Large scale experimental study on isolated shallow foundations submitted to overturning moment

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ABSTRACT
The majority of power substations in Quebec were built between the 1940s and 1970s. Today, these substation foundations no longer meet the requirements of current standards for overturning resistance. Nevertheless, these foundations have experienced numerous forces in the years since their commissioning, including wind-induced lateral forces. In the present study, a full-scale experimental program has been developed for evaluation of the ultimate and serviceability resistance of existing shallow foundations of the "Montreal-Nord" substation, to determine the real safety factor against overturning moments. The foundations consist of unreinforced monolithic square piers cast in place on the rock without anchorage, confined by 1.5 to 2.0 m of granular backfill and granular road base. Several measurement devices with complementary characteristics were used to collect as much data as possible, enabling an extremely precise follow-up of the applied forces and deformations occurring throughout the tests. According to the findings of this study, analytical solutions failed to adequately recognize the overturning resistance of these foundations by underestimating soil resistance.

RÉSUMÉ
La majorité des postes électriques au Québec ont été construites entre les années 1940 et 1970. Aujourd'hui, ces fondations dans les postes ne répondent plus aux exigences des normes en vigueur en matière de résistance au renversement. Néanmoins, ces fondations ont subi de nombreuses forces au cours des années depuis leur mise en service, y compris des efforts latéraux induits par le vent. Dans la présente étude, un programme expérimental à grande échelle a été développé pour évaluer la résistance ultime et en service des fondations peu profondes existantes au poste « Montréal-Nord », afin de déterminer le coefficient de sécurité réel contre le moment de renversement. Les fondations en place sont constituées de piles carrées monolithiques non armées coulées en place sur le roc sans ancrage, confinées par 1,5 à 2.0 m de remblai et d'une fondation granulaire. Durant les essais, plusieurs appareils de mesure aux caractéristiques complémentaires ont été utilisés afin de collecter un maximum de données, permettant un suivi extrêmement précis des efforts appliqués et des déformations survenant tout au long des essais. Selon les résultats de cette étude, les solutions analytiques n'ont pas adéquatement estimé la résistance au renversement de ces fondations en sous-estimant la résistance du sol.

1. INTRODUCTION

Shallow foundations generally composed of solid masses such as concrete pillars and embedment caissons are among the most commonly employed foundations in the electrical industry such as electrical substations, electrical poles, and transmission lines. These foundations are typically located at a shallow depth beneath the surface and embedded in the surrounding soil. The design process often includes an in-depth analysis of foundations subjected to lateral forces such as winds and earthquakes. This is encountered in several different applications, such as bridges, abutments, and retaining structures. However, in this study, attention is given particularly to the foundations of power substations which consist of perfectly rigid foundations with low slenderness.

Despite being enclosed by their surrounding soil, these concrete blocks are prone to lateral rotation because of an overturning moment. Consequently, the infinitely rigid mass will undergo a displacement in the form of a translation and a rotation in response to the submitted lateral forces. These displacements can be very diverse and remain a source of disorders in the structures. Therefore, the assessment of the geotechnical resistance of these foundations for expected design loads and moments is of critical importance.

In order to design these foundations against overturning, it must first be determined that the ground surrounding them can withstand lateral pressures. As such, understanding the soil resistance and behavior on the lateral face of the foundation is a key element in the design, since the buried depth has a significant effect on the overturning resistance.

