Resolving structural challenges brought by complex geotechnical conditions using geo-seismic engineering, performance-based design and soil-structure interaction, case studies : the new Baie-St-Paul Hospital and new CNESST headquarters

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ABSTRACT

When structural engineering challenges caused by complex geotechnical conditions occur along the length of a project, various design approaches can be adopted. Indeed, one can head towards "safe-methods" or conservatism, whereas taking a closer, deeper look at the problem could be appealing to others. For two recently completed projects in the Quebec city area, similar structural engineering challenges brought by difficult geotechnical conditions were resolved following different approaches. This paper emphasizes how design approaches are influenced by the buildings usage (importance factor and associated performance objectives), the project realization mode, and the geo-political context of the projects.

The new Baie-St-Paul Hospital Project was announced in 2013 following seismic studies of the old hospital. The expected seismic behavior was qualified as deficient, mainly due to high soil liquefaction potential, thus compromising the public safety. The new hospital project design included the treatment of the liquefiable layers with ground improvement techniques and a concrete mat foundation allowing for averaging the settlements in case the site properties would remain partly heterogeneous.

The new CNESST headquarters project originated from foundations deficiencies discovered at the existing headquarters building. The relocation of the facility was planned on the d'Estimauville site, in Quebec city. Soil improvement was expected for the project due to soil liquefaction potential during high seismic events. However, the benefits of soil improvement using methods such as the dynamic compaction came with risks, and a high cost. An alternative structural concept with a concrete mat under the building and parking structures was investigated and selected. The effects of the post-liquefaction bearing capacity loss (and settlements) on the structure were studied with a performance-based approach.

Keywords: Soil-structure interaction, Performance-based design, Building, Liquefaction, Foundation

INTRODUCTION

When structural engineering challenges caused by complex geotechnical conditions occur along the length of a project, various design approaches can be adopted. Indeed, one can head towards "safe-methods" or conservatism, whereas taking a closer, deeper look at the problem could be the preferred approach for others.

The impacts of ground conditions on the seismic behavior and structural components of buildings are well documented and thoroughly covered by the Code. The NBCC [1] provisions, through the parameters accounting for natural vibration period, PGA, soil average shear wave velocity, standard N values and undrained soil shear resistance, provide reliable approximations of the ground movement effects on building structures. Therefore for most projects, the designer can remain within well known territory and use the Code values. However, for *F* class sites (such as liquefiable soils), the NBCC 2015 requires that a site-specific analysis be conducted to develop the motions and associated response spectrum to be used for design – if the soil mechanical properties are not improved by a densification technique. For other types of sites and/or buildings, it is also interesting, in some cases, to look closer at the soil-foundation-structure interaction problem.

The interaction between the soil, foundations and structure, commonly referred to as "SSI", can be integrated to the analysis in different ways. Per the NIST GCR 12-917-21 report [2], SSI effects can be regrouped in two categories : kinematic SSI (response spectrum, base slab averaging, embedment effect, damping) and inertial SSI (flexibility levels at the interface and damping).

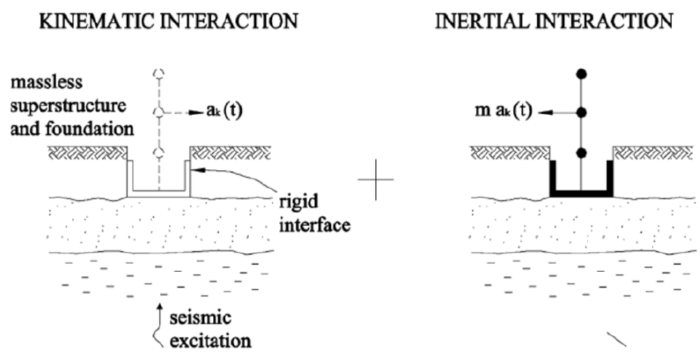


Figure 1. Decoupling of kinematic and inertial response (from Mylonakis, Nikolaou, & Gazetas, 2006)

Soil liquefaction induced by ground motions can considerably impact the seismic behavior of buildings and their structural components. As a reminder, soil liquefaction occurs when an excess of pore water pressure in a loose sandy soil results in substantial friction loss between the grains, thus reducing soil capacity and stiffness. To initiate this phenomenon, a substantial amount of stress and energy is required such as a ground motion event. Soil liquefaction can induce important settlements to building structures. While ground improvement methods can be implemented to reduce the amplitude of the settlements associated with liquefiable soils, the technique can be disturbing to the immediate surroundings and costly. These important disadvantages appeal designers to investigate alternative solutions. The feasibility of those alternative solutions, and the preferred one, often depend on the project background, the site constraints and the structural performance objectives.

