was a danger that imperfections might result in an out-of-control situation, where the necessary balancing forces would be outside of feasible ranges. A statistical feasibility study was, therefore, performed based on a virtual simulation of casting. The measurement of the geometry of segments during casting was performed and the consequent geometry of the next segment was updated. The statistical simulation of this technological process was aimed at the decision-making process before launching and thus at assessing the reliability of the entire project. The successful launching of the subway tubes with segment geometry updating demonstrated good agreement with the preliminary statistical simulation.

KEY WORDS

concrete tunnels, imperfections, statistical simulation, decision-making process, reliability.

INTRODUCTION

Uncertainties of geometry, material, environmental conditions and load are recognized in code development and structural reliability assessment studies. In spite of the many achievements of the theory of structural reliability focusing on failure probability calculation, some structural problems call for relatively simple statistical treatment. The Monte Carlo type of simulation is the most transparent and understandable technique. This paper describes decision-making support based on such a statistical simulation of a very special technological process – the launching of large concrete subway tunnels onto a river bed. Both the selected technology of construction and the virtual statistical treatment of the feasibility of launching are unique. The numerical statistical simulation methods used are also briefly described.

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[1] Professors, Faculty of Civil Engineering, Brno University of Technology, Veveri 331/95, 602 00 Brno, Czech Republic, Phone +420541147360, FAX +420541240994, kersner.z@fce.vutbr.cz, novak.d@fce.vutbr.cz, teply.b@fce.vutbr.cz

[2] Professor, Chief design expert of Metrostav, a.s., Kozeluzska 5, 180 00 Prague 8, Czech Republic, Phone +420266709317, FAX +420266709193, vitek@metrostav.cz

The imperfections of the individual segments were simulated as random variables – the total number of variables used in the study was 211. Virtual simulation of casting was performed. The measurement of the geometry of segments during casting was performed and the consequent geometry of the next segment was updated. The statistical simulation of this technological process was aimed at the decision-making support before launching and thus at assessing the reliability of the entire project. The successful launching of the subway tubes with segment geometry updating demonstrated good agreement with the simulation.

CASE DESCRIPTION

An extension of the subway system in Prague, Czech Republic, crosses the Vltava River. A couple of large concrete tunnels, which are curved in plan as well as in elevation, were cast in a dry dock excavated in the bank of the river, Figure 1 (Vítek, 2001, 2002). After the first tube was cast, it was launched in a trench excavated in the river bed. Each tunnel was cast in 12 m long segments. The total number of 14 segments formed a large tube, 168 m long. The outside width of the cross-section was 6.48 m and the height was 6.48 m, too. The thickness of the walls and the top and bottom slabs was about 0.7 m. During launching, the tube was suspended at one third of its length from its front on the pontoon, and at the back end the tube was supported by hydraulic telescopic sliding shoes, Figure 2. During launching the tube was subjected to two forces-actions acting in opposite direction; i) that of its own weight and ii) that of the buoyancy of the water. Both these actions exhibit statistical scatter due to the differences in dimensions and in the density of the concrete. The actual load is the difference between the two actions, and therefore it is extremely sensitive to the scatter of geometrical imperfections. Due to the expected variability, the balancing forces (tanks of water) were considered in some ranges and then applied in reality, Figure 3. There was a danger that such imperfections might result in an out-of-control situation in which the necessary balancing forces would be outside of the feasible range. A statistical feasibility study was, therefore, needed.