Under normal circumstances, the forces acting on the foundations of electrical substations may include a vertical force due to the descent of loads carried by the substation and its dead weight, a horizontal force due to wind or earthquake, and overturning moments. This allows for the mobilization of the passive resistance of the soil in contact with the foundation, which results in an asymmetrical stress state along the foundation's base, as well as horizontal and vertical displacements that are oriented in the direction of the applied forces There are several analytical methods used for determining the stress state and the displacements resulting from it, such as the state network method (Porcheron & Martin, 1968), the simplified method of balancing the forces applied by the reactions exerted (frontal reaction and shear resistance at the base), and the rotation method specifically the elastic center method (Cassan, 1978) which is based on the principle of reaction modulus. Numerous other calculation methods have been gathered in the literature (Berthomieu, 1977) for foundations subjected to overturning, and as indicated by (Ayeb, et al., 1983) they can be divided into three main categories namely elastic, plastic, and based on experiments. In the so-called elastic methods, the displacement of the foundation is associated with stresses at the interface. As long as the deformations remain small, the ground around the rigid foundation has a quasi-elastic behavior, and Winkler's hypothesis (Winkler, 1867) considering a beam on an elastic subgrade constituted of independent springs holds true. In contrast, with larger deformations, the soil may locally reach a state of plasticity. Accordingly, the elastic problem involves determining the amplitude of the soil deformations which, in view of the rigidity of the concrete mass, will be linear, as well as verifying from the reaction moduli that the stresses in the soil are below the limit stresses.

One of the old methods still used today to verify the stability of solid masses to overturning is the formula developed by (Andrée & Norsa, 1966). This method relies on the elastic behavior of the ground and a rotation of the solid mass around its lower edge. It considers both vertical and lateral pressures acting on the soil. A parallelepiped is assimilated to the solid mass. The stresses at the soil-foundation interface are normal, proportional to the displacement, and to the soil reaction modulus (K) which itself is proportional to the depth.

The drawback of elastic methods is that they are limited to small deformations (which are commonly applied for serviceability loads) and cannot be applied for larger deformations that represent failure behavior. In other words, these methods allow for the calculation of the limit overturning moment, but not of foundation displacements. Moreover, most of these models are only applicable in two dimensions, where the efforts are applied along a single axis. Meanwhile, the finite element method can provide a more accurate and realistic estimate of ground motions in 2D or 3D. This is because it uses more complex constitutive laws that can model the deformation of structures when subjected to different stresses. The most commonly used constitutive laws are the elastoplastic ones with or without soil hardening, where at larger strains, plastic deformations are simulated by a plastic flow rule.

Recently, some authors have been using FEM to study the overturning resistance of bucket and caisson foundations (Liu, et al., 2017), (Zhang, et al., 2021). However, previous studies have been using finite element programs which do not model the soil regarding its constitutive law but rather consider it as a nonlinear spring reaction (Rojas-Gonzales, et al., 1991), (DiGioia, et al., 1997). Nonetheless, elastic-based methods are still very often used to analyze the movements of soil masses and structures due to their simplicity.

For design purposes, several tests can be conducted which provide insight into the soil's properties and represent the stress-strain behavior, including the pressuremeter, the triaxial test, and the plate loading test. Even though these tests provide a solution, they are limited by several technical limitations. For example, it is almost impossible to have a borehole with intact walls, especially in sandy soils for the pressuremeter test. When it comes to laboratory tests, the quality of the results depends on the quality of the samples. Oftentimes, these samples may not be capable of reproducing the same initial condition in-situ. Moreover, most soil tests offer few or only one type of parameter. For these reasons, the design of the foundations is based on very conservative assumptions and does not consider the soil-foundation interaction. Generally, there is a lack or limited examination of the relationship between the overturning moment and the rotation angle of the foundation, which is essential to the estimation of the overturning resistance.

Only a full-scale experiment can answer these questions to validate the modeling carried out and to identify simple practical rules for the calculation and dimensioning of rock masses subjected to overturning forces. To this day, only a few studies have been focused on real testing. Most of them are focused on laboratory testing (Jianguo, et al., 1989), (Liu, et al., 2017) and very few real-scale studies have been conducted, (Lazard, 1957), (Ayeb, et al., 1983), (Rojas-Gonzales, et al., 1991), (DiGioia, et al., 1997).

This paper presents a case study in which the design safety factor of buried substation foundations, is compared to the actual factors of safety obtained using real-scale experimental approaches for the same foundations. To achieve this, the following sections provide a detailed description of FEM modeling using PLAXIS 3D and describe the experimental procedure, as well as how field data are collected and analyzed.

2 CASE STUDY

Originally constructed in the 1940s, the foundations of Montreal-North substation no longer meet the requirements of the current standards in terms of overturning resistance. Currently, the load cases have overturning factors of safety that are below the threshold required by the updated standards. Such a scenario is not uncommon to encounter with foundations that have been installed for a long time in substations. These foundations were designed based on previous specifications that were less restrictive than the most recent ones.

