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Foundation Structure of the CN Tower (Toronto)

Fondation de la tour de télécommunication "CN Tower" (Toronto)

Fundation des Fernmeldeturms "CN Tower" (Toronto)

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1. Description of Structure

The recently completed CN Tower in Toronto (Canada) is the highest free standing structure of the world rising to a height of 550 m (Fig. 1). It consists of a tapered, Y-shaped, multi-cellular concrete shaft up to 447 m and a steel antenna mast of 103 m covered by fiber reinforced plastic cylinders (Fig. 2).

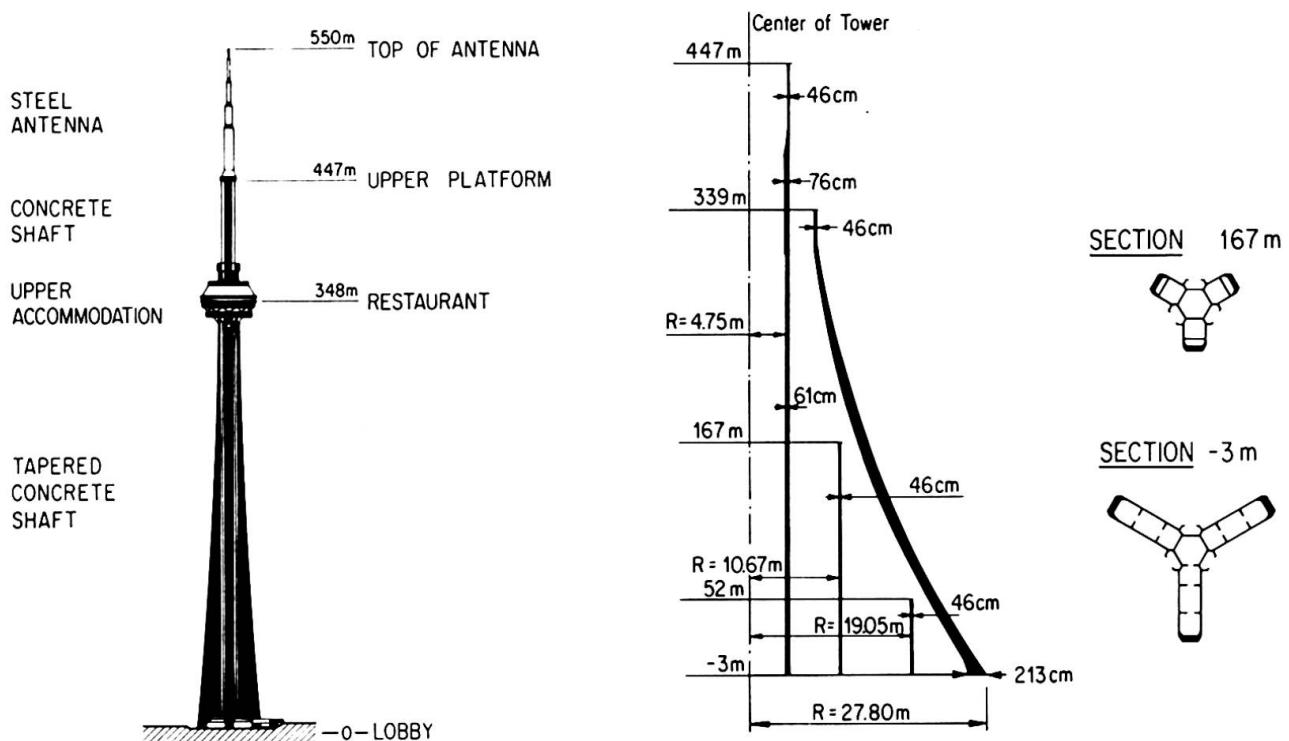


Fig.1: CN Tower, Toronto

Fig.2: Typical Dimensions of Tower Shaft

The tower houses various telecommunication transmission facilities. In addition a restaurant and observation decks at the 348 m level and an upper observation platform at the 447 m level are open to the general public.

The selection of the shape and the cross section of the concrete shaft was influenced not only by statical and architectural considerations. Due to the fact that only three walls, i.e. the outer walls of the three legs are sloping the application of slip forms in casting the entire shaft became possible. Vertical prestressing of the tower resulted in a number of advantages and cost saving:

- No tensile stresses under the 50 year wind.
- About 75% less steel weight for the same strength, cost savings relative to the unit prices of prestressing and ordinary reinforcement.
- Concentrated forces, no splices, less congestions due to reinforcements.
- Great reduction in the quantity of ordinary steel to be placed during the slipping operation of the formwork.