The new Baie-St-Paul hospital is an example of a case where the design team assessed that proceeding with the ground improvement was the solution that best served the project interest, and the design approach will be further detailed below. For another project, the new CNESST headquarters, a multi-storey office building (*normal* protection level), the soil-foundation-structure interaction was investigated in order to assess the stress level caused to the structure by the soil liquefaction, and determine whether it was acceptable or not.

DESIGN APPROACH FOR THE NEW BAIE-ST-PAUL HOSPITAL PROJECT

Background

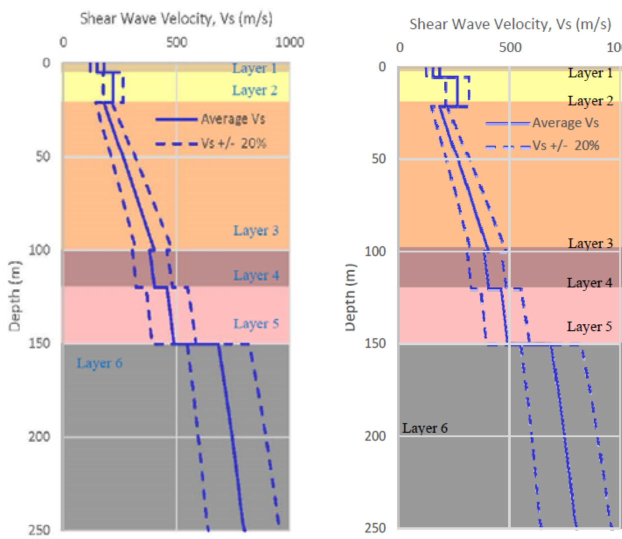
The new Baie-St-Paul Hospital Project was announced in 2013 following seismic studies of the old hospital performed according to NBCC 2005 provisions. The studies identified a high probability that the structure would behave poorly in the event of a large earthquake – mainly due to soil liquefaction, thus compromising the safety of the occupants. The soil liquefaction potential didn't prevent, however, the new hospital project from being built less than 500 meters away from the old one, for numerous – non-related to engineering - good reasons. The soils on the site were to be densified to prevent the liquefaction phenomenon to be initiated under large earthquake events.

Acting as the Owner Engineer for this Design-Build project, CIMA+ was tasked to ensure that the Client (SQI) got the most quality and the best value out of the tender process. Given the nature of a Design-Build project, CIMA+ also had to be prescriptive enough with the solution, both for the soil improvement performance criteria and the foundation system, to get the robust structural solution that a post-disaster building constructed in Baie-St-Paul commands.

Recognizing the site particularities and challenges, CIMA+ opted for adding geo-seismic expertise to its design team. The main objective was to investigate the site challenges, and assess the opportunities for construction cost optimization.

Site conditions

The site is composed of heterogeneous soil layers having variable thicknesses - the result of numerous landslides in the *Rivière du Gouffre* valley that formed the bottom of the "bowl" where Baie-St-Paul was constructed. As a result, the thickness of the liquefiable sand layer (Layer 2 on figure 2) varies from approximately 5 to 20 meters across the length of the new hospital buildings.



a) before densification of the sand *b) after densification of the sand*

Figure 2. Average shear wave velocity measured at the new Baie-Saint-Paul hospital site

The overall depth of the soil before bedrock was estimated to 250 meters, with a stiffer interface measured at a depth of 150 meters.

Analysis and performance criteria

The new Baie-St-Paul hospital (Figure 3) was designed at a *post-disaster* seismic protection level (including the long time care wing of the building). Therefore, it is expected that all services shall remain operational following the 1 in 2475 years earthquake event.

Figure 2. New Baie-St-Paul hospital

Considering the project's background, the realisation mode and the importance of the structure for the community, the following decisions were made regarding the performance criteria to be used for design :

- The performance criteria established for the ground improvement methodology aimed at eliminating the soil liquefaction hazard for the 1:2475 years earthquake;
  - Allow, however, some flexibility for the methods to be used for soil densification, to get the best value. To do so, the design team opted for a combination of in situ measurements and control means that did not favor one technique over the other;
- Concrete mat foundation under the new hospital (prescriptive);
  - Represents a robust solution in case the site remains partly heterogenous;
  - Allow the tenderer some room for optimization of the mat, but oblige a demonstration that proper soil-foundation-structure analysis is performed for its design.