The foundations were designed to withstand the most severe load conditions equivalent to 305 kN.m in the ultimate state. A factor of safety of 1.25 was required.

Thus, in November 2021, Hydro-Québec's design team wanted to test the real resistance to overturning on several existing concrete foundations to establish its overturning factor of safety under the anticipated loads, by conducting a series of real-scale load tests on four of the foundations of the Montreal-North substation.

In order to achieve this, an experimental setup has been designed and constructed to conduct these studies, which included instrumentations that would collect all necessary data during the experiments that would be utilized for future analysis, as well as complementary tests to document soil properties and their geotechnical characteristics.

A realistic assessment of the expected loads was required to design the loading system. Therefore, the PLAXIS 3D software was used to perform finite element analysis. A section will be devoted to discussing the development of this model.

2.1 Foundation condition and stratigraphy of the site

These foundations were constructed using unreinforced concrete without footings and were installed directly on the rock which is between 1.60 and 1.82 m deep at the locations of the four foundations tested. The foundations were 1.22 m wide and were put in place surrounded by 2 different layers of fill material. The surface layer is a granular fill composed of a 0-20 mm caliber crushed stone followed by a granular backfill on top of the bedrock. Both layers had medium to dense compactness. The water level was at the rock surface.

2.2 Evaluation of the overturning moment

The following section provides a description of the two main methods used for the evaluation of the overturning moment of foundations. The (Andrée & Norsa, 1966) method was used as a pre-evaluation, followed by finite element simulations, to gain a better understanding of the failure mechanism that may be involved, and to estimate the forces involved in light of designing the loading system. Following are descriptions of the modeling steps and the parameters selected.

2.2.1 Andrée-Norsa method

This method assumes that the ground is elastic and that the solid mass rotates about its lower edge. The mechanism of resistance is limited to the passive resistance soils in abutments that opposes to the rotational movement. It accounts for both vertical and lateral pressure on the ground. A parallelepiped shape is attributed to the massif. Using Andrée-Norsa's formula, one can determine the moment of stability for the rock mass:

$$M_s = \left[\frac{PL}{2} - \frac{2P^2}{3Bq}\right] + \left[\frac{80\, B^2 q^2 H^3}{6561\, P}\right] \quad [1]$$

where:

M: maximum overturning moment;
P: weight of the foundation and the structure acting on it;
B,L,H: with, length and height of the foundation;
q: maximum admissible pressure.

This formula has been derived from several simplifying assumptions. It is known to provide acceptable results in granular soils. In contrast, it is excessively pessimistic when it comes to pure cohesive soils.

Assuming the maximum admissible soil pressure to be 400 kPa, the maximum overturning moment calculated for an embedment depth of 2 m is anticipated as 370 kN.m.

2.2.2 Numerical modeling with Finite Element Method (FEM)

As an additional step, modeling is also conducted using the PLAXIS 3D software to determine the overturning resistance of the foundations. The benefit of this method over analytic methods is that it provides a better prediction of the behavior of the system as it accounts both for the soil-structure interactions according to the problem geometry and the forces exerted during the loading process.

As opposed to limit analyses and analytical solutions, FEM analysis allows one to calculate and quantify the distribution of stresses and deformations throughout the loading process. In addition, it allows one to calculate the passive resistance, which constitutes the predominant resistance against the overturning of a foundation. This analysis also provides an overview of the extent of the deformation zone in the ground to establish the zone of influence at the perimeter of the foundation.

Unlike the previous method, this analysis also considers the friction resistance of the foundation surfaces in contact with the ground. In general, it is assumed that the angle of friction mobilized between the concrete foundation and the soil corresponds to two-thirds of its angle of internal friction.

