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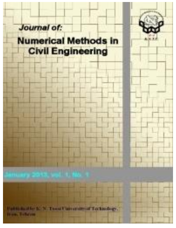

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An alternative practical solution to identify the base level location of tall buildings

Shima Taheri[*], Alireza Bagheri Noghredehi[**]

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Abstract:

One of the topics that are always disputed by structural engineers in the design of buildings with underground stories is the location of the base level. Regardless of the complex approach of considering the interaction of soil and structure, generally, most guidelines propose a qualitative approach to determine the position of the base level. Unfortunately, this qualitative approach is generally binary and proposes only two locations for the base level: on the top of the foundation or the top of the retaining wall. But in tall buildings or buildings with a significant number of basements, this binary qualitative approach can create a significant difference, even in the design of upper stories. In this article, an alternative practical solution has been proposed to obtain a quantitative method for determining the location of the base level, using the main concept of the base level, i.e. where the seismic displacement of the building is insignificant compared to the surrounding soil. The method has been applied and discussed in a real project for the design of a high-rise building in Tehran.

1. Introduction

The increase in urban population around the world as well as economic, cultural, and political issues has led to the construction of more high-rise buildings in recent decades. Figure 1 shows the global trend toward higher buildings that reach heights of above 200 meters. In recent years, high-rise building locations have also experienced an important change, shifting from North America to the Middle East and Southeast Asia. Over 80 percent of the top 100 skyscrapers in the world were located in North America in 1990. But in 2010, 80 percent of the top 100 tallest structures were located in Southeast Asia and the Middle East.

The majority of these high-rise structures need to make enough space to accommodate numerous parking lots and other specialized infrastructure, which causes the “podium”, or the stories below the ground to have considerably greater dimensions in the plan than the “tower”, or the stories above the ground. Typically, large, weighted concrete retaining walls surround podium floors. Compared to the upper floors of the tower, these floors have a significant mass and stiffness. The most important factors in explaining the dynamic properties of the structures are stiffness and mass. In tall buildings, the dynamic characteristics of the structure also have a significant impact on how the earthquake force is distributed in height and how the structure responds. The presence of a significant mass in the lower stiff floors also affects the dynamic content of the structure, leading to the consideration of further modal shapes to satisfy the minimum modal mass participation ratio, considering the fact that higher modes have a greater impact on the design of tall structures.

On the other hand, these floors are primarily surrounded by soil and also embedded, with their foundation level at a depth below the ground's surface. Due to this issue, the majority of seismic loading codes use the “base level” concept, which describes how seismic forces enter and leave the building. If certain conditions are met, the seismic force below the base level is zero; hence, floors below the base level have no contribution to the seismic mass and forces of the structure.

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[*] *Corresponding Author: Assistant Professor, Department of Civil Engineering, Payame Noor University, Tehran, Iran. E-mail: taheri@pnu.ac.ir.*

[**] *Graduated M.Sc. student, Faculty of Civil Engineering, Tehran University, Tehran, Iran. E-mail: alireza.bagheri.ir@gmail.com.*

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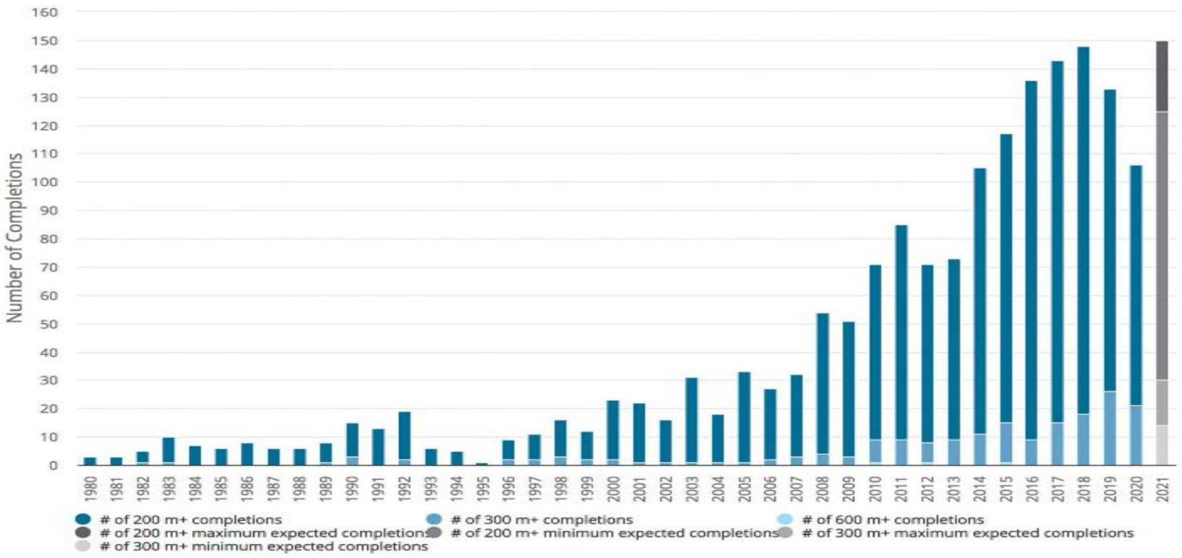


Fig. 10: The number of tall building projects completed in the last three decades (adapted from CTBUH [1])

On one hand, the applicability of the base-level requirements in high-rise buildings is in doubt, even though they are primarily qualitative and can only be met in the majority of lightweight low-rise buildings with shallow foundations.

On the other hand, in the last decade, the use of a new generation of performance-based design approaches based mainly on loss and risk assessment, e.g. FEMA-P58 approach [2], has widely been considered [3]. As opposed to classical methods which only focused on the estimation of the mean of structural responses, determining an accurate probability density function of responses is very important, and design with a wide margin of safety factor is not recommended [4].

Unfortunately, the conventional qualitative approach is predominantly binary, suggesting only two potential base-level locations: either at the top of the foundation or at the top of the retaining wall. However, in the context of tall buildings or structures with multiple basement levels, this binary approach can lead to substantial discrepancies, even affecting the design of the upper stories. This article proposes an alternative quantitative and practical solution to address these issues with a sensible safety margin, using a case study of one of Tehran's tallest buildings. In the next section, we will review the background of determining the base level and the soil-structure interaction in the technical literature.