Considering the high seismicity of the region and the bedrock depth, a site-specific response spectrum was developed in order to represent the post-improvement soil conditions. Since the ground surface movements (and response spectrum to be used for structural design) are very sensitive to the Vs profile (stiffness) of the upper layers, it was important that the improvement targets were attained but not strongly overpassed. In order to be able to correlate data and not rely only on standards N values empirical conversion to shear wave velocities, MASW lines, Cross-Holes and CPTs were used to measure the performance of the ground improvement work.

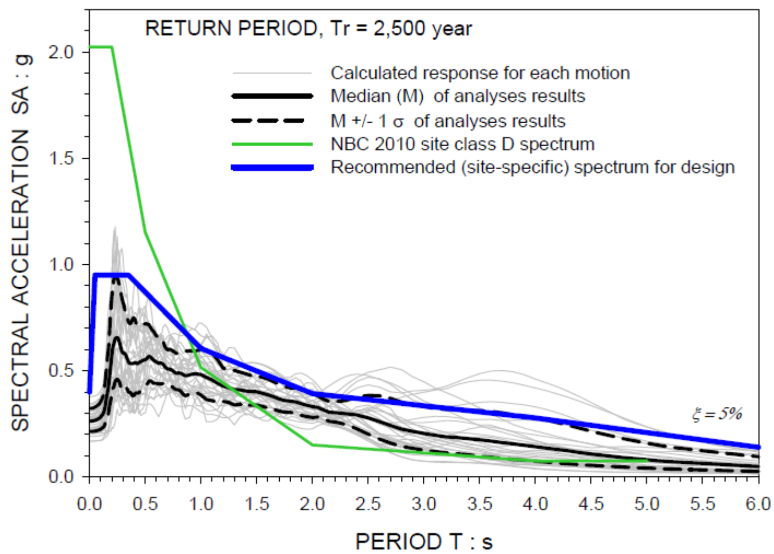


Figure 3. Site-specific analysis and response spectrum for the new Baie-St-Paul Hospital design

A minimum of 80% of the spectral ordinates from the NBCC 2010 site class D spectrum was taken for the design of the structure.

The new Baie-St-Paul Hospital opened on September 23rd, 2018.

DESIGN APPROACH FOR THE NEW CNESST HEADQUARTER

Background

The new CNESST headquarters project originated in 2015 from deficiencies observed to the foundations of the existing headquarter building during refurbishment work. The relocation of the 1 850 employees was thereafter planned in a facility to be constructed in the d'Estimauville area in Quebec city, on a sandy site located nearby the St-Lawrence river. Soil improvement was expected for the project due to the potential that soil liquefaction occurs during high seismic events. Various soil improvement techniques were assessed with respect to their efficiency and their effects on the immediate surroundings (services, infrastructures, buildings, etc.). Various alternatives were investigated to optimize design in accordance with performance objectives.

The new CNESST headquarters project consists in two separated constructions located at the same site. First, it features an eight-storey office building designed with a structural steel frame for sustaining gravity loads. A dual system composed of moderately ductile reinforced concrete shear walls along with concentric steel bracings of restrained ductility was used to withstand wind and seismic loads. Adjacent to the office building is built a seven-storey reinforced concrete parking. Both these buildings feature a one-level deep basement supported on a structural mat foundation. The entire project layout is presented conceptually on figure 4.

Figure 4. The new CNESST headquarters project

Site conditions

The site geotechnical stratigraphy was determined from data collected through a thorough in-situ tests campaign. The buildings mat foundations rest on a 30-meter sand deposit of medium to loose density. This sand layer sits atop a 18-meter silty clay deposit. Then, a 12-meter glacial till layer was encountered before attaining the bedrock. The site location is characterized by a moderate seismic hazard, featuring eastern Canada common seismologic characteristics. In addition, following preliminary analyses showing soil liquefaction potential, the site was classified to a *F* soil class according to NBCC 2015 recommendations. A site-specific response spectrum (figure 5) was therefore developed, as required by the Code. The guidelines provided in the 2015 NBCC appendices were used in order to develop the site-specific response spectrum.

