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Geotechnical and Soil-Structure Interaction Considerations for Definition of Building Base in Seismic Design

Morteza Esfehani[1*]

[1] Director of geotechnical expertise, WSP Canada, Montreal, QC, Canada
[*]morteza.esfehani@wsp.com (Corresponding Author)

ABSTRACT

In the National Building Code of Canada 2020 (NBCC 2020) [1], the seismic site designation is determined using V_{S30} (average shear wave velocity, Vs, in top 30 m) calculated from in situ measurements. Questions have been arisen among engineering practitioners about the top-level datum from which the V_S values should be considered: (e.g., Measurements from surface or from foundation base? From existing surface or from final surface after earthwork? From crest or from toe level of sloping ground?).

Moreover, the determination of base level for seismic design is primordial for at least two main purposes: 1) The depth of soil to be considered in site response analyses; 2) the level of seismic load transfer to the building for structural design. The location of ground motion transfer to the building is often a function of structure configuration and foundation type. The seismic behaviour of a building on pile foundation may be quite different from the one seating on a raft foundation. In many buildings, the buried part of structure (underground storeys and pile foundation) will interact with the ground, not only at the base level but also along the side soil-structure interface. Consequently, thorough soil-structure interaction analysis and effective communication between geotechnical and structural design engineers are essential for a safe seismic design.

The paper attempts to provide answers, in some extend, to the above-mentioned questions and concerns. Codes definition for base level from other jurisdictions are cited as well for comparison. The paper intent is to provide guidance for better understanding of code requirements for engineering practitioners.

Keywords: Codes seismic requirement, site designation, building base level, geotechnical consideration, foundation, seismic ground motion, site seismic response, soil properties, shear wave velocity, soil-structure interaction.

INTRODUCTION

Seismic loading is the application of an earthquake-generated agitation to the structure at contact surfaces with the ground. Although, for a given seismic event, the source of the seismic load is the same for surrounding sites, several factors influence the wave propagation for a specific site, such as characteristics of soil medium between the bedrock and the site location. The effects of site conditions on seismic ground motions usually refer to how seismic waves from the underlying rock are affected by the geometry and geology of the softer surface deposits during wave transmission to the ground surface. Although the seismic loading is a complex subject, it depends mainly on seismic hazard (source motion), geotechnical properties of the site (amplification), and structure dynamic behavior (geometry and flexibility):

- The seismic hazard refers to the source motion characteristics (magnitude, frequency, duration), usually defined at bedrock level.
- The structure dynamic behavior is related to the geometry and the natural frequency of the structure.
- The site geotechnical properties refer to the medium behavior between the bedrock and the structure. The soil medium is usually prone to the amplification of the bedrock motion known as site seismic response.

The site seismic response can be provided by geotechnical engineer by two methods:

- The seismic site designation (classification): In many building codes, including the NBCC 2020, the seismic site designation is used to capture the amplification effects of local soil conditions on ground motions and consequently on the seismic design loads. The amplification effect by local conditions is represented by soil geotechnical properties. Ranges of ground condition (geotechnical properties) are defined, and spectral accelerations are associated with each of them.

- The site-specific seismic response analysis: It is a procedure in geotechnical engineering that is used as a direct method to evaluate the influence of local soil conditions under earthquake ground shaking at a specific site. Numerical models are used to predict the behavior of soils under seismic loads.

The geotechnical practitioners choose frequently the first method which allows to use the data from conventional geotechnical investigation in the definition of site seismic designations. The paper will expose the related challenges and attempts to provide some clarifications for ambiguities that may arise by this method.

The second method is more detailed and accurate if it is carried out by an expert in soil dynamics. This paper does not cover the site response dynamic analyses method.

CONVENTIONAL METHODOLOGY FOR DETERMINATION OF SEISMIC SITE DESIGNATION

Most of the code provisions for civil structures considers the soil geotechnical properties of the top 30 m as the main parameter for site seismic designation.

Adopting a depth of 30 m was originally associated with the typical exploration depth of geotechnical boreholes. The top 30 m of ground properties are of interest also because it usually (not always) governs the resulting seismic response at the ground surface. This is based on some in situ recorded accelerations showing that the seismic amplification is often developed in the top 20 to 30 m of the ground.