2. Background

Building structures built on compliant soil may respond dynamically differently due to the complex "seismic soil-structure interaction" (SSI). "Inertial forces" and "kinematic interaction", which take place as a result of the presence of stiff podium components on or in soil, respectively, contribute to this complex process. According to studies of the seismic SSI response analysis of structures, the interdependent SSI effects have a significant influence on the seismic force demand and dynamic characteristics of the tower.

When earthquake ground motions are characterized for use in structure design and response simulations, the resulting motions typically correspond to a "free-field" and "ground surface" condition. Free field implies that there is no appreciable influence of structures on the properties of ground shaking. The phrase "ground surface" denotes that the estimated motions occur at the earth's surface [5]. Stewart & Tileylioglu (2007) discuss how ground motion prediction equations and seismic hazard analyses can be utilized for the analysis and design of buildings with subterranean levels. The authors address the kinematic interaction effects that can cause reductions of ground motion translation and the introduction of rocking, which are not accounted for in practice at that time. The report also reviews simple models that describe those effects based on finite element modeling for embedded rigid cylinders [5].

The majority of the studies have only focused on shallow and deep foundations, and, there have been very few studies on building structures with embedded basement levels [6].

Considering the SSI even in the design of regular and low-rise buildings has many complications. In this regard, most of the regulations and design codes that focus more on providing practical methods instead of academic approaches to solve engineering problems, try to simplify this concept. One of the ways to solve this problem is to introduce the base level.

According to Kelly (2009), the base should be located where seismic forces enter and depart the building, and if there is any dispute, the base should be placed at a lower elevation. The article explains that the definition of the “base” is intentionally broad, as many factors affect its location. Some of the factors include the location of the grade relative to floor levels, soil conditions adjacent to the building, openings in basement walls, location and stiffness of vertical elements of the seismic-force-resisting system, location and extent of seismic separations, depth of the basement, manner in which basement walls are supported, proximity to adjacent buildings, and slope of grade. The article also guides how to locate the base for different types of buildings, such as buildings without basements on level sites, buildings with basements on level sites, and buildings on sloping sites [7].

Elias & Khouri (2012) provide a procedure for locating the fixed base of a building structure with a constant stiffness over its height in an earthquake zone. They propose a procedure that allows designers to locate the fixed base when subjected to seismic excitation, considering the type of soil surrounding basements. The authors also provide an upper and lower limit for the structure that should be chosen, considering the soil-structure flexibility [8]. Further explanations about their approach will be provided in the next section. Jahankhah et al. (2013) propose a new method for solving the kinematic interaction problem of soil-structure systems with embedded foundations. The authors used a new approach based on the concept of the “equivalent foundation” to solve the problem [9].

Tehranizadeh & Barkhordari (2018) investigate the influence of peripheral wall openings in the basement and the number of basement floors on the location of the base level under near-field earthquakes, taking into account the SSI effect. The authors used five 2D metal-braced frame models with different numbers of floors and soil around them, which were subjected to near-field earthquakes. The results showed that where the opening was greater than half of the base level had to be considered one story lower than the usual ground level, thus, disregarding the effect of openings in high-rise structures could lead to non-conservative results[10]. They also in another article investigate the impact of changing the properties of the soil around the underground perimeter walls on the base level of braced framed tube systems. The study aims to identify the location of the base level, taking into account the effects of SSI effect. The results showed that the base level is considered on the top of the basement wall in cases where reinforced concrete walls are being run by an integrative structure in the underground perimeter, and the surrounding ground is dense and compressed. The study also concluded that taking into account the level of the upper stories is possible by performing appropriate walls integrated with the structure even without compacting the soil around the structure [11].

Caglar et al. (2021) emphasized the significant role of basement stories in the seismic performance of tall reinforced concrete buildings. They stated, that in earthquake-prone regions, basement levels act as foundational elements for the structure and have a substantial impact on seismic behavior, and this aspect should receive special attention during building design [12].

In a state--the-art article, Tadesse et al. (2022) explore seismic soil-structure interaction (SSI) studies concerning buildings with underground levels supported by various foundation types. They go through alternative approaches for modeling foundation-soil interactions and analyze seismic response methods. The article also addresses compliance with seismic design codes and SSI guidelines. Notably, the review sheds light on previously overlooked aspects and underscores the importance of addressing fissures in earlier research [6].

Section 3 will discuss how regulations and guidelines are affected by the conducted research and studies. As will be demonstrated, the conventional approach in codes for tall buildings presents certain issues, which will be addressed in section 4.

3. Codes of practice and standards on SSI and base-level

In this section, a brief review of the different code approaches is presented in three parts. Let's start with the introduction of the last part in which the approach of Iranian standard 2800, IS2800, for buildings with podium is explained. Due to the similarities of the IS-2800 standard with the ASCE7-16, the explanations related to this regulation are presented in a separate part, and in the first part, a brief overview of the approach of other guidelines of different countries is discussed.

3.1 Codes of practice and standards on SSI and base level

Eurocode 8 classifies soils using qualitative indicators such as stratigraphic descriptions and soil characteristics. These indicators aid in predicting how the soil-structure system will behave during earthquakes. Eurocode 8, Part 5 specifies the requirements, criteria, and rules for the seismic siting and foundation soil of structures. It also recommends the use of the SSI effect for tall structures, particularly those with high second-order effects (P-d) or deeply embedded foundations. However, the code does not provide explicit guidelines for computing SSI effects [13].

According to the Japanese standard, JSCE 15, in buildings having deeply buried foundations the consideration of the dynamic interaction effects between the structure and the soil is necessary. The analysis should include the complete structural system, including the subterranean and surrounding soil because the near-field soil in the close vicinity of the substructure levels greatly influences the response of a structural system when subjected to seismic excitation. Moreover, the code recommends the inclusion of interface elements to describe the separation and sliding of the structure and the soil to take into consideration the impact effect and the reaction of the structural system that is expected to be affected by the separation of surrounding underground soil. However, there is no reference in the code to which circumstances necessitate the SSI effects to be neglected [14].

The French seismic code PS92 (1995), is the only code that describes the explicit position of the base level, it has been defined by three categories of soil condition. As represented in Figure 2, If H_0 is the height of the tower, H_1 is the height of the podium and H is the effective height of the building:

- • $H=H_0$ if the structure is constructed on the category “a” soil with good geotechnical properties.
- • $H=H_0 + 0.5H_1$ if the structure is constructed on category “b” soil with intermediate geotechnical properties.
- • $H=H_0 + H_1$ if the structure is constructed on category “c” soil with poor geotechnical properties [15].