2.2.2.1 FEM Model and parameters

The 3D model uses 13 630, 10-node tetrahedral elements. It is assumed that the soil follows an elastic perfectly plastic Mohr-Coulomb constitutive law, while the concrete foundation, the rock, and the loading application system are represented by an elastic model (it is presumed that the soil will fail before the concrete foundation or the rock). A 0.66 strength reduction factor representing the friction between the soil and the foundation is applied to the foundation-soil interfaces. To allow the foundation to lift during the analysis, the axial elastic stiffness at the foundation-rock interface was reduced to 0.01 kN/m^3.

Over the bedrock, the soil layer was considered to extend for 2 meters. It is assumed that the top of the structural base is located one meter above the top of the foundation. Both the foundation and the structural base are supposed to be infinitely rigid. As a simplification, this approach is acceptable and satisfactory since the purpose of the modeling is to assess the loads necessary to cause the overturning of the foundation. A representation of the 3D PLAXIS model is shown in Figure 1. The properties of the materials used in the model are shown in Table 1.

Table 1. Characteristics of tested soils

Parameters	Fill	Roc	Concrete[1]
Constitutive model	Mohr-Coulomb	Linear-Elastic	Rigid body
Unit Weight (kN/m^3)	22	25	23.5
Angle of Friction (°)	37.5	-	-
Angle of Dilatancy (°)	7.5	-	-
Cohesion (kPa)	0	-	-
Elastic Modulus (MPa)	85	1 000	-
Poisson’s Ratio	0.35	0.2	-

[1]Concrete and moment application system

According to these analyses, the moment required to overturn the foundations buried 2.0 m in the ground and resting on the rock is about 900 kN.m.

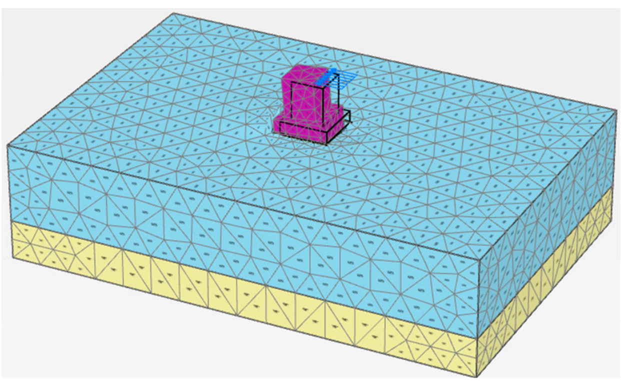

Figure 1. Mesh and boundary conditions for 3D FEM using PLAXIS 3D

3 MOMENT APPLICATION SYSTEM

The application of 900 kN.m requires an extremely high lateral force. It is a challenging task to establish a resisting system for this load to be applied. Thus, for the sake of practicality, it was decided to use a solution using a lower force. An advantageous method decided for this project was to apply an external vertical load on the end of a 5 m long cantilever. By utilizing this option, the vertical force can be applied by a hydraulic excavator. This method permits the excavator to operate with a lower weight, while maintaining a high moment on the foundation. Using a CAT 345 hydraulic excavator, it was possible to apply the force needed to overturn the foundation.

Two other challenges had to be resolved in order to be able to complete the tests. The first one was related to the structural elements (angle bars) supporting the superstructure as shown in Figure 2. They are anchored in the foundations and the analysis made on them revealed that they could yield by the application of such moment.

Figure 2. Disassembled Existing foundations

Moreover, the concrete was not reinforced and could easily break due to traction induced by the applied moment. The solution was to cut the angle bars and instead use deep anchors so that they would take the traction-compression efforts from the overturning moment as shown in Figure 3. Three of the foundations were anchored to prevent fracturing the unreinforced concrete.

Figure 3. Installation of the foundation overturning system

The other one was tested without any modifications on the most severely damaged foundation to observe if either the concrete would break up or the angle bars would start to yield. For this reason, the assembly of the lever arm was mounted directly on the existing angles by use of a special adapter as shown in Figure 4.

