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Dimcho Evstatiev
Geological Institute of the Bulgarian Academy of Sciences, Sofia, Bulgaria

Yordan Evlogiev
Geological Institute of the Bulgarian Academy of Sciences, Sofia, Bulgaria

Mariana Nedelcheva
Geological Institute of the Bulgarian Academy of Sciences, Sofia, Bulgaria

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FOUNDATION WORK OF HIGH TV TOWER IN COLLAPSIBLE LOESS

Dimcho Evstatiev, Yordan Evlogiev, Mariana Nedelcheva
Geological Institute of the Bulgarian Academy of Sciences
1113 Sofia, Acad. G. Bonchev St., Block 24
dimcho_e@geology.bas.bg; evlogiev@mail.bg; mariana_nd@mail.bg

ABSTRACT

The TV tower in Rousse city is the highest in the Balkan area with its 198 m height. It is built up on loess with thickness of the collapsible zone about 15-16 m. The collapsibility has been overcome by excavation deepening up to 14.50 m, dynamic compaction of the excavation bottom with 7.0 tons tamper and building of a 4.5 m soil-cement cushion. A comparison between the calculated and measured settlement and of the soil base moisture content before and after TV tower construction is presented. Geodetic measurements have been made during and after the tower construction. Several calculation methods were used for settlement prediction: Soviet building code for large-size foundations and restricted active zone, the corrected Burmister formula, the method of Kushner and the finite element method. For the load of 146 kPa of the tower, the total settlement in 2005 reached 5.75 cm. The calculated settlement using the finite element method is 6.85 cm, and according to Burmister – 6.75 cm. After 10 years of operation of the tower, increased water content was established in the backfill around it and some increasing of the facility settlement. The next measures were applied: drying of the backfill with quicklime columns, injection of cement-sand mortar in the cavities under the concrete sidewalk, repair of the water & sewerage installations, performance of new vertical planning.

INTRODUCTION

During the eighties of the last century 5 high TV towers were built in Northeast Bulgaria. All of them were situated in a region with hazardous geological processes, the most important of them being the high seismicity – VIII according to the MSK scale and loess collapsibility. The subject of the present paper is the most representative of these towers – the TV tower in Rousse.

The TV tower construction took place in the period 1975-1983. Its foundation work represents an interest because of the combination of methods applied for preventing the hazard of collapse of the loess base and the results obtained during the 20 years of geotechnical monitoring.

The principal scheme of the TV tower foundation was marked in the general report of Prof. Mitchel at the X-th Int. Conf. Soil Mech. and Found. Eng., Stockholm 1981. The system for geodetic control and the first settlement data are considered elsewhere (Milev et al., 1992; Milev, Karachorov, 1992, Evstatiev et al., 1985).

The total height of the tower is 198 m and it consists of a reinforced concrete tube with height of 120 m and external diameter of 21 m, a metal mast with height of 62 m and 16 m high additional antenna. The top part of the reinforced tube is widened and there are control premises and coffee-confectionery in it. Two one-storey administrative buildings are contiguous to the main tower body in violation to its project, which did not envisage the construction of other buildings in the tower immediate proximity due to the hazard of moistening of the loess base in case of eventual accidents.

ENGINEERING – GEOLOGICAL CONDITIONS

The geological structure of the soil base is presented in Fig. 2. The thickness of the loess complex is about 30 m. After an artificial embankment (E) follow five loess horizons (L_1 to L_5) divided by four very well expressed fossil soils (FS_1 to FS_4). Thin loess horizons and fossil soils (FS_5, FS_6, FS_7 and maybe FS_8) with a total thickness of about 7 m follow in depth.

Fig. 1. General view of the TV tower in Rousse city

Red dense clays and gravels of the covering gravelly-clayey layer of Lower Pleistocene age (0.94-9.82 Ma) are embedded under the loess complex and beneath them are situated the basal gravels and sands of the Upper Romanian-Lower Pleistocene (2.59-0.94 Ma). The total thickness of the two layers is about 35 m.

It has been established from the borehole explorations and laboratory investigations prior to the tower construction that down to the depth of 6-7 m the initial load of collapsibility ($p_c = 0.2$ MPa) is higher than the geological burden ($p_\gamma = 0.12$ MPa), i.e. loess is collapsible to this depth due to the additional load of the facility.