In the NBCC 2020 [1-2], the seismic site designation is determined using V_{S30} (average shear wave velocity, Vs, in top 30 m) calculated from in situ measurements. This requirement seems clear a priori, but some questions were arisen among engineering practitioners about the top-level datum from which the V_S values should be considered:

- For structures having multiple underground levels, should the V_s measurements be considered from ground surface or from foundation base?
- Should the Vs measurements be considered from existing surface or final surface after earthwork?
- For sloping ground, should the V_S measurements be considered from crest or from toe level of the slope?
- How the site designation for building on pile foundation should be defined?

CODES DEFINITION OF TOP DATUM LEVEL

It is not practical to define a unique definition of the datum level for all purpose of seismic design of structures. The NBCC 2020 considers the soil properties of the top 30 m as datum level for definition of seismic site designation. The datum is therefore the ground surface for consideration of shear wave velocity or any other geotechnical parameters for the purpose of seismic site designation. Another definition of datum level is provided in this code for structural design referring to the base of the building for the level of application of seismic loads. Misinterpretations may occur where there is considerable gap between ground surface and the base level of the structure (foundation). In many cases, if the foundation level is considered as datum, the site designation may be faulty, and the seismic loads may be unsafely underestimated. An efficient communication between geotechnical and structural engineers is required for proper definition of these two geometrical items.

Standard ASCE/SEI 7 is an integral part of building codes in the United States. In section 20.2 of the Standard ASCE/SEI 7-22 [3], it is indicated that the site soil should be classified based on the average shear wave velocity parameter, Vs, which is derived from the measured shear wave velocity profile from the ground surface to a depth of 100 ft (30 m). Therefore, this standard refers as well to the ground surface as a datum for the site classification. On the other hand, in section 11.2 of this Standard [3], the structure base is defined as “The level at which the horizontal seismic ground motions are considered to be imparted to the structure.” As mentioned above, usually the base level is not located at or close to the ground surface, and this may create ambiguities for appropriate evaluation of seismic ground motions. However, the Commentary to this Standard provide warnings by indicating that the soil profile should not be taken from the foundation-level elevation downward when that elevation is below the ground surface.

GEOTECHNICAL VERSUS STRUCTURAL UNDERSTANDING OF BASE LEVEL

The discrepancy in the definition of base level may be related to the difference in point of view of the engineer. Geotechnical engineers have stratigraphical-geological-oriented vision and are only interested the soil medium transferring the seismic motion. Structural engineers are rather interested in the level at which the ground motions are imparted to the structure. An appropriate seismic design should consider the combination of both visons which can be capture by using soil-structure interaction design method. Efficient communication between structural engineer and geotechnical engineer becomes therefore primordial for proper development of seismic design model.

SPECIAL CASES OF AMBIGUITY OCCURRENCE

As mentioned previously, when the base level is not located at or close to the ground surface, it may create ambiguities for appropriate evaluation of seismic site destination, and consequently the applicable seismic ground motions. Here are some other cases that may result in misevaluation of seismic ground motions:

- Structures having multiple underground levels
- Structures on pile foundations
- Structures on slopping ground
- Structure close to adjacent buildings or close to auxiliary structure such as retaining walls

Some of these cases is discussed in more detail in the following paragraphs.

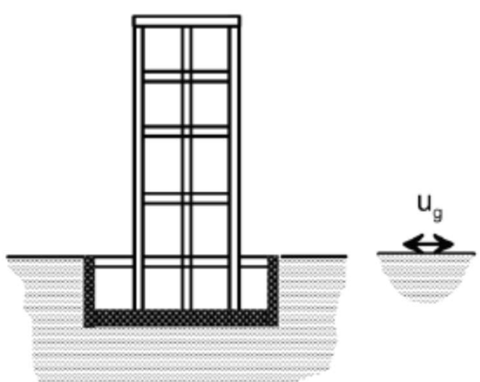
Case of embedded foundation

The response of a building to earthquake shaking is affected by interactions between three parts of the system: the structure, the foundation, and the geologic media underlying and surrounding the foundation (FMEA, 2009) [4]. The increase in depth of embedded levels of building will increase somehow the dynamic rigidity of the foundation and consequently modifies the seismic response of the building. The Appendix D of Eurocode8 [5] indicates that the seismic response of a flexibly-supported structure differs in several ways from that of the same structure with fixed-base. For instance, for a given free-field ground motion, the fundamental period of vibration of the flexibly-supported structure is longer than that of the fixed-base structure [4].