Elias & Khouri (2012) based on this approach and by expanding it by introducing a new constant, $\frac{1000.M.S}{E.I}$, proposed a new simple, quantitative method to locate the base level, or as they call it fixed base level [8]. The parameters used are:

M: the total mass of the slabs in the building;
S: the total surface of the slabs in the building;
E: module of elasticity of concrete, and
I: shear walls inertia in the direction of the earthquake.

3.2 ASCE considerations on the base level

According to the ASCE7-22 [16], many factors are effective at the base level location:

- The position of the ground level concerning the level of the floors;
- Characteristics of the soil adjacent to the building;
- Openings in retaining walls;
- Position and stiffness of vertical elements resistant to seismic loads;
- Position and location of seismic isolators;
- Underground height;
- Characteristics and behavior of underground walls;
- Proximity to neighboring buildings, and
- The slope of the earth's surface

It is also mentioned that if the base level is raised to the top of the retaining wall, the surrounding soil should not:

- Experience the liquefaction at the maximum considered earthquake (MCE).
- Be made of sensitive clay or weak cement soil, which may be prone to collapsing during the MCE.

If the base level is considered on the top of the foundation, ASCE7-22 suggests to use of the dynamic analysis method for the proper distribution of the seismic forces and to prevent the transmission of large seismic forces from the massive podium to the tower. However, due to the code’s limitation and determining a minimum ratio between static and dynamic shear, this issue will not solve the problem.

It has been specified that in the analysis the equivalent to soil springs should not be used, because this technique reduces seismic forces, and it is totally against conservatism.

Furthermore, it has been stated that the floor diaphragm at the base level should have considerable stiffness for migration of forces from the vertical elements of the lateral seismic force-resisting system to the wall through the diaphragm, and if the diaphragm of the floor does not have the required resistance, the base level cannot be raised. And finally, in sloped places, the base level should be considered at the lowest level of the ground.

In this part, the qualitative recommendations of ASCE7-22 are only discussed, and practical methods concerning similarities to Iranian standards are explained in the next part.

Other American guidelines have suggested more complex SSI methods, e.g. NEHRP's (2012) guideline for soil-structure interaction for building structures as shown in Figure 3. However, in this article, the use of a more practical and engineering approach is considered.

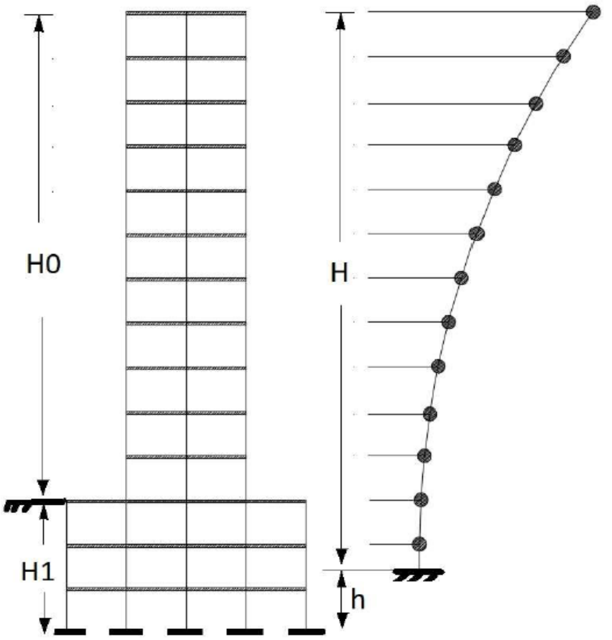


Fig. 2: Base level location by French seismic code PS92

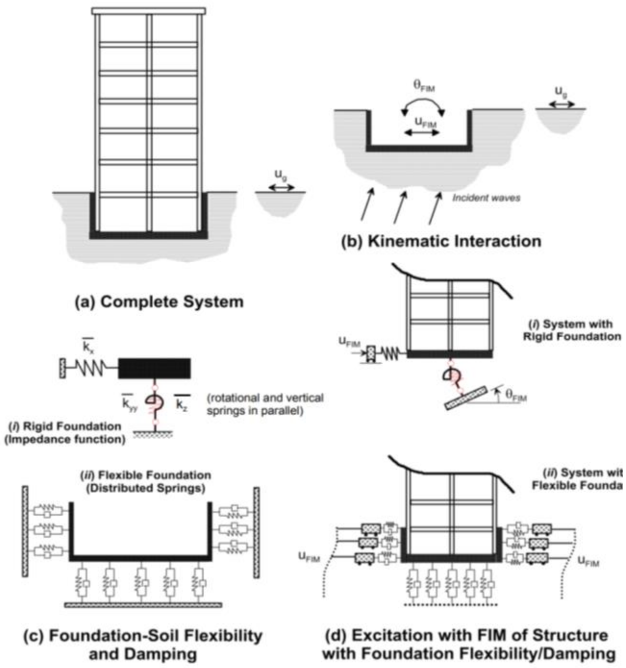


Fig. 11: Schematic illustration of a substructure approach to analysis of soil-structure interaction using either: (i) rigid foundation; or (ii) flexible foundation assumptions [17].

3.3 IS-2800 approach towards buildings with podiums

In the Iranian standard No.2800, there are not many quality recommendations similar to ASCE7-22. However, similar to ASCE7-22, there are three approaches with minor differences in IS-2800 towards buildings with podiums [18]:

1- Considering the SSI and reducing the seismic base shear due to the increase in the fundamental period of the building based on the following equation:

$$\mathbf{T}_{\boldsymbol{e}} = \mathbf{T}\sqrt{\mathbf{1} + \frac{\overline{\overline{\boldsymbol{K}}}}{\boldsymbol{K}_{\boldsymbol{y}}}\left(\mathbf{1} + \frac{\boldsymbol{K}_{\boldsymbol{y}}\overline{\overline{\boldsymbol{h}}}^{\mathbf{2}}}{\boldsymbol{K}_{\boldsymbol{\theta}}}\right)} \qquad (1)$$

Where:

T_e: Effective fundamental period of the building;
T: Fixed base fundamental period of the building;
$\overline{K}$: Fixed base stiffness of the building;
K_y: Horizontal stiffness of the foundation;
K_θ: Rocking stiffness of the foundation and
$\overline{\overline{h}}$: Effective height of the building.