The 7-16 m interval (layers L_2, FS_2 and L_3 in Fig. 2) possesses collapsibility under geological burden (unloaded collapsibility) of 2-3 %. Non-collapsible loess is found at a depth of 16 m with collapsibility tending to $\delta_{c\gamma} = 0.00$ % under geological burden $p_{B\,\gamma} = 0.3$ MPa.

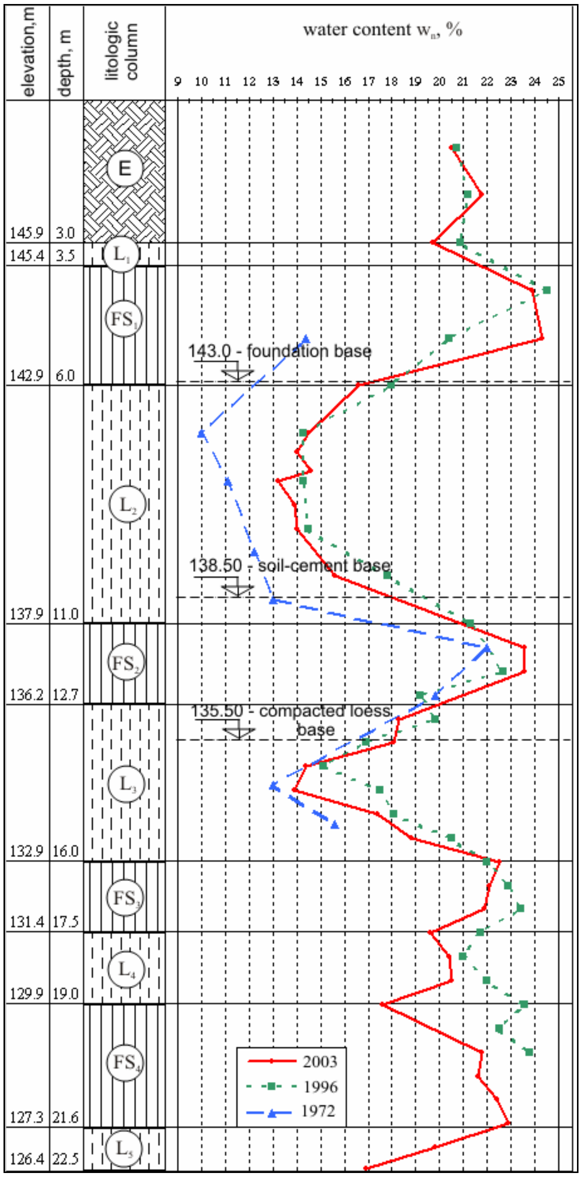

Fig. 2. Geological structure of the soil base
The curves of the moisture content investigated in 1972, 1996 and 2003 are presented in the right

The collapsible layers of the loess base are characterized by the following geotechnical parameters.
Layer L_2. It is represented by typical loess with clayey content of about 16-18 %, with high amount of finely dispersed carbonates. Its thickness is 5-6 m. According to data from 15 samples the layer is characterized by the following averaged parameters: natural moisture content $w_n = 11.30\%$; bulk density $\rho = 1.58$ g/cm^3; dry density $\rho_d = 1.40$ g/cm^3; porosity n = 49 %; water saturation degree Sr = 0.33; relative collapsibility $\delta_{col} = 2.4$ % for p = 0.3 MPa.
Two stamp loadings were performed in layer L_2 – to p = 0.25 MPa, for natural w_n and for additional moistening. The deformation modulus value under natural conditions was $E_0 = 38.5$ MPa, and after moistening it became five times lower - $E_0 = 6.9$ MPa.

Layer FS_2. The thickness of the second fossil soil is 1.70 m. With respect to its clay content (d < 0.005 mm up to 25 %), according to Minkov (1968) it is referred to clayey loess. On the basis of data from three samples it is characterized by the following averaged physico-mechanical parameters:

$w_n = 21.50$ %, $\rho = 1.64$ g/cm^3; $\rho_d = 1.37$ g/cm^3; $n = 48.8$ %; $Sr = 0.66$; $\delta_{пр0.3} = 3.2$ %.