Figure 1: A Subway Tube in Dry Dock (left) and after Launching

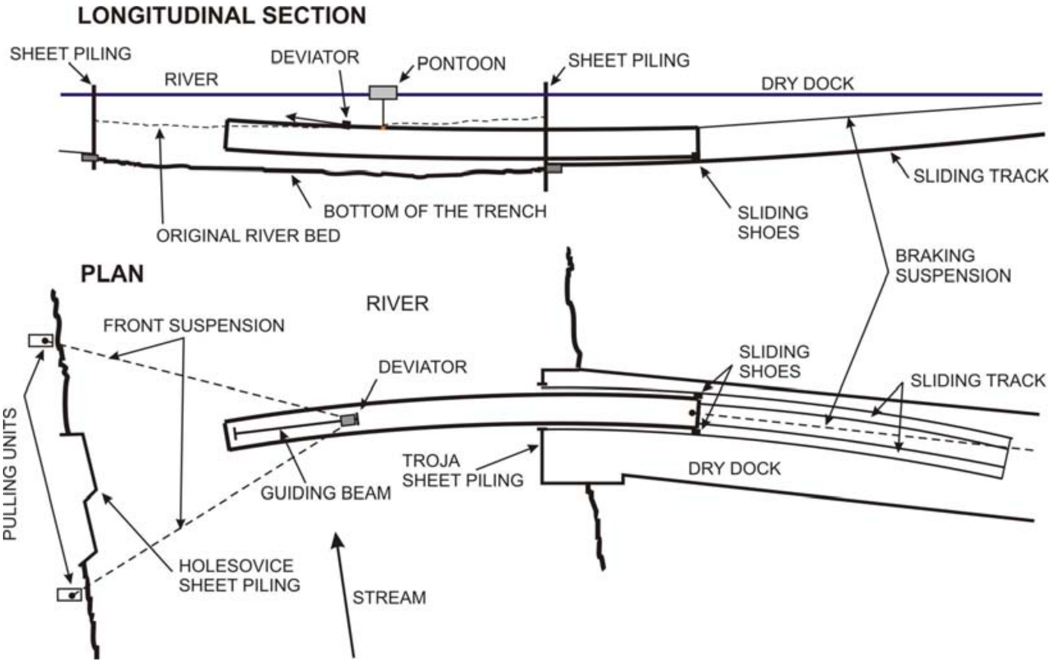

Figure 2: Launching of the Tube – Illustrative Scheme

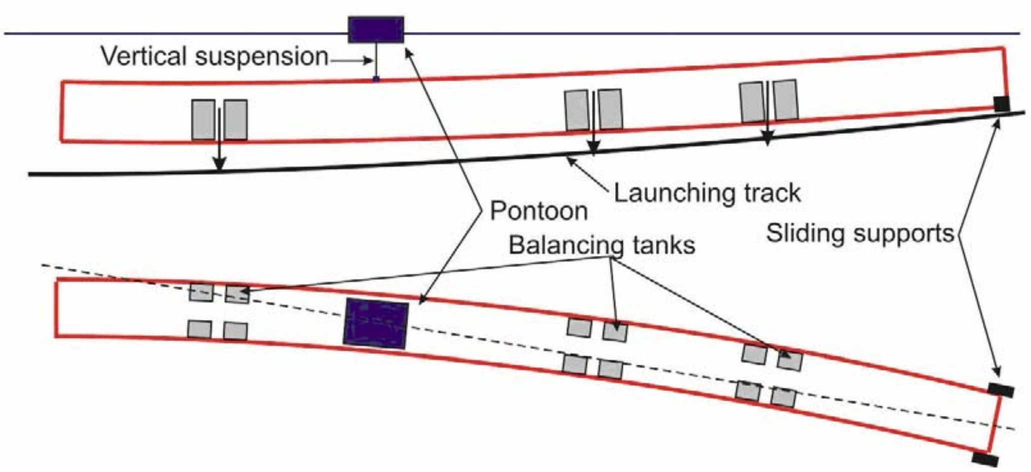

Figure 3: Launching of the Tube – Static Scheme, Forces Acting on the Tube

VIRTUAL STATISTICAL SIMULATION

GENERAL REMARKS

The stratified simulation method of the Monte Carlo type called Latin Hypercube Sampling (McKay et al. 1979, Novák et al. 1998) was applied using the multipurpose probabilistic software by Novák et al. (2003, 2006). This software, presently utilized mainly for the statistical and reliability analysis of nonlinear behavior for concrete structures (Novák et al. 2005), enables efficient and stable statistical analysis in spite of the large number of random variables.