It should be noted here that, unlike the ASCE7-22, the reduction of the base shear is limited only to 15% instead of 30%.

$$\Delta V_u = \left[C - \overline{\overline{C}}\left(\frac{0.05}{\beta_e}\right)^4\right]\overline{\overline{W}} \leq 0.15 V_u \qquad (2)$$

Where:

C: Fixed base coefficient of seismic forces;
$\overline{\overline{C}}$: Effective coefficient of seismic forces;
β_e: Effective critical damping of the building;
$\overline{\overline{W}}$: Effective seismic mass of the building

2 -Another effective and common solution is to reduce the effective height of the building or somehow move the seismic base level from the top of the foundation to the podium level. Unlike the ASCE7-22, in which comprehensive conditions are defined for the basic level, in the IS-2800, only two conditions are stated for the basic level:

- The retaining walls should be made of reinforced concrete and connected to the main structure, and the last floor of the podium should have considerable rigidity.
- The gap between the excavation and the retaining wall should be filled with dense compacted soil.

The level of the foundation is considered to be the closest structural floor to the compacted soil.

3- In this method, seismic lateral forces are calculated in two steps as follows:

- The flexible structure of the upper part is considered separately and with rigid supports and its seismic shear base is only calculated by the behavior coefficient of this part.
- The rigid structure of the lower part is separately considered and its seismic forces are calculated by considering the behavior coefficient of this part. The reaction forces resulting from the analysis of the upper part which is multiplied by the ratio of coefficient of behavior coefficient of two parts are added at the above level.

In this case, the significant stiffness and mass of the podium will not affect the design of the tower. And the result is completely similar to the second approach. However, there is a limitation that the fundamental period of the whole structure should be less than 1.1 times the fundamental period of the tower. Although this condition can be met easily in towers with a moment frame system, it is difficult to meet in buildings with shear walls, which almost include most tall buildings.

As observed, the first method presents numerous practical complications. In contrast, the second and third methods, while more practical and straightforward, are binary. This means they do not introduce an intermediate solution for most conditions. They strictly assume the base level is placed on the foundation, or the podium. Such conservatism in these methods is irrational when designing tall buildings, or buildings with considerable basement levels.

4. Methodology

4.1 Problem statement

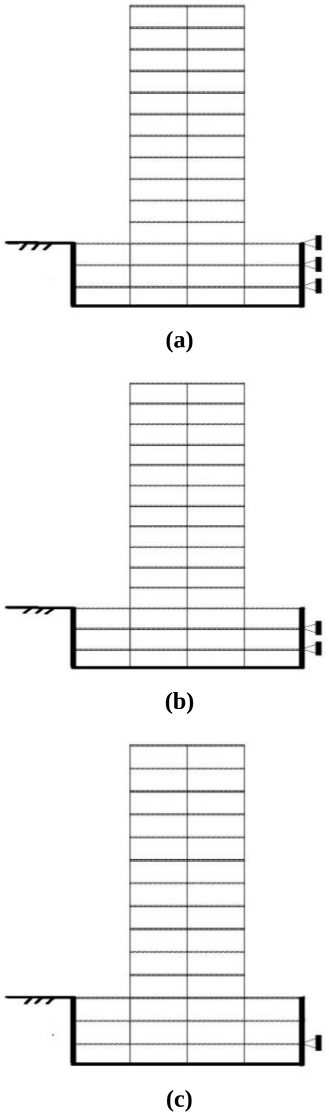
According to the contents discussed in the previous section, it can be concluded that the proposed solutions are mainly divided into two approaches, and the use of both approaches is effective only for simple and short buildings:

- Considering the SSI explicitly or implicitly, although both methods are not recommended for tall buildings due to their complexity and difficulty, which themselves have intrinsic, numerical, and computational complexities, the validation of the results provided by these methods in the particulars of these buildings will be doubted.
- Eliminating the effect of seismic forces on podium floors by using the concept of base level or combination of systems in height, which is mainly operational in buildings with a few underground stories and with moment resisting frame system in the tower.

Using the second method is a more suitable solution for practical engineering problems, but the approach of the code in this regard is binary. It has been recommended to consider the base level on the foundation level, if there is any doubt about the location of the base level, quite conservatively. This approach severely affects the seismic responses in tall buildings with substantial podiums, and its degree of conservatism is increased unrealistically. But as it is mentioned in the PS-92 and considering that the zero shear level in these tall buildings is somewhere between the top of the foundation and on top of the surrounding retaining wall, this article has presented a novel practical method based on the concept of the base level, to determine the location of the base level with a simple analytical method.

4.2 Developing the idea

As mentioned in IS-2800, the base level refers to the level in the building, and below that level, there is no movement observed in the structure relative to the ground. The absence of displacement in the structures corresponds to the concept of restraints in finite element models. In other words, it can be concluded that the base level is the fixed base support of the structure in the dynamic analysis of the structure and the seismic shear base remains constant below that level. As we know from the structural analysis, imposing displacement in any joint leads to generating internal forces in the structure, and vice versa. Therefore, annexing any constraints or restraints in joints with zero displacement does not generate internal forces in the direction of constraint and consequently does not affect the structural characteristics of the building. Hence, appending support constraints for floors below the base level should not change the dynamic response of the structure at higher levels. In other words, any change in restraint condition below the base level is considered insignificant.



(a)

(b)

(c)

Fig. 12: Schematic description of the proposed method. (a) All subterranean stories restrained, laterally; (b) The story at the top of podium released; (c) Other stories released, gradually.

Fig. 13: 3D model and a real picture from the case study building

Therefore, in this method, all the joints below the assumed base level are restrained in the lateral direction, and then by moving up or down the assumed base level, the response of the structure is investigated based on the defined benchmark criterion.

It should be noted that the piles, both vertical and battered, generally move laterally with the horizontal ground motions and have little to no impact on the level at which horizontal seismic ground motions are imparted to a building [7]. Therefore, in structures with piles, there is no need to model them in the investigation

4.3 Benchmark criteria

Various benchmark criteria can be considered to control the dynamic response of the structure, such as the fundamental period of the building, target or roof displacement, the dynamic base shear before matching with static base shear, or even the base shear at the ground or foundation level, etc. The benchmark must satisfy two important issues:

- 1. It should be solely dependent on the dynamic characteristics of the structure.
- 2. It should have a distinguishable boundary above the base level compared to below the base level. For instance, its value should remain constant below the base level but show noticeable variations above the base level.