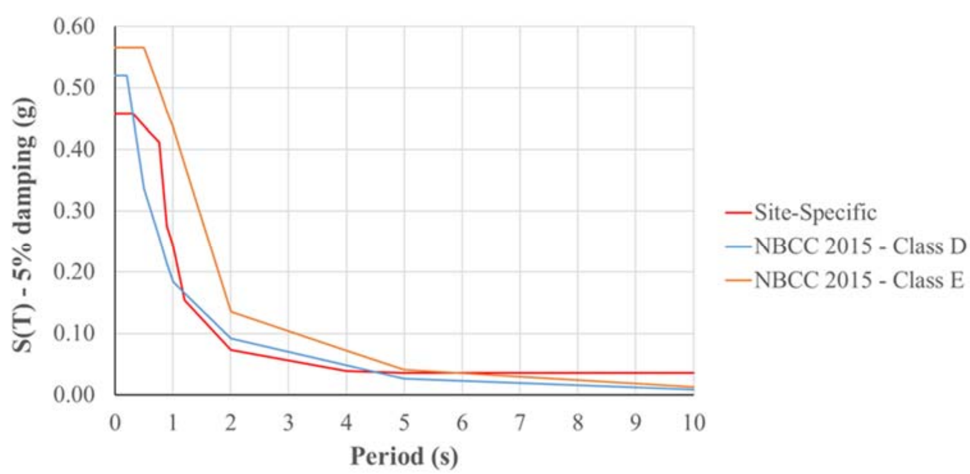


Figure 5. Site-specific response spectrum for the new CNESST headquarter project

Detailed geotechnical analyses revealed the (limited) magnitude of the settlements expected following soil liquefaction at the d'Estimauville site, as only a thin strata of the sand deposit is expected to display a liquefied behavior. The analyses that led to this conclusion will be described in a dedicated section of this paper.

Performance criteria

Specific criteria for seismic performance-based design were established in compliance with NBCC 2015 and CAN/CSA A23.3-14 Code [4] requirements and in collaboration with the Client (SQI) and the architect. The analysis was performed for a *normal* protection level at a seismic ground motion probability of exceedance of 2% in 50 years (1:2475 years return period). The main criteria used for design are summarized below:

- The performance of the building shall allow for the safe evacuation of the building;
- Repairable damages can be induced to the building's ductile structural components;
- Sustained damages shall only require localized, moderate repair before restoring the building full service.

While the criteria established for this project are qualitative, they were assessed using stress and strains values that allowed for the estimation of the damage levels sustained by the structural components of the buildings. For instance, a damage level corresponding to a ductility demand of Rd =2.0 was allowed to the mat foundations under combined seismic and soil liquefaction effects.

Geotechnical analysis

The method developed by Zhang et al. [5] estimated a value of 20 mm for total settlements and a value of 10 mm for differential settlements occurring at the soil-foundations interface. In addition, the potential risks linked with soil liquefaction using this method were considered to be light. These results were validated through various analyses using 1D geotechnical numerical models in Shake2000 [6] and CLiq [7] softwares. Another method used to determine soil liquefaction potential in this study was the analysis of CPTs results in a continuous manner as proposed by Robertson [8]. This approach estimated that only thin strata of the sand deposit exhibit factors of safety suggesting probable soil liquefaction occurrence. It should be mentioned that a comprehensive study by Boulanger [9] concluded that liquefiable soil strata should be continuous in a building footprint for settlements to be observed at the surface. In the case of the new CNESST headquarters project, continuous strata of potential liquefiable soil was not encountered during the site investigation study. Nonetheless, in order to perform a diligent design, the 20 mm (total) and 10 mm (differential) settlements were considered at the buildings foundations and soil interface (analysis detailed below).

If the design team was to opt for soil densification to prevent post-liquefaction settlements, "dynamic compaction" was the only suitable ground improvement technique for this site, due to various constraints. Despite offering the advantage of eliminating the loss of bearing capacity following an earthquake, the soil improvement by dynamic compaction had little benefit on the static (serviceability limit state) settlements. To reduce the project costs, CIMA+ proposed a structural concept where both the building and parking structures rests on a concrete mat and no densification of the natural sand deposit was to be performed. The effects of the post-liquefaction bearing capacity loss (and settlements) on the structure were investigated with a performance-based approach, studying the stresses caused to the structure by the loss of bearing capacity and assessing the associated damage. The solution was developed in compliance with NBCC 2015 general performance objectives.

Structural analysis and design

The potential settlements induced by soil liquefaction were integrated in a 3D numerical model to assess their impacts on structural components behaviour and evaluate the performance criteria. These analyses were performed by generating losses of soil stiffness in the models. These losses resulted in 20 mm total and 10 mm differential settlements at different locations using an iterative process. In addition, the settlements were considered to occur on the complete length of the building along a single structural bay for each analysis. The mat foundations were numerically included in the model using thick shell finite-elements supported on distributed springs. These springs modelled soil stiffness and were evaluated in collaboration with the geotechnical engineering team to take into consideration different soil strata, stages of construction and the complete in-service building structure. Sensibility analyses were performed to assess the impact of different design hypothesis such as mat foundations relative rigidity and spatial variation of soil stiffness modulus. It should be mentioned that a conservative approach was used as the worst seismic event was considered in concomitance with the worst soil liquefaction spatial position. The critical soil liquefaction case for the office building mat foundations design is presented in figure 3. It should be noted that this figure does not presents the concomitance with the worst seismic event.