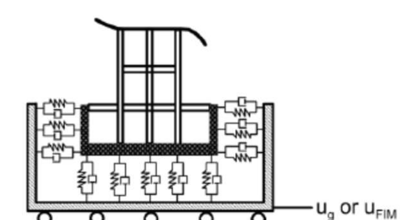
In the section C20.2 of Commentary to Standard ASCE/SEI 7-22 [3], it is clearly indicated that the soil profile should not be taken from the foundation-level elevation downward when that elevation is below the ground surface. This is sometimes done with the intent of accounting for foundation embedment effects on ground motions. This is a wrong way for consideration of possible beneficial effect of embedment, and it may result in an unsafe seismic design since the ground motions at the foundation level of embedded structures are often lower than those at the ground surface. The risk can be especially pronounced for sites with a soft soil layer overlying a much stiffer material, on which the embedded structure is founded.

For appropriate consideration of embedment effects, the above-mentioned Commentary [3] recommends the use of models of kinematic soil-structure interaction combined with site-specific ground response analyses. A seismic Soil-Structure Interaction (SSI) analysis evaluates the collective response of these systems to a specified free-field ground motion (FMEA, 2009) [4]. It is believed that the use of methods will reduce (optimize) the short period spectral accelerations. The requirement for soil-structure interaction in seismic design is provided in chapter 16 of Standard ASCE/SEI 7-22 [3]. Explicit guidance for soil-structure interaction analysis is provided in NIST-GCR-12-917-21 [6].

Un example of simplified SSI system for an embedded foundation building is shown in Figure 1, illustrating the input motion location and the distribution of springs and dashpots. Response analysis is performed with springs and dashpots representing soil-foundation interaction along basement walls and below the base slab.



(a)



(b)

Figure 1. Illustration of SSI model for a building with embedded levels and flexible foundation: (a) complete system; (b) simplified SSI model. (from [6])

For most common building structures, the effects of soil-structure interaction tend to be beneficial since they reduce the bending moments and shear forces in the various members of the superstructure. However, in some cases, the soil-structure interaction effects might be detrimental. Some of these special cases are listed in chapter 6 of Eurocode8 [5] where it is strongly recommended to consider the effects of dynamic soil-structure interaction. The list includes structures with massive or deep-seated foundations, such as bridge piers, offshore caissons, silos, and slender tall structures such as towers and chimneys.

Locating the fixed base (neutral deflection) at the embedded portion of structure is often required for the seismic design of tall buildings. The dynamic effect of the surrounding soil on the basement structure was parametrically analysed by Khouri and Elias (2014) [7] in order to determine the location of the fixed base. Results showed that when the basement height increases, the fixed base level raise to a higher level towards the ground surface far from the foundation level. Similar behavior was observed for pile foundation as explain in the next paragraph.

Case of structures on pile foundations

At sites with low competent soils (such as clayey deposits, liquefiable soils, and fill materials), buildings are usually founded on pile-supported foundations. Some engineers may have the wrong impression that piles move laterally with the horizontal ground motions and have negligeable impact on the level at which seismic ground motions are imparted to the structure (Kelly, 2009) [8]. Like the embedded structure, pile foundations will increase the dynamic rigidity of building foundation. Moreover, the pile group interact with wave propagation below the base slab, which can further modify foundation-level motions at the base of the structure. This is consistent with the fact that short piles and long slender piles embedded in the earth behave differently when subject to lateral forces and displacements (FEMA 2009) [4].