In the next sections, in the form of a case study, a more detailed investigation will be carried out to select the appropriate benchmark criterion. Just as a summary, the distribution of the dynamic shear force at the height of the building has been selected as the appropriate benchmark criterion.

4.4 Proposed method

As illustrated in Figure 4, the initial step involves constraining the lateral displacement of all basement levels. Next, the structure undergoes linear spectral analysis (Fig. 4.a). The dynamic and static shear forces are compared, ensuring that the static-to-dynamic base shear ratio complies with relevant regulations. As previously explained, the distribution of dynamic seismic shear serves as a benchmark criterion. Consequently, a diagram representing the seismic force distribution along the structure's height—from the podium level to the roof level—is generated.

In the subsequent step (Fig. 4.b), the foundation of the ground floor is removed, and the structure is reanalyzed. The new ratio of dynamic and static shear force is recalculated, and the structure is reanalyzed using the updated scale factor for input response spectra. This process generates a new diagram of seismic force distribution. By comparing the current diagram with the previous one, any discrepancies indicate that the zero-shear level is situated on lower floors. The process continues by releasing one additional floor against lateral displacement (Fig. 4.c), repeating the previous steps. This iterative process continues until the diagrams align with each other. The floor for which constraining by restraint support or releasing lateral displacement has no impact on the seismic shear force distribution will be chosen as the base level.

5. Case study description

The case study building is an asymmetrical twin tower that is symmetrical in plan but has distinct heights; one tower is five stories shorter than the other. Two towers share a single podium and a large basement with their sister counterpart. Each tower has an area of 2500 square meters in each story, and they all sat on a single podium that is 10,000 square meters in each story. The main direction of the two towers creates an angle of 120 degrees to each other, as shown in Figure 5. The authors of this article designed this building using the Iranian standard code, numbered IS2800. This tower's lateral force-resisting system is a dual system comprised of a special reinforced concrete moment-resisting frame and special reinforced concrete shear walls.

The taller tower rises 175 meters from the foundation level. The typical height of the stories above ground is 4.5 meters, and the typical height of the stories below ground is 3.6 meters. In contrast to other stories, the heights of the first stories above and below the ground are 9 meters due to architectural concepts for considering the lobby, amphitheater, restaurant, and commercial spaces. Shear walls, as illustrated in Figure 5, are positioned on the tower's sides as well as along the stairs, elevators, and restrooms. The lowest levels have a one-meter-thick shear wall and columns with a maximum size of 950 mm x 2300 mm. The height of the main beams is 900 mm on all floors. The retaining wall thickness is 600 mm throughout all floors. Concrete has a typical strength of 40 MPa while steel has a strength of 400 MP.

For the floors, a 150 mm thick flat concrete slab with secondary beams was used. The flexural capacity of the slab in lateral load-bearing was disregarded, considering the stiffness modification factor ($m_{11}=m_{22}=0.001$ & $m_{12}=0.01$). The TBI guidelines were applied to adjust the stiffness factors of the members [19]. For example, the stiffness modification factor for coupling beams was considered a maximum of 0.15, which differs from the conventional ACI standards [20]. The stiffness modification factor for shear walls was considered in the range of 0.35 to 0.7 based on internal forces.

One of the significant challenges in structural design was meeting the criteria for maximum story drift, which determined the required cross-sectional area for shear walls. Considering the building's fundamental period of the building (greater than 4 seconds), the seismic force was calculated based on the minimum shear force criteria. In this case, the design earthquake force equaled the force required to control drift, making it more challenging to provide the necessary lateral stiffness compared to conventional buildings.

Due to the interaction between the moment-resisting frame and the shear wall, the contribution of frames to the lateral force of the structure significantly increased from the tenth floor upwards. However, in the design, the stiffness and strength of the lower floors were always greater than those of the upper floors.

Figure 5 also shows a real picture of under-construction building and a 3-model for the analysis and design of the building.

When two towers share a common podium, it becomes imperative to model them simultaneously. This approach facilitates precise analysis of their structural behavior, particularly when evaluating seismic displacement and base levels. By integrating both towers into a unified model, engineers can effectively capture interactions between the structures, including the effect of a non-rigid podium on the lateral load transfer and foundation response. In this study, three design approaches are investigated: individual design for each tower and joint design for the two towers, to assess the mutual effects between them.

The first modes of the structure are given in Figures 6–9 to help comprehend the dynamic behavior of the structure. As previously stated, special attention has been paid in the new edition of Iran Standard 2800 to the concept of rigidity in the last roof of the basement, which is one of the fundamental and vital concepts of the podium to migrate forces from the lateral load-resisting systems of the tower to the retaining walls. This idea is crucial in the design of tall structures with several stores in the basement. Although the retaining walls have continued up to the ground floor level in the above structure, a relatively large portion of the retaining walls have been cut off at this level due to architectural considerations and the need to access the amphitheater space, which is located on the negative one basement floor.

Can the base level in the basement floor be considered minus one, given the large height of basement-1, according to the usual definition of 2800? The study results suggest that the actual drift in this level caused by the earthquake force is roughly 10 millimeters. Is this drift regarded as insignificant? Is the qualitative definition used in the 2800 standard for calculating the base level applicable to all buildings? Can we be pleased with this qualitative definition of the 2800 standard, given that the height of the foundation to the ground level of this building is around 40 meters?

Given that the removal and consideration of basement floors had a significant impact on the dynamic characteristics of the structure and the design results, the authors of this article have presented an analytical method to determine the base level to answer the questions raised above. It can be noticed below.