Layer L_3. The thickness of the third loess horizon is 3.30 m. It is built of clayey loess with clayey content of 24-26 % and high carbonate content in the finely dispersed fraction. According to data from three samples it is characterized by the following averaged physico-mechanical parameters: $w_n = 14.30$ %, $\rho = 1.61$ g/cm^3; $\rho_d = 1.42$ g/cm^3; $n = 47.6$ %; $Sr = 0.46$; $\delta_{пр0.3} = 1.5$ %.

Under the collapsible layer, in the interval 16-30 m, follow compacted by the geological burden layers, which are non-collapsible.

The groundwater level is under the loess complex in the Pliocene sediments and there is no danger that it would rise and spread in the loess complex, which is well drained in the slope from north to south.

FOUNDATION WORK

Foundation with borehole piles of the "Benoto" type, with their lower end reaching 38 m, i.e. the basal gravels and sands, was initially considered. The method was abandoned due to its high cost. An alternative solution was accepted using loess improvement methods with the aim of avoiding the collapsibility hazard. This solution included deepening of the excavation, compaction of its bottom by means of a heavy tamper (Minkov et al., 1980) and construction of a thick soil-cement cushion, on top of which is built the reinforced concrete foundation (Fig. 3).

Briefly, the foundation works were realized in the following manner:

- Excavation for the foundation to elevation -14.50 m (absolute elevation of 138.50 m), which was not difficult even for the vertical excavation slopes due to the low moisture content of loess w_n=12-14 %;

- Compaction of the excavation bottom using a 7 ton tamper (Photo 1), reaching $\rho_d > 1.50$ g/cm^3 to a depth of 3 m and modulus of total deformation $E_o = 20$ MPa;

Photo 1. Heavy tamping of the excavation bottom - L_1, FS_1, L_2 and FS_2 can be distinguished on the vertical slope

- Construction of a soil-cement cushion with a thickness 4.5 m and a diameter of 45 m. The cushion consists of three layers, 1.5 m each – with increasing cement content respectively 2, 4 and 6 % in an ascending direction and modulus of total deformation E_o 50, 80 and 120 MPa, measured *in-situ* with stamp testing. The layers were built of 15-cm thick strata by *in-situ* mixing of cement and soil and by roller compaction. Soil from the excavation was used, which was stored at the surface and then returned back in the pit with dump trucks along a ramp in the slope;
- The foundation was set at a depth of -10.0 m (absolute elevation of 143.0 m). It consists of two bodies – 1.5 m thick common reinforced concrete slab with a diameter of 36.0 m and radial reinforced concrete ribs on the top surface of the slab with varying cross-section – height of 1.0 m in the end and 3.5 m in the center.

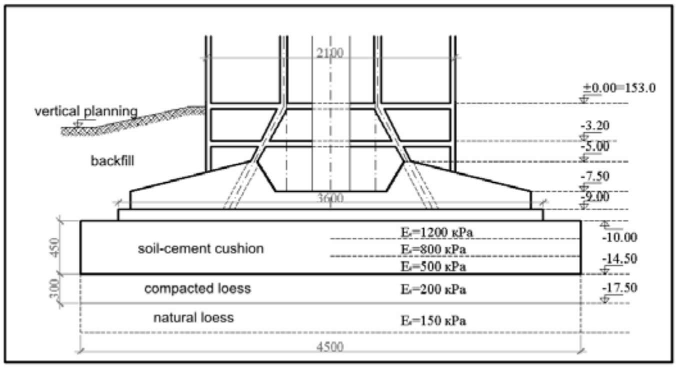

Fig. 3. Foundation scheme of the TV tower in Rousse city

The method described so far prevents the hazard of collapsibility for the layers L_1, FS_1, L_2 and FS_2 and the top part of L_3. In fact the lower 2.6 m of L_3 remained unchanged, its w_n being increased at the transition to FS_3. The small thickness of the potentially collapsible layer, its situation at a great depth and the absence of a project for buildings in the tower vicinity – the surrounding space being intended to be a lawn, as well as the envisaged network for geodetic control, were the most important motivations for the absence of apprehensions about this thin collapsible layer. The eventual deformations in it would have been expressed in additional settling instead of collapsing.