2. Foundation Base

The foundation base consists of the Meaford-Dundas shale formation which is typical for the downtown area of Toronto. Some twenty borings and four observation test wells of 76 cm diameter were made, one reaching a depth of 40 m. Under an unconsolidated fill of about 9 m the bedrock comprises a sedimentary sequence of horizontally thinly bedded or laminated shales, calcareous shales and limestones. Some narrow zones of rubbed shale, 15 to 45 cm thick occur. Some clay seams up to 1.5 cm thick are also present. These seams together with the presence of vertical cracks in the shales lead to the use of prestressing of the foundation structure as will be explained later on. The ground water level is at a depth of about 6 m.

In the following Table 1 the unconfined compression strength of the rock samples is listed.

	Shale	Calcareous Shale	Limestone
Amount of Sequence			
Unconfined Compression Strength	84 kg/cm ²	190 kg/cm ²	1100 to 2000 kg/cm ²

Table 1: Compression Strength of Rock Base

3. Foundation Structure

The foundation structure is shown in Fig. 3. It follows the Y-shape of the tower shaft. The hollow core slab has a thickness of 5.50 m. The live anchors of the prestressing cables of the tower walls are located in these caverns. The prestressing operations for these cables, up to 450 m long, could hence be executed in this protected area without interference of the work on the platform of the slip form.

The outer walls of the three tower legs are inclined with respect to the vertical as illustrated in Fig. 4. The horizontal components of the forces in these walls due to dead load and wind moment produce considerable tensile forces in the foundation slab. Resisting forces can be built up by (1) the reinforcement of the

slab, (2) friction forces between slab and rock and (3) resistance of the rock wall around the perimeter.

It was decided to take up these permanently acting spreading forces by posttensioned cables, Fig. 5. Frictional forces (2) could not be relied upon because of the above mentioned clay seams and high pore water pressures in response to dynamic wind forces. Resisting forces (3) along the perimeter would only be activated after substantial horizontal movements. Hence, in order to prevent vertical cracking of the foundation slab and the tower walls above as well as of the rock layers below prestressing was chosen.