The seismic behavior of buildings founded on pile foundations is a function of dynamic stiffness of piles as well as dynamic properties of surrounding soils as shown in Figure 2 where the impedance of pile foundations in the translational and vertical modes of vibration is represented by equivalent springs. The rotational stiffness is typically derived from groups of piles supporting the pile cap slab (NIST, 2012) [6].

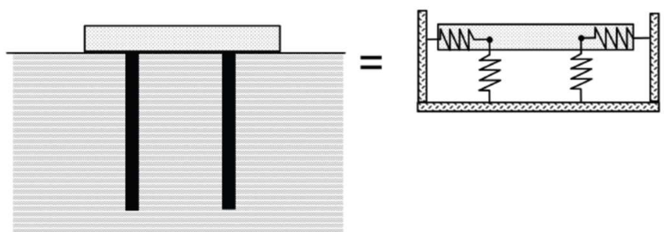


Figure 2. Simplified illustration of pile foundation system using equivalent springs for translational and vertical (rotational) impedance. (from [6])

In general, a pile does not deflect over its entire length in response to lateral loading (defining the neutral deflection depth) as shown in Figure 3. The active pile length is on the order of 10 to 20 pile diameters, depending on pile-soil stiffness contrast, soil homogeneity, and fixity conditions at the pile head (Karatzia and Mylonakis 2012) [10].

The impedance of a pile group cannot be determined by simple addition of individual pile impedances because grouped piles interact through the soil and through waves emitted from their periphery. This is called group effect which can significantly affect the impedance of a pile group as well as the distribution of head loads among individual piles in the group.

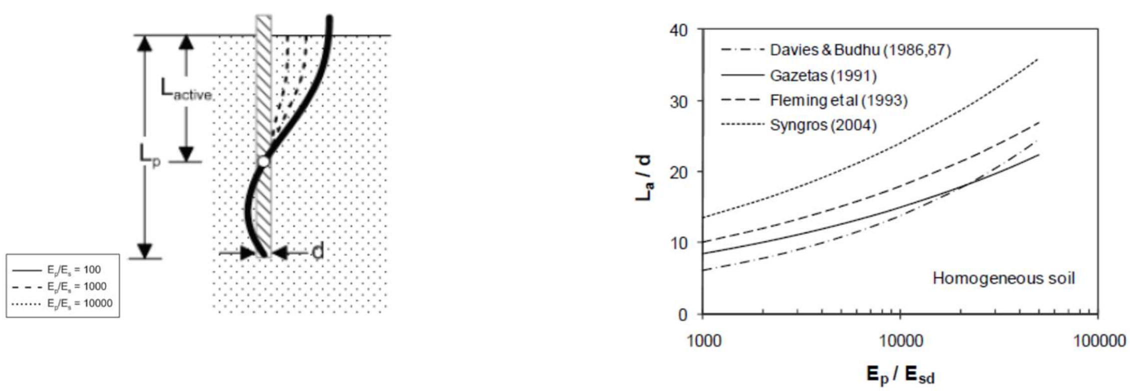


Figure 3. Active pile length for different soil and pile dynamic stiffness for single piles. (from [6 and 8])

It can be concluded that the shear base level for pile funded structure is not at a unique level but over the active pile length. Moreover, the natural periods, mode shapes of the flexibly-supported (mat foundation) structure are different from those of the fixed-base (pile founded) structure. Proper seismic design of such configuration can be captured through a soil-structure interaction analysis.

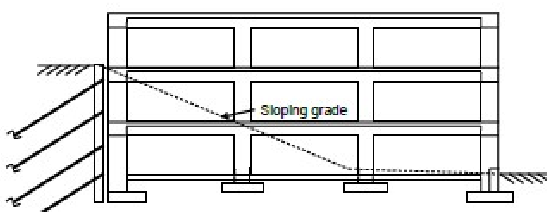
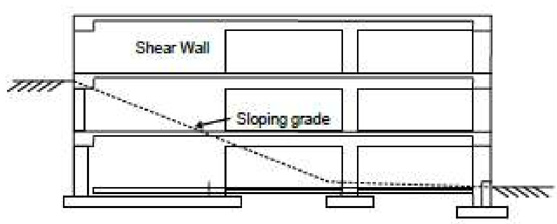
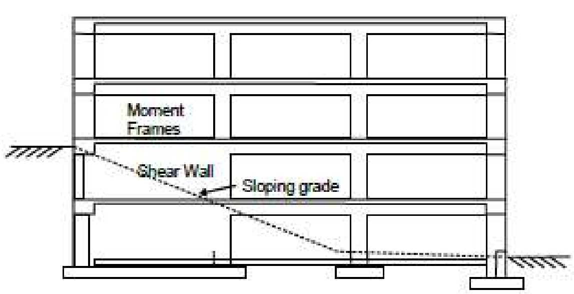
Building on slopping ground