Fig. 6: The first mode shape of the building

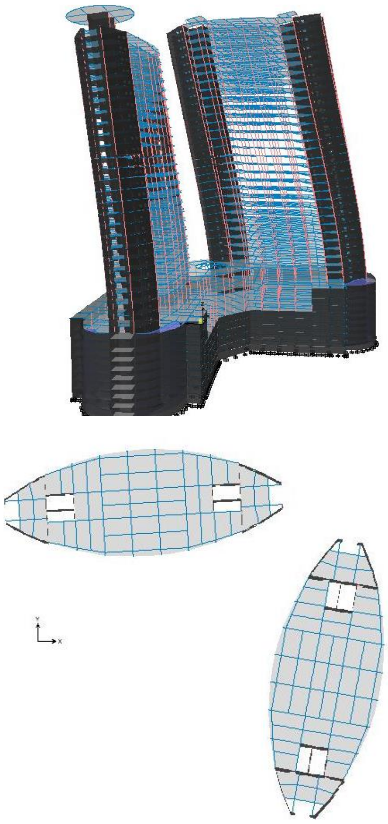


Fig. 7: The second mode shape of the building

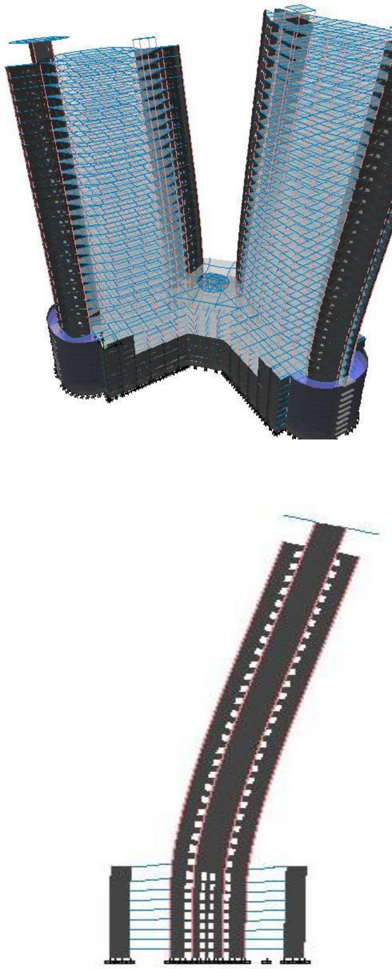


Fig. 8: The third mode shape of the building

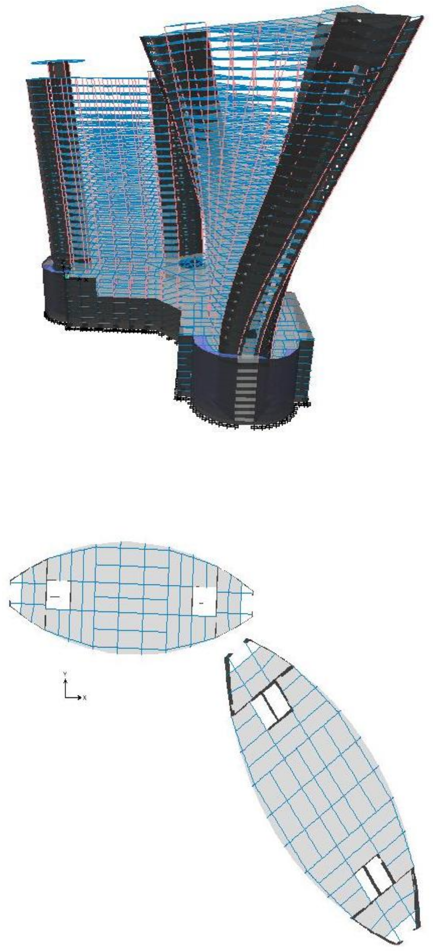


Fig. 9: The fourth mode shape of the building

6. Discussion on results

6.1 Investigating the Benchmark Criterion

Table 1 provides an overview of the building's dynamic responses based on the proposed method, considering different base levels. In this table, B1 to B6 correspond to the basement levels, where the horizontal displacement of joints is restricted in both translational directions.

As shown in Table 1, the shear modification factor ratio for the fourth to sixth floors is equal. Therefore, it is expected that these floors are below the base level. On the other hand, this ratio is also similar for the first and second floors. Although this ratio is a rational guideline, it cannot solely be used to judge the position of the base level.

Table 2 illustrates the horizontal displacement of the centers of mass for different floors of the tower. Although the absolute value is greater on the upper floors (e.g. 24 mm. from 424 to 448 at the roof), the rate of increase is significantly higher on the lower floors (e.g. 130 percent from 6 to 14 at the ground floor). It appears that the lower floors are more affected by the position of the base level due to their proximity to the base level and their drastic changes to the dynamic characteristics. In contrast, on the upper floors, the increase in the tower's height from the base level multiplied by the tilt angle results in greater displacement values, but the rate of increase is lower. Similarly, the displacement of mass centers in the floors is not a suitable benchmark for controlling the dynamic response of the structure.

Table 3 presents the dynamic shear force at various levels of the building. The results indicate that the base shear benchmark criterion across different floors is not sufficiently accurate to determine the dynamic behavior of the structure. For instance, the shear caused by the earthquake on the fifteenth floor is almost identical in all cases, while the seismic shear on the fifth floor exhibits a different pattern compared to other floors. As mentioned, the difference in shear behavior of the floors is related to their distance from the base level. In other words, the shear of floors from the fifteenth floor upwards is not affected by changes occurring below. However, the shear magnitude and even the inflection point of the diagram on the lower floors are significantly influenced by their proximity to the base level. Investigations reveal that although criteria based on floor displacement or shear lack the necessary accuracy for assessment, the criterion based on the distribution of horizontal seismic dynamic force along the building's height is suitable for benchmarking the dynamic response of the structure.

6.2 Lateral force distribution as the benchmark criterion

In Figure 10, the distribution of seismic forces in the floors of the building is shown with the assumption of base level at the top of the basement stories B1 and B2, respectively. It is obvious that the distribution of the dynamic shear forces at different stories, especially in the lower stories of the tower, is completely different from each other.

Table 8: Dynamic characteristics of different cases for base-level assumptions

	Assumed base level					
	B1	**B2**	**B3**	**B4**	**B5**	**B6**
Fundamental period of the building (Sec.)	4.36	4.40	4.43	4.47	4.50	4.51
No. of mode shapes in the analysis*	20	20	40	50	50	50
Static base shear (ton)	7675	8017	8360	8702	9078	9387
Dynamic base shear (ton)	2300	2420	2675	2915	3017	3120
Modification ratio for the base shear	3.33	3.31	3.13	2.99	3.00	3.01

* No. of used mode shapes is defined based on achieving 90% for the modal mass participation ratio.

Table 2: Lateral displacement of different cases for base level assumptions in millimeter

	Assumed base level					
	B1	**B2**	**B3**	**B4**	**B5**	**B6**
Story 30th	424	429	435	440	445	448
Story 25th	344	349	355	360	364	366
Story 20th	261	267	272	278	280	283
Story 15th	187	190	193	198	199	201
Story 10th	116	118	121	124	125	127
Story 5th	55	58	61	63	65	66
Story GF	6	8	11	14	14	14

* Reported displacement is the real nonlinear displacement at the center of mass by dynamic analysis.
** Dynamic shear base has not been increased by modification factor due to static shear base.