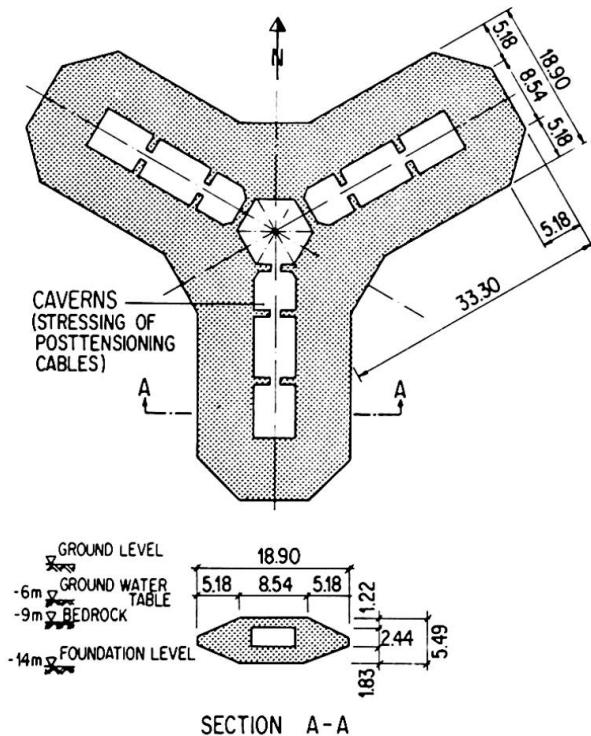


Fig.3: Foundation Slab

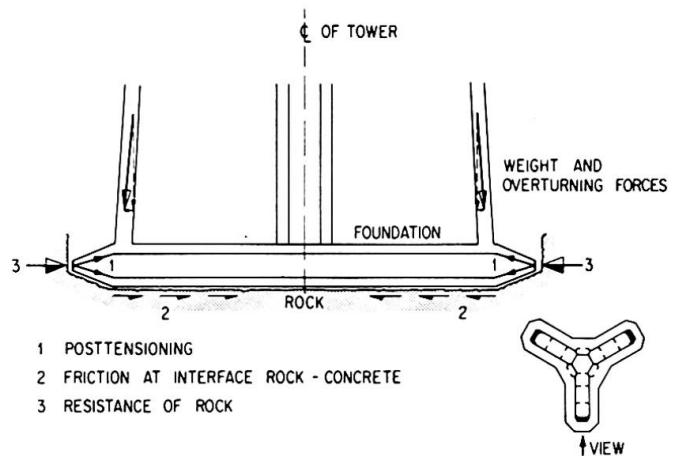


Fig.4: Horizontal Forces on Foundation

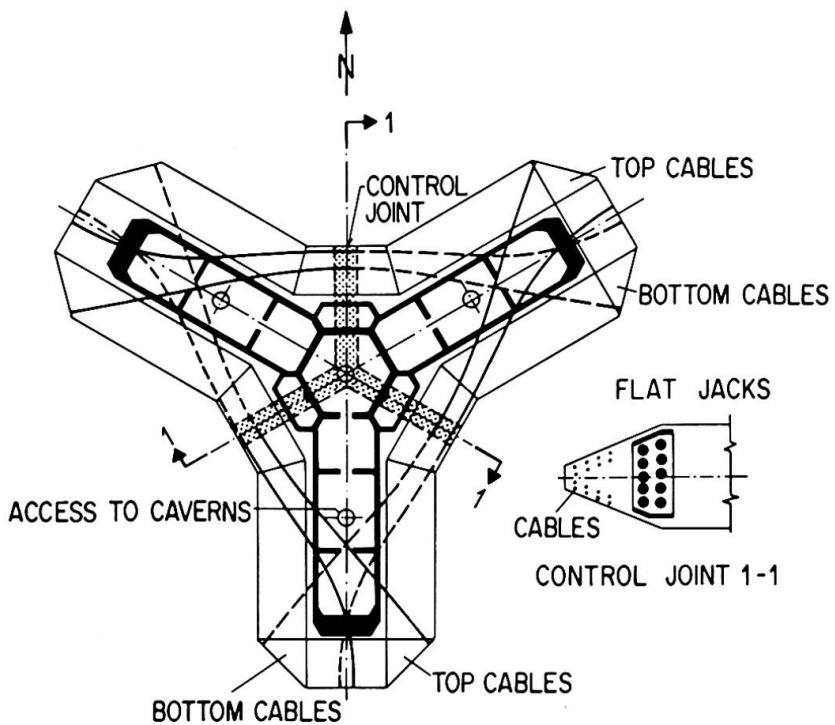


Fig.5: Prestressing of Foundation Slab

Bands of prestressing cables in the arrangement of Fig. 5 were placed running below and above the slab caverns. Control joints 1-1 separated the three legs completely. A sequence for the posttensioning operation was developed such that the outer edges of the three legs remained fixed. In this way vertical cracks in the shale at these critical points and a possible deterioration of its resistance could be avoided. By activating the active anchors at both cable ends and the flat jacks in the control joints in an appropriate sequence this condition could be met. A subsequent analysis of the jack forces showed that the rock base provided practically no frictional resistance as anticipated.

In order to reduce volume changes due to hydration heat and shrinkage a modest dosage of cement of 210 kg per 1 m³ of concrete was used.

Tapering edges (see cross section Fig. 3) around the foundation slab were selected on the basis of a stress analysis on the interaction between slab and rock. In such a way a considerable reduction of the local shear stresses along the edges was achieved and the possibility of vertical cracking of the shale greatly reduced.

4. Summary of Design Data

The most pertinent results of the analysis of the foundation structure are as follows:

Loading

Wind: Predicted extreme mean hourly gradient wind speed, 50 years return period:

$$v_{50} = 167 \text{ km/h}$$

Base Forces, 50 years period:

$$\text{Moment } M_{50} = 4.42 \cdot 10^5 \text{ m} \cdot \text{to}$$

$$\text{Shear } V_{50} = 1800 \text{ to}$$

During the initial design period the exact dimensions and contours of the antenna mast, the upper and lower accommodation levels and other details were not yet fixed. Hence, 25% higher reference values were selected for making the design calculations. This corresponds also to about a 10% increase in the wind speed.