Figure 4. Connexion with the existing angle bars

3.1 Field instrumentation system

The site tests were conducted with the use of appropriate monitoring equipment. This data was continuously recorded by an instrumentation acquisition system. The following components of the instrument are shown in Figure 5:

1- 3D Lidar
2- photogrammetry (4 cameras)
3- inclinometer
4- strain gauge (2)
5- load cell
6- laser distance meter
7- data acquisition system

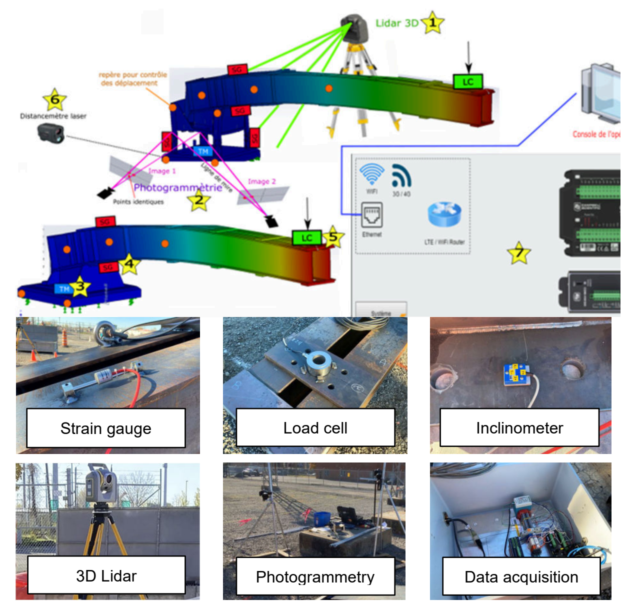

Figure 5. Illustration of the instrumentation and data acquisition system

The hydraulic excavator applies a vertical load at the end of a cantilever beam on the load cell that records the applied force at each second. The foundation rotation is monitored through the use of inclinometer mounted on the concrete base. As an alternative means of verifying the stresses and moments transmitted to the foundation, strain gauges are installed on the top and bottom of the beam. Similarly, a laser distance meter was installed behind the foundation to precisely measure top displacement and double-check the rotation of the foundation. This system was used to simultaneously record and control the tests by allowing real-time monitoring of the sensors during the course of the test.

The displacements of the concrete foundation and the ground surface along the perimeter of the foundation were tracked using two technologies (photogrammetry and 3D lidar), which are both capable of providing a 3D reconstruction of the displacements of the concrete foundation and the ground surface.

4 IN-SITU TESTS AND RESULTS

The first test consisted of bringing foundation no. 1 to failure. This is the most damaged foundation, and the test was initially meant to determine if the unreinforced concrete or the angle bar would resist the ultimate overturning moment. The concrete acted better than anticipated as it only cracked close to the base of the foundation. Therefore, since there was no failure in the foundation, this test also provided the ultimate overturning resistance. The applied force versus the rotation of the foundation at each step of loading is show in Figure 6.

Figure 7 shows the crack in the foundation as well as the global failure surface. Accordingly, it indicates that the foundations that were poured in place have made significant adhesions with the roc, which increases their resistance to overturning. However, the angle bars started to yield when the maximum load was applied but did not fail as shown in Figure 8.

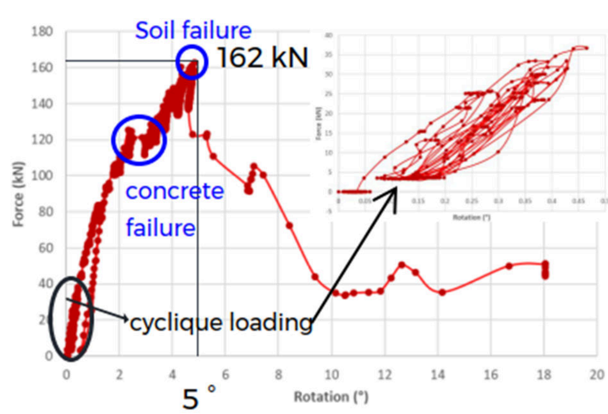

Figure 6. Force-rotation curve illustrating soil and concrete failure

Figure 7. Unreinforced part ot Foundation cracked during test.

This was followed by testing of foundations n^{os} 2 and 3 in which these anchor-enhanced foundations were brought to failure. These tests were conducted in order to verify the overturning resistance of the foundations without causing any damage to the foundations. The loading apparatus was attached to the previously installed anchors. A final test was carried out on foundation n° 4 at an angle of 45 degrees with respect to its principal axis, in order to determine how the foundation would behave given a combination of moments acting on its two principal axes.