RANDOM VARIABLES

The cross-section geometry of the tube is shown in Figure 4. Quite a large number of basic random variables – 211 – were considered for statistical simulation. This number resulted from the fact that there were 14 segments, geometrical parameters were considered to be constant along one segment, and for simplicity no statistical correlation of the geometrical parameters was considered among segments. The statistical parameters of the random variables are summarized in Table 1. They were extracted from accepted imperfections inherent in concrete casting technology – the maximal deformation of the framework system. Statistics for concrete density were analyzed directly based on samples from different parts of the cross-section. Analysis of the measured data supported the assumption of log-normal two-parametric probability distribution. The mean value was used directly, standard deviation was considered as being higher in order to be conservatively on the safe side. In spite of the fact that the variability of the geometrical parameters was not very high, we can assume that all imperfections during step-by-step casting will eventually be much more highlighted. Therefore, the parameters are considered to be statistically independent.

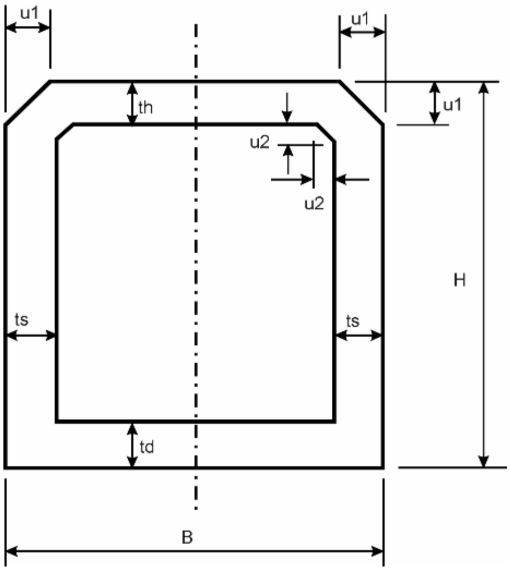

Figure 4: Cross-section of the Tube

PROCEDURE AND VIRTUAL SIMULATION

A simulation of the random process of concrete tube casting (geometry) with the statistical assessment of forces was performed. The updating of weights according to the results of the casting of previous segments was suggested and implemented into the virtual numerical procedure. The simulation (random realizations) consisted of the following steps:

- Random simulation of parameters for the first segment and actual uplift force calculation
- Actual and required uplift forces are compared – based on the comparison, the updating of parameters of the next segment is suggested in order to reach the required uplift force
- The simulation of the second segment is performed, again randomly, and also the third etc. untill all 14 segments have been cast
- The segments are continuously updated – segment 2 based on segment 1, segment 3 based on segment 1 and 2, etc. An improvement in the forces in each random realization can be expected – finally, the resultant uplift force will be close to the target one. Geometry and weight updating will also decrease the statistical variability of the resultant uplift force.

The good convergence of the procedure is shown in Figure 5, using several Monte Carlo type simulations only. The basic starting nominal thickness of the first segment was 0.7 m, the target uplift force being app. 9 kN/m (per meter of tunnel tube). The good convergence of both means and percentiles was observed, which obviously contributes to reliability.

Based on this statistical simulation, histograms of balancing forces were obtained; in Figure 5 the operating feasible limits of one selected force (tanks of water) are shown. Note that this was a key outcome of the virtual statistical simulation – to verify confidence intervals for balancing forces in order to maintain the reliability of the technological process. Let us also note that balancing forces outside of the limits (0 and 64 tons) would be impossible to easily ensure. Probabilities that the force needed will be smaller than 0 or greater than 64 t were quite acceptable and were the part of risk considerations.