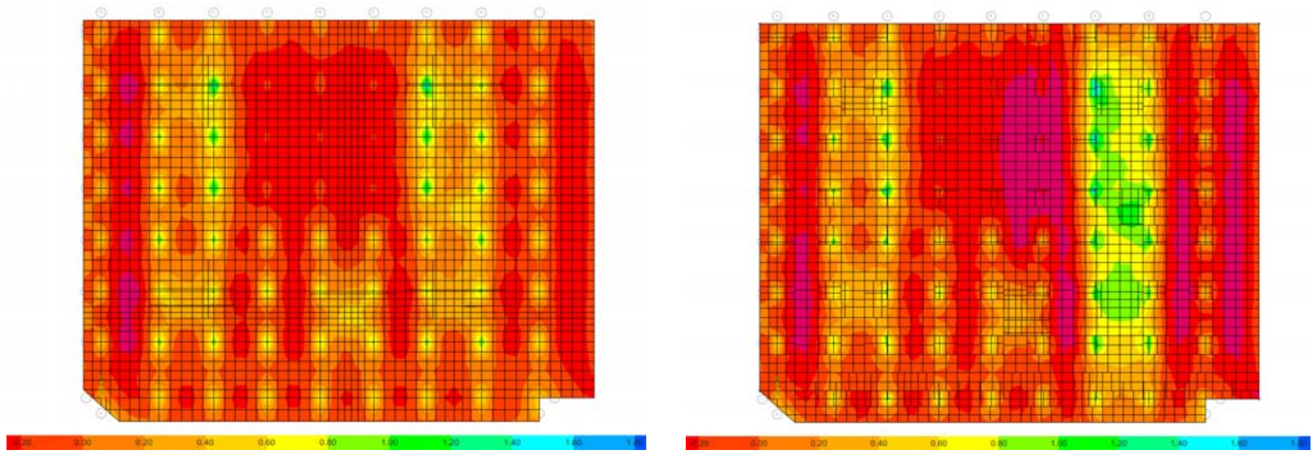


Figure 6. Comparison between new CNESST headquarters office building mat foundations stress state with (right) and without (left) soil liquefaction

From detailed structural analysis, the design team assessed that soil liquefaction occurrence should result in:

- Mat foundations flexural rebar yielding, as the maximum stress evaluated exceeds by 40% the limit. These damages are estimated to occur only in localized areas of the mat foundations;
- Mat foundations concrete cracking due to flexural rebar yielding. These damages are estimated to occur only in localized areas of the mat foundations;
- No damage to steel and reinforced concrete gravity load resisting structures as the loads transferred were limited.

These damage levels comply with the specific design performance criteria established in this study and demonstrate the limited impact of soil liquefaction on the buildings foundations analyzed in this study. The structural mats were designed to sustain gravity and seismic loadings without any further inclusion of soil liquefaction effects. In addition, it should be emphasized that the use of ground improvement methods was abandoned following these analyses and this resulted in significant cost savings and construction time optimization.

CONCLUSIONS

For those two major buildings where the site presented various seismic challenges, the rational approach based on a targeted performance and considering the project realization mode and background, resulted in two different designs. Strong and unpredictable ground motions characterized the new Baie-Saint-Paul hospital site, while the buildings foundations system rests on a heterogeneous soil deposit presenting soil liquefaction potential. The combined solution adopted in order to meet project's specific performance objectives at a *post-disaster* protection level included both ground improvements methods and a structural mat foundations system. This design was analyzed thoroughly and results confirmed that it is sufficient to prevent damage to the foundations structural components at a seismic ground motion probability of exceedance of 2% in 50 years. In the case of the new CNESST headquarters, both buildings rests on a homogeneous soil with predictable layers presenting a light soil liquefaction potential while a moderate seismic hazard defined the site. This project was analyzed for a *normal* protection level and damages to the structural mat foundations system were allowed when the worst seismic event was considered in concomitance with the worst soil liquefaction spatial position. In both these projects, the inclusion of soil-structure interaction analysis to assess the compliance with performance objectives that were established early in the design process allowed the development of robust solutions and provided the best value for the Client. These two projects emphasized that the inclusion of SSI and performance-based notions in the design process should not only be seen as an optimization mean. When included early in the design process, in specific cases, the results can provide important global orientations to the projects.

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