Table 3: Dynamic shear force of different cases for base-level assumptions in tones

	Assumed base level					
	B1	**B2**	**B3**	**B4**	**B5**	**B6**
Story 30th	215	220	240	255	260	260
Story 25th	775	790	800	820	825	825
Story 20th	1055	1070	1100	1125	1125	1125
Story 15th	1320	1335	1335	1360	1355	1350
Story 10th	1465	1510	1560	1600	1600	1600
Story 5th	1785	1765	1760	1765	1755	1745
Story GF	2300	2345	2475	2515	2495	2475

Similarly, the distribution of the dynamic response of the structure by moving the base level one more level below is shown in Figure 11. It was shown that the seismic force in the level on the top of the podium has changed very drastically and has increased by 2.7 times. This is partly due to the significant area and mass of the basement floors.

However, with the continuation of this process and moving to the lower floors, as shown in Figure there is no significant change in the results and even the force of the earthquake on the top of the podium. In other words, removing or adding support constraints on these floors will not affect the dynamic response of the structure. Therefore, it can be claimed that the displacement of the structure in basements minus three and below is insignificant. To allow a more appropriate comparison, the graph related to case 3 is included in both graphs.

As shown in Figures 10 to 12, the changes in the lower floors are significantly more distinct compared to the upper floors. This is because, as previously explained, the floors closer to the base level exhibit more pronounced and noticeable changes. However, as seen in the figures, moving away from the base level, for instance, from the fifteenth floor onwards, the impact of base level displacement on the tower becomes minimal.

Another observation from these figures is the drastic increase in earthquake forces in the top four floors of the tower. This is similar to the previous method in Standard 2800, which applies a concentrated force in addition to the triangular distribution of forces for the top floor. Interestingly, approximately one-fourth of the earthquake force is applied to the top four floors of the tower, which aligns with the concentrated force suggested by Standard 2800.

$$\boldsymbol{F_t = Min(0.07 \times T \times V, 0.25V) = Min(0.07 \times 3.8 \times V, 0.25V)} \tag{3}$$

$$\boldsymbol{F_t = 0.25V = 0.25 \times 2675 = 660\ ton}$$

here:

T: fundamental period of the structure;

V: total shear force, and

F_t: concentrated seismic force at the top of the building.

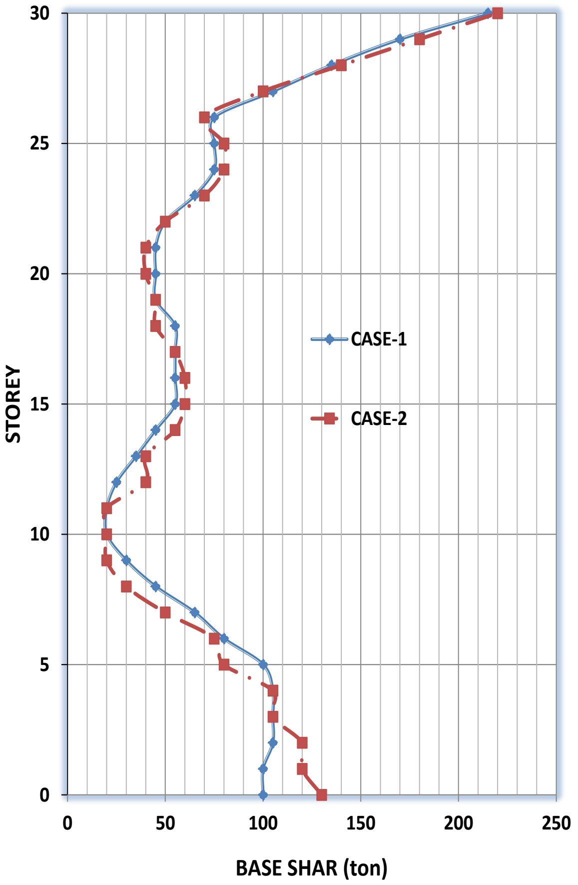


Fig. 10: Distribution of seismic forces along height of the tower in two cases: Case 1: base level is assumed to be at the top of the podium and all stories below is restrained laterally. Case 2: base level is assumed to be at the top of the basement 2, and all stories below are restrained laterally

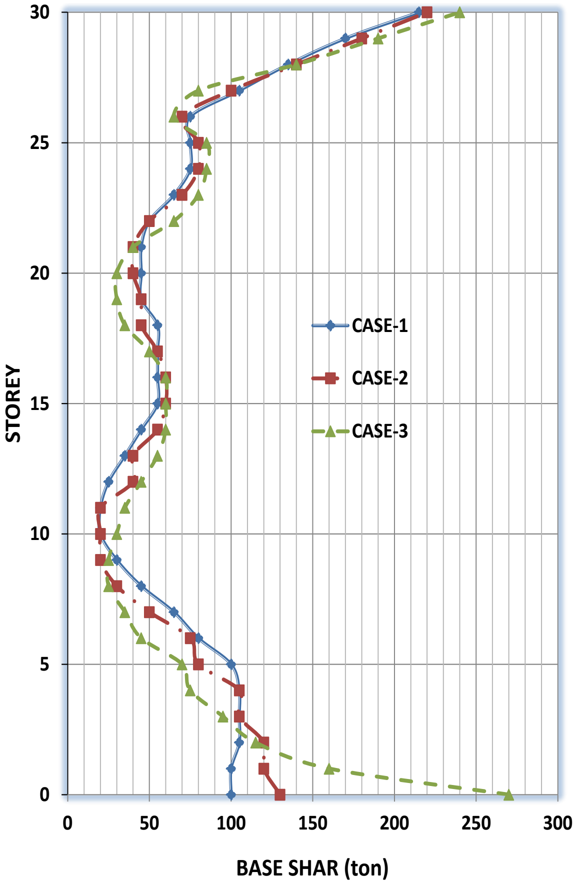


Fig. 11: Distribution of seismic forces along height of the tower in two cases: Case 3 is added: base level is assumed to be at the top of the basement 3 and all stories below are restrained laterally.