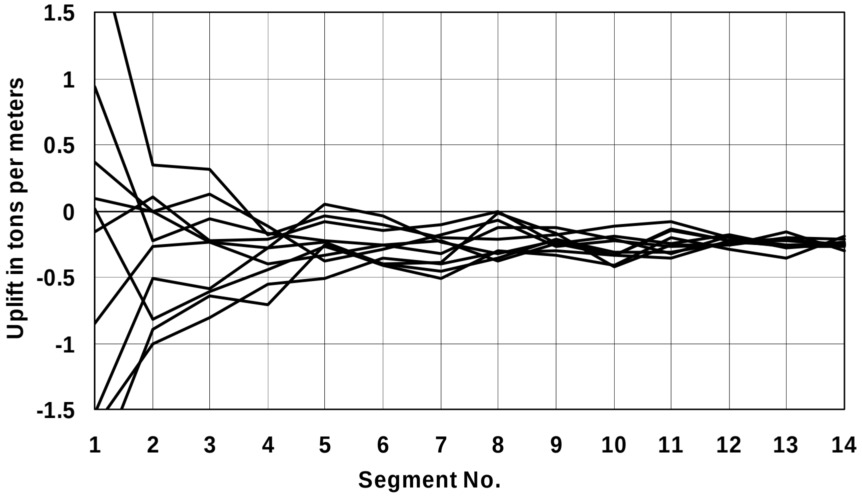

Figure 5: Random Realizations of Uplift Force Using Segment Updating

Table 1: Statistical Parameters of Basic Random Variables

No.	Symbol	Random Variable	Unit	Mean Value	Standard Deviation	PDF
1	Φ	Model Uncertainty Factor	–	1.0	0.05	N
2–15	H_I	Inside Depth of Section	m	5.07	0.02	LN
16–29	B_I	Inside Width of Section	m	5.02	0.02	LN
30–43	u_{1BL}	Horizontal Outside Bevel Edge (Left)	m	0.7	0.01	N
44–57	u_{1BR}	Horizontal Outside Bevel Edge (Right)	m	0.7	0.01	N
58–71	u_{1HL}	Vertical Outside Bevel Edge (Left)	m	0.7	0.01	N
72–85	u_{1HR}	Vertical Outside Bevel Edge (Right)	m	0.7	0.01	N
86–99	u_{2BL}	Horizontal Inside Bevel Edge (Left)	m	0.3	0.01	N
100–113	u_{2BR}	Horizontal Inside Bevel Edge (Right)	m	0.3	0.01	N
114–127	u_{2HL}	Vertical Inside Bevel Edge (Left)	m	0.3	0.01	N
128–141	u_{2HR}	Vertical Inside Bevel Edge (Right)	m	0.3	0.01	N
142–155	tsl	Thickness of Wall (Left)	–	1	0.017	N
156–169	tsp	Thickness of Wall (Right)	–	1	0.017	N
170–183	th	Thickness of Slab (Top)	–	1	0.021	N
184–197	td	Thickness of Slab (Bottom)	m	0.72	0.025	N
198–211	γ_b	Density of Concrete	kN/m^3	23.3	0.2	LN

Legend: Probability Distribution Function (PDF): N … normal, LN … log-normal.

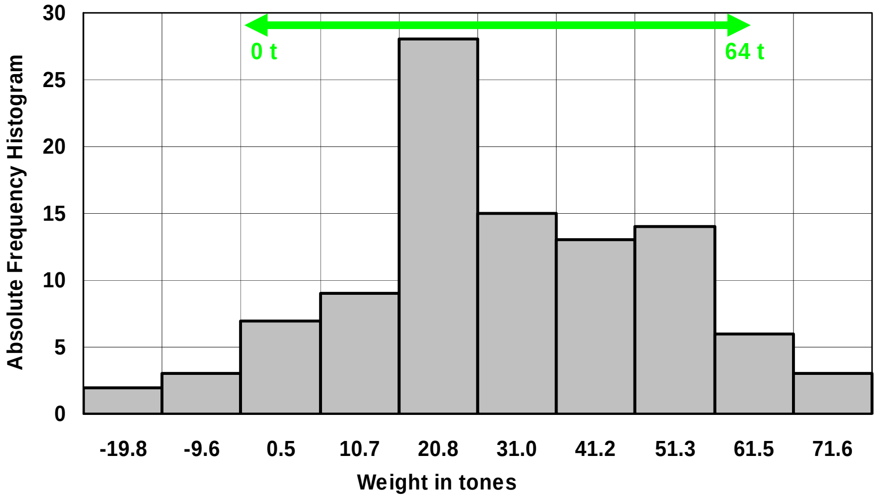

Figure 6: Histogram of Balancing Force with Real Limits

DISCUSSION: SIMULATION VS. REALITY

Virtual simulation above was purely theoretical, and so the question naturally arises: what will the result be during the real casting of tubes? The suggested methodology of segment updating was followed in reality as much as possible. Measured concrete densities also varied from segment to segment too, see Figure 7. Real values for uplift forces based on geometry and density measurements are shown in Figure 8. The behavior seen confirms the efficiency of the updating procedure tested virtually before casting.