The geodetic network includes two reference borehole benchmarks, their lower ends being at a depth of 25 m resting on a non-collapsible layer, and a system of deep benchmarks with lower ends in the foundation and the soil base at depths beneath the foundation of 5.0, 7.5 and 10 m, i.e. in the soil-cement cushion base, at the boundary between the natural and compacted loess and in the natural loess. There are 10 leveling marks in the tower body for monitoring the deformations. The measurements with accuracy of 0.01 mm were made both during the construction and after its completion at certain time periods but at least once in a year.

RESULTS OF THE GEOTECHNICAL MONITORING AND OF THE IMPROVEMENT ACTIVITIES

In the course of its existence the tower was subjected to several earthquakes that caused oscillations in its upper part but without visible construction damages.

The geotechnical monitoring of the soil base includes two basic activities:

- Measurement of the settlements in a geodetic way using the described above benchmark and leveling network during the construction of the tower and its operation;
- Measurement of the moisture content by sample collection from boreholes prior to the tower construction (1972), after slight increase of the settlements (1996) and after the water supply and sewerage (WSS) system repair (2003) and drying the backfill embankment (2005).

Settlement of the tower

The settlement of the tower was measured after its construction to elevation 0.00, and after construction of ¼ part of it and with certain interruptions during its up to date operation (Fig. 4).

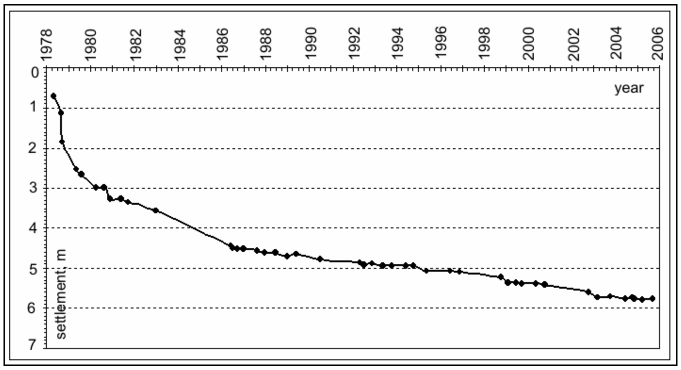

Fig. 4. Averaged graph "time – settlement" of the leveling marks

During the construction of the tower the settlement was relatively more intensive, reaching 3.57 cm after its completion in 1983.

It increased with another 1 cm till 1987 and then slow attenuation started, increasing only with 0.5 cm in the course of 8 years, i.e. with about 0.62 mm annually till 1995. It may be presumed that this fading rate would have continued in the next years too, if the accidents in the WSS system did not occur. As a result of them, the non-compacted backfill embankment (Fig. 3) was over-moistened and irregular settlement of the built on it contiguous to the tower low structures occurred. Part of the water had permeated into the non-compacted part of the soil base (loess horizon L_3), provoking certain increase in its moisture content (Fig. 2).

The over-moistening of the backfill had caused cracking of the sidewalk and a 20-cm wide gap appeared between the sidewalk and the tower, allowing the permeation of precipitation water flowing down the tower body into the soil base. This rise of water content caused slight increase in the settlement – up to 1 mm annually and very slight, rather below the admissible, inclination of the tower, these processes being interrupted after the repair of the sewerage system in 2003 and the drying of the backfill in 2005.

Comparison between measured and calculated settlements

Several computational methods were used for predicting the settlement (Table 1): the method described in SNiP II-15-74 (Soviet building code) for large-sized foundations and restricted active zone; the method proposed by Karachorov, in which the coefficients in the known formula of Burmister were corrected on the basis of experimental data from tests with models, the method of Kushner and the finite element method (FEM) (Karachorov, 1984, 1989).

Table 1. Calculated and measured settlement of the TV tower in Rousse

Loading p, kPa	Calculated settlement s_{av}, cm				Measured settlement s_{av}, cm
	SNiP II-15-74	Corrected formula of Burmister	Method of Kushner	FEM	
60.5	1.55	4.02	2.10	-	1.84
98.1	2.50	6.62	3.40	-	2.98
146.0	3.73	6.75	4.78	6.85	3.57 (82) 5.75 (05)

For the load of 146 kPa, i.e. after the tower completion, the biggest calculated settlement is obtained by means of the finite element method (6.85 cm) and according to Burmister (6.75 cm), which are comparable with the measured total settlement in 2005 (5.75 cm). The lowest settlement value (3.73 cm) is obtained according to SNiP II-15-74.