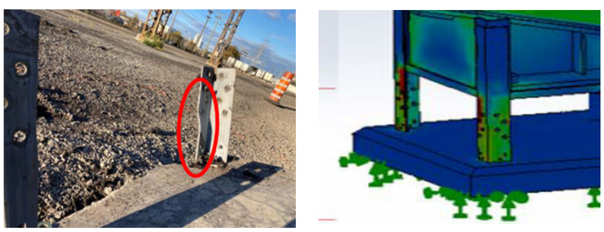

Figure 8. Detail of the local failure of the steel bracing.

As part of the first phase of the experiments (elastic phase), several quasi-static elastic loading/unloading cycles were performed in order to simulate the behavior of the foundation when subjected to strong winds. An increasing load by increments of 10 to 20 kN was applied during the second phase (plastic phase) to bring the foundation to failure. Figure 9 shows foundation n° 1 at the final stage of loading.

Figure 9. Foundation n°1 after being overturned

The results of the real-scale overturning moment and the associated factors of safety are summarized in Table 2.

Table 2. Real-scale overturning moment and the associated factors of safety (FS)

Foundation / (Buried depth)	Moment axis	Moment[1] (kN.m)	FS
N°1	0°	850	2.8
N°2	0°	730	2.4
N°3	0°	615	2.0
N°4	45°	445	1.5

[1]This includes 37.5 kN.m of the applied moment from the experimental setup weight.

Table 3 compares the real overturning moment of each foundation based on their buried depth to the ones estimated by Andrée-Norsa and the FEM methods.

Table 3. Real and estimated overturning moments

Foundation / Buried depth	Overturning Moment (kN.m)		
	Andrée-Norsa	FEM	In-situ
N°1 (1.82 m)	310	800	850
N°2 (1.60 m)	245	700	730
N°3 (1.70 m)	235	750	615

5 CONCLUSION

Foundations of the Montreal-North power substation located in Montreal area which was constructed in the 1940s do not meet new regulations regarding the safety factor against overturning. Theoretical and analytical solutions seem to underestimate the overturning resistance of these foundations with a factor of safety against overturning lower than 0.5 while a value of 1.25 is required. Therefore, an analysis based on the Andrée-Norsa equation was first evaluated followed by a 3D numerical modeling performed with estimated in-situ soil parameters using PLAXIS 3D to obtain a better assessment of the overturning resistance. These results were used to define the required overturning moment for in-situ loading tests and design the loading system as well as establish the experimental protocol and instrumentation monitoring. Several challenges were soon discovered from the results of the 3D numerical model, including the breakdown of the unreinforced concrete of the foundation. The experiment was controlled by means of numerous monitoring devices such as an inclinometer, load cell, distance meter, 3D Lidar, and photogrammetry, which allowed precise monitoring of the deformation field and the overturning moment acting on foundations. These observations made a better understanding of the failure surface in the soil and at the rock-foundation interface. The results confirmed the underestimation of the factor of safety by more than two times from analytical solutions and the advantage of using 3D numerical modeling for more complex overturning loading conditions.

The foundation behavior predicted by the FEM method agreed well with the actual load test foundation behavior. The FEM analyses used limited soil variability parameters and did not fully consider the variability conditions of foundation tests on a full-scale. However, it proved not only to provide more considerably more accurate predictions of the overturning moment and soil resistance but also provided detailed information about the soil and foundation deformations.

Following the excavation of the soil near the foundation, it was found that there is a bond between the poured foundation and the rock beneath. This contributes to the overturning resistance and has to be considered in further in model calibration and further calculations.

This study was limited to experimentally evaluating the overturning moment of cast-in-place shallow foundations. As a potential outcome of this work, all the data collected combined with photogrammetry images taken at one-second intervals will enable us to better understand the behavior of soil at the limit stages of loading. Various laboratory tests will be conducted on gathered soil samples, including a triaxial test, to calibrate the 3D PLAXIS model used in the study with actual soil characteristics.

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