Reference Forces:

$$M_{\text{ref}} = 1.25 M_{50} = 5.52 \cdot 10^5 \text{ m} \cdot \text{to}$$

$$V_{\text{ref}} = 1.25 V_{50} = 2250 \text{ to}$$

Foundation Stresses

1. Dead Load + Live Loads + Buoyancy

$$\text{Normal Force } N = 94'800 \text{ to}$$

$$\text{Average Stress } \sigma = 5.5 \text{ kg/cm}^2$$

2. 0.9 (Dead Load + Live Loads + Buoyancy)

$$\text{Reference Base Moment } M_{\text{ref}}$$

$$N = 85'300 \text{ to}$$

$$M_{\text{ref}} = 5.52 \cdot 10^5 \text{ m} \cdot \text{to}$$

$$\text{Max. Edge Stress } \sigma = 10.5 \text{ kg/cm}^2$$

Oversetting Moment

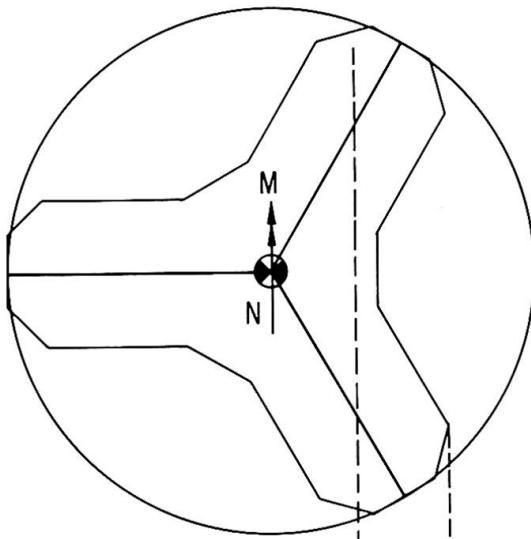
In Fig. 6 the conditions are listed. A conservative estimate for the maximum edge stress $\sigma_{max} = 84 \text{ kg/cm}^2$ equal to the unconfined compression strength of the shale (Table 1) is used. Assuming a normal force due to 0.9 (Dead Load + Live Loads + Buoyancy), $N = 85'300 \text{ to}$, the following value results:

Oversetting Moment:

$$M_{over} = 1.68 \cdot 10^6 \text{ m} \cdot \text{to}$$

Hence, the safety margin becomes:

$$s = \frac{M_{over}}{M_{ref}} \approx 3$$



Conditions:

$$N = 0.9(\text{Dead Load} + \text{Live Load} + \text{Buoyancy}) = 85'300 \text{ to}$$

$$M_{REF} = 552'000 \text{ mto}$$

$$S_{OVER} = \frac{M_{OVER}}{M_{REF}} \approx 3$$

Fig.6: Overturning Moment

5. Acknowledgement

CN Tower Ltd., Toronto, are owners of the structure. The architects were John Andrews and Webb, Zerafa, Menkès, Housden, Toronto. For the structural design and the technical supervision R.R. Nicolet and Associates, Montreal, with F. Knoll in direct charge, were responsible. The Boundary Layer Wind-Tunnel Laboratory, University of Western Ontario, London, Ontario, was charged with the analysis of wind loads. The writer was consultant to CN Tower Ltd. and R.R. Nicolet and Associates and reviewed the structural design. He expresses his sincere appreciation to all parties involved for a most effective and stimulating collaboration.

6. Reference

Franz Knoll: "Structural Design Concepts for the Canadian National Tower, Toronto, Canada". Canadian Journal of Civil Engineering, Vol. 2, No. 2, 1975, pp. 123 to 137.

SUMMARY

The 550 m high CN Tower (447 m concrete shaft, 103 m steel antenna mast) is presently the highest free standing structure of the world. The Y-shaped foundation slab resting on a shale formation is prestressed. The reason for pre-stressing, the arrangement and stressing of the cables and some pertinent design data are presented.

RESUME

La "CN Tower", de 550 m de hauteur (la colonne en béton armé mesure 447 m et l'antenne métallique 103 m) est aujourd'hui l'ouvrage le plus haut du monde. La dalle de fondation précontrainte repose sur une couche de schistes argileux. Les raisons en faveur de la précontrainte, la disposition et la tension des câbles ainsi que différents aspects importants du dimensionnement sont présentés.

ZUSAMMENFASSUNG

Der 550 m hohe CN Tower (447 m Beton-Schaft, 103 m Antenne aus Stahl) ist heute das höchste freistehende Bauwerk der Welt. Die Fundationsplatte in Y-Form ruht auf einer Formation von Schieferfelsen und ist vorgespannt. Die Gründe für die Vorspannung, die Auslegung und das Spannen der Kabel sowie weitere wichtige Angaben über die Bemessung, werden aufgeführt.