When subjected to earthquake-induced ground shaking, sloping ground can pose a hazard to structures located on a slope. The potential severity of the hazard depends mainly on the steepness of the slope, the strength and duration of ground shaking. Unlike the common embankments, the movements of more than a few millimeters may be unacceptable for the building located on the slope. A critical first step in the assessment of the seismic slope stability is to establish the performance criteria.

Buildings on sites with sloping ground or bedrock or having highly variable soil deposits across the building area require careful study since the input motion may vary across the building (for example, if a portion of the building is on rock and the rest is over weak soils). Site-specific studies may be used in such cases to evaluate the subsurface conditions and site and superstructure response (FEMA, 2009) [9].

Locating the seismic base level for buildings located on a sloping ground may be complicated in some cases. Three specific configurations of building on slopping sites were presented by Kelly (2009) [8] along with the simplified approach to locate their seismic base as summarized in the following Table 1. In the case of partial embedded building with a basement that does not have retained earth on one side, the loading caused by the soil pressure on one side is typically analyzed separately and then added to the building inertial loading by linear superposition.

Table 1. Cases of building on slopping sites as presented by Kelly (2009) [8].

Illustration	Characteristic	Suggested seismic base location
	Building with independent retaining wall at uphill side	At building foundation level
	Seismic resistance system supporting the lateral earth pressure	At building foundation level
	Building supporting the lateral earth pressure	At building foundation level combined with the use of two-stage equivalent lateral forces

Topographic amplification

Typically, a one-dimensional soil column extending from the ground surface to bedrock is adequate to capture site response characteristics. Three-dimensional models may be required for sloping ground sites since the wave propagation may be anisotropic and may differs directionally (FEMA, 2009) [4].

The Appendix D of Eurocode 8 [5] gives some simplified amplification factors for the seismic stability verification of slopes. Such factors are an approximation and not related to the fundamental period. These amplification factors are to be applied to linear topographies, such as long ridges and cliffs with height greater than 30 m.

CONCLUSIONS

The knowledge of base level for seismic design is primordial to define the portion of soil to be considered in site seismic designation and to define the application level of seismic load to the building. Questions have been arisen among engineering practitioners about the definition of datum level.

The seismic loading is a complex subject, and depends, among others, on seismic hazard, geotechnical properties of the site, and dynamic behavior of the structure. It is therefore not practical to provide a unique definition of the datum level for all purpose of the seismic design.

The discrepancy in the definition of base level may be even related to the difference in point of view of the geotechnical and structural engineers. Hence, effective communication between these engineers is required for a safe seismic design.

The site seismic response may be provided by geotechnical engineer by two methods: seismic site designation, and site-specific seismic response analysis. The geotechnical practitioners employ frequently the first method. The paper attempt to expose some challenges and try to provide some guidance for ambiguities that may arise by this method.

When the base level is not located at or close to the ground surface, it may create ambiguities for appropriate evaluation of seismic site destination, and consequently for the applicable seismic ground motions. Similarly, the pile foundations interact with wave propagation below the base slab, which can modify motions at the base of the structure. The input motion may vary as well across the buildings on sites with sloping ground or sloping bedrock or having highly variable soil deposits across the building area.

For the exposed special cases, it is recommended to use soil-structure interaction analysis along with site-specific ground response analyses. For most common structures, the use of SSI and site-specific ground response analyses is beneficial and leads to optimization of seismic demand.

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