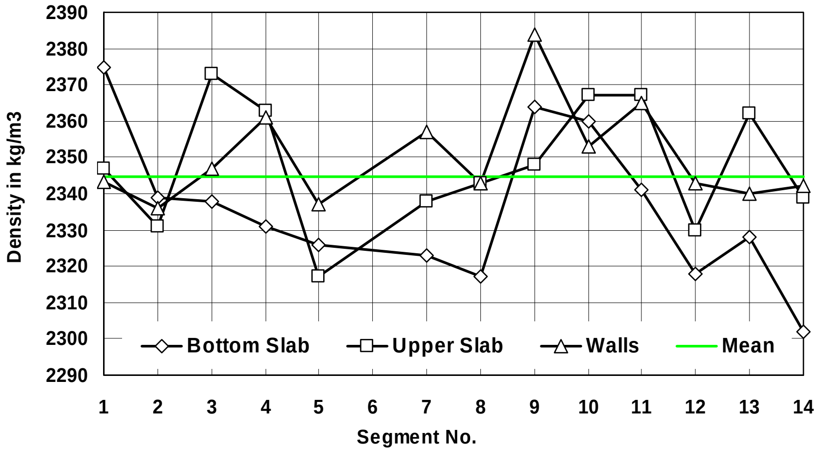

Figure 7: Density of Segments

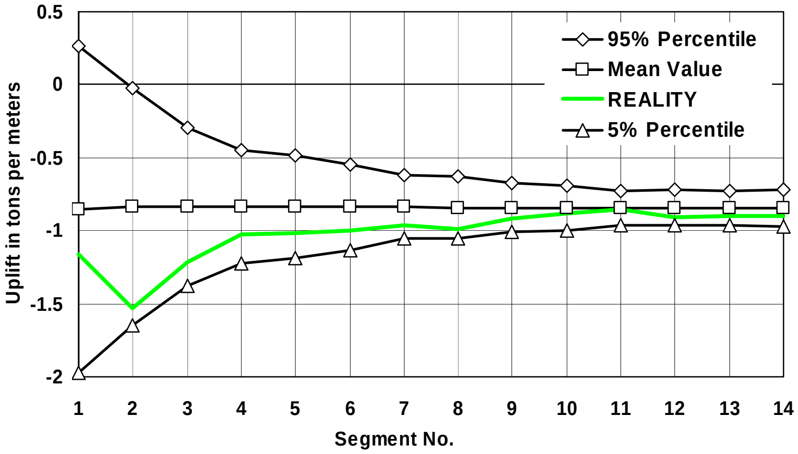

Figure 8: Uplift Force – Reality vs. Virtual Simulation

CONCLUSIONS

Statistical analysis was used for the preliminary simulation of random uplift forces acting on concrete tubes during launching. The results confirmed the importance of this preliminary verification step. The technological feasibility of the project was verified. Analysis enabled the assessment of variability for balancing forces in order to achieve the prescribed reliability. Simulated histograms of the balancing forces served as decision-making support regarding the feasibility of non-traditional technology.

The suggested procedure of segment updating was firstly verified by a virtual statistical simulation of the Monte Carlo type. The statistical simulation of this technological process was aimed at the decision-making process before launching and thus at assessing the reliability of the entire project. The successful launching of the subway tubes with segment geometry updating resulted in a good agreement with the preliminary statistical simulation.

At the end it is necessary to note that realistic execution resulted in a very accurate balance between the weight of the tunnels and the buoyancy of the water. The weight of the tunnels was about 6700 t, while the buoyancy of the water 6630 t in the case of the first tunnel and 6640 t at the second tunnel. The reactions carried by the pontoon and by the sliding back shoes were altogether 70 and 60 t, respectively. It means that the reactions of the tunnel were reduced to approximately 1% of the real weight. It was a real success, which was supported by the presented analysis and which would not be possible without careful work on the site, precise measurements and the preliminary virtual simulation using the advanced probabilistic approaches.

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