Measurment of the moisture content. Soil improvement and waterproofing activities

The establishment of the degree of moistening of the loess base under the tower foundation and the tracing of these changes in the course of time is an important element of the monitoring (Fig. 2). As already mentioned, 2.60 m of collapsible loess remained under the heavy tamper compacted loess. The moisture content in it had increased from to 2 to 4 % till 1996 (with respect to the recorded one in 1972), with a maximum in the lower part of the layer. Due to this moistening the settlement of the tower has not attenuated entirely. The main sources of moistening are the permeating surface water via the deformed vertical planning and the damaged WSS networks.

The vertical planning and the low buildings are built on the backfill embankment, filling the space above the tower foundation and in horizontal direction – the space from the excavation contour to the tower main body. Its thickness decreases from 8.5 m along the periphery to 4 m next to the tower. The WSS installations pass through this embankment. The backfill consisted of inhomogeneous loess soil mixed with construction waste. At some places the embankment was not well compacted ($\rho_d = 1.52$ g/cm^3) and possessed high moisture content (w = 25.4-28.4 %), which was a prerequisite for its further additional compaction when moistened due to the deformation of the concrete pavement, the passing through it WSS installations and the low buildings contiguous to the tower. The precipitation and technogenic waters that had permeated into the backfill reached the foundation and permeated into the soil base under the tower along the soil-cement cushion.

The occurring unfavorable changes had brought the necessity of taking measures, including drying and strengthening of the backfill embankment with quicklime columns, injection of cement-sand mortar in the cavities formed under the concrete sidewalk around the tower and the gap between them. A combination of quicklime columns and borehole concrete piles was used at some places. In this case the lime columns have been built in the bore hole interval of 3 –5 m and the space to the surface was filled up with concrete.

The total number of lime columns is 299 (one column for 1.3 m^2). Their diameter is 220 mm and the total length - 1384.5 m. The decreasing of the soil water content of the natural loess between the lime columns was 2-5 %. Besides this case, quicklime columns have been successfully used in Bulgaria for drying of school building collapsible loess base and of 400 m long over-moistened railway embankment.

New vertical planning was performed after the backfill strengthening. The WSS installations were repaired too.

The effect of activities undertaken to 2003 consisted in reducing the moisture content of the collapsible layer with 1-2 % (Fig. 2). The entire stabilization of the backfill embankment completed in 2006 will lead to further attenuation of the settlement.

CONCLUSIONS

The TV tower in the city of Rousse was founded on collapsible loess after the performance of the following improvement of the soil base: deepening of the excavation, compaction with a 7 ton heavy tamper and construction of a thick (4.5 m) soil-cement cushion. In this way the hazard of collapsibility had been eliminated but the possibility remained for certain additional settlement in case of increasing the moisture content of in-depth loess.

Under the low administrative buildings that were incorrectly constructed in contiguity to the tower and founded in the backfill, collapse of the insufficiently compacted embankment had occurred due to the load of these structures.

After the establishment of the increased moisture content in the backfill around the tower, soil improvement and waterproofing measures were undertaken: compaction and drying of the backfill embankment with quicklime columns, injection of cement-sand mortar in the cavities under the concrete sidewalk and in the gap between the tower body and the sidewalk, a combination of quicklime columns and cast concrete piles at some places, construction of a new passable collector for the water supply and sewerage installations, construction of new vertical planning.

Decreasing of the moisture content in the deeply embedded loess layer L_3 with 1-2 % was established in 2003. The drying and waterproofing measures completed in 2006 will lead to further decrease of the moisture content in the soil base and to fading of settlement. It is necessary also to perform strengthening and repair works for the lower buildings around the tower, which continue to be a source for permeation of water to the soil base.

Good correspondence between the measured and predicted settlement values has been established. The settlement recorded so far and the inclination of the tower, are within the admissible limits.

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