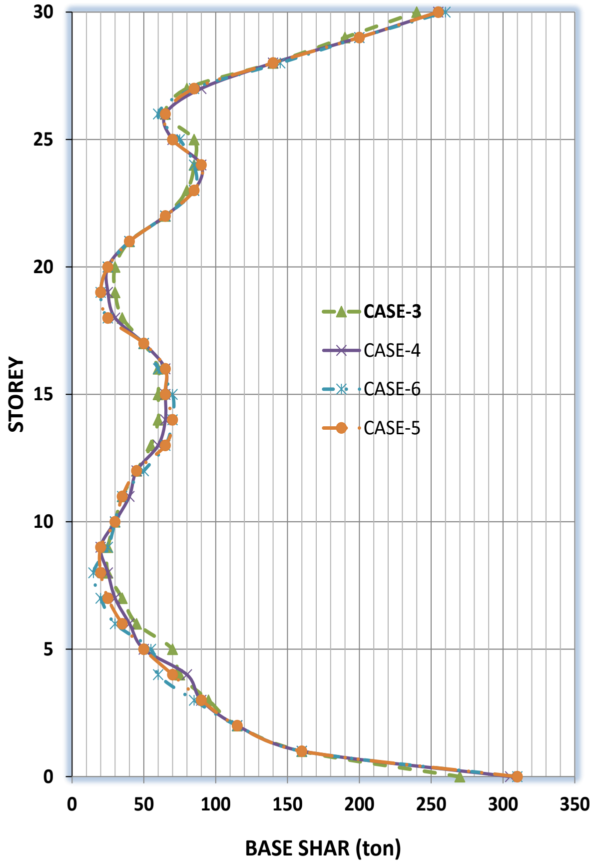


Fig. 12: Distribution of seismic forces along height of the tower in different cases: Case 3 to 6 demonstrate the base level assumption at the top of the basement 3 to basement 6 and all stories below are restrained laterally.

It is completely similar to the calculation in the code, but instead of one floor, it is applied to four floors.

It should be noted that the role of the first floor is very key in determining the basic level. As can be seen, by raising the base level, the horizontal force of the earthquake on the ground floor is greatly reduced. Because the addition of support constraints near this level prevents the free movement of this floor and the possibility of creating a dynamic force of an earthquake on this floor is decreased.

Furthermore, the effect of higher modes in the dynamic distribution of seismic earthquake force is obvious. It is obvious that the distribution of forces at the top of the tower is independent of the location of the base level, in a triangular shape on four floors

As it is clear from the graphs, the amount of whiplash force on the upper four floors is the same in all cases and is equal to 650 tons.

7. Conclusion

The concept and location of the base level play a key role in determining the force and lateral force distribution of buildings, especially tall buildings. Despite the apparent differences in the definition of the base level in different regulations, all definitions have the same concept and the insignificant displacement of the building below this level can be introduced as a key parameter in this field.

Iranian Standard 2800, in addition to the above definition, introduces some qualitative concepts to determine the location of the base level. Although these concepts can be used to determine the base level in low-rise buildings, their implementation in tall buildings is in doubt due to the complex behavior of these structures. In this article, with a case study of a high-rise building in Tehran, an analytical solution for determining the base level in high-rise buildings has been proposed.

Clear results were obtained from this research which are briefly summarized below:

- Variations in the base level of each building arise due to factors such as geometry, mass, and floor stiffness both above and below ground. A one-size-fits-all qualitative recommendation doesn’t suffice. Instead, it’s advisable to determine the base level for each building individually, particularly in tall structures. The analytical method outlined in this article, along with an assessment of seismic forces distributed throughout the tower’s height, provides a more accurate approach.
- Also, it seems that the concept of concentrated force at the top of the building is also obvious even in taller buildings, but the implementation of this force may change from a concentrated load at the roof level to a widespread load at the top stories.
- Since this method employs linear dynamic analysis, the processing time for different building types and site specifications is relatively insignificant. However, the presence of multiple basement levels necessitates repeated nonlinear analysis (e.g. about an hour for each case in a computer with normal processing speed). On the other hand, the outcome of this method is of great importance to determine the more realistic effect of earthquake force in buildings, especially tall buildings.

References

[1] CTBUH, «Council for Tall Buildings and the Urban Habitat, » 2020. [En ligne]. Available: www.ctbuh.org.

[2] FEMA-P58, Seismic Performance Assessment of Buildings: Volume1—Methodology, Washington, D.C., USA, 2018

[3] Taheri, S., & Mohammadi, R. K. (2022). Probabilistic prediction of engineering demand parameters using Bayesian inference approach. Soil Dynamics and Earthquake Engineering, 161, 107320.

[4] Taheri, S., & Mohammadi, R. K. (2022). An enhanced sequential ground motion selection for risk assessment using a Bayesian updating approach. Journal of Building Engineering, 46, 103745.

[5] Stewart, J. P., & Tileylioglu, S. (2007). Input ground motions for tall buildings with subterranean levels. The Structural Design of Tall and Special Buildings, 16(5), 543-557.

[6] Tadesse, Z. L., Padavala, H. K., & Koteswara, V. R., «Seismic response assessment of building structures with underground stories: a state-of-the-art review,» Innovative Infrastructure Solutions, vol. 7, n° %16, p. 336, 2022.

[7] Kelly, D. J. (2009). Location of base for seismic design. Structure Magazine, December.

[8] Elias, W. J., & Khouri, M. F. (2012). Identifying the fixed base location of building structures under seismic excitation. Int J Sci Res (IJSR), 3(12), 2612-2618.

[9] Jahankhah, H., Ghannad, M. A., & Rahmani, M. T. (2013). Alternative solution for kinematic interaction problem of soil–structure systems with embedded foundation. The Structural Design of Tall and Special Buildings, 22(3), 251-266.

[10] Tehranizadeh, M., & Barkhordari, M. S. (2018). Effect of peripheral wall openings in basement and number of basement floors on the base level of braced framed tube system. International Journal of Civil Engineering, 16, 1157-1173.

[11] Barkhordari, M. S., & Tehranizadeh, M. (2018). The effect of soil around the basement walls on the base level of braced framed tube system. Civil Engineering Journal, 4(9), 2060-2074.

[12] Çağlar, N., Sert, S., & Serdar, A. H. (2021). Basement-storey effect on the seismic response of RC buildings on soft surface soil. Arabian Journal for Science and Engineering, 46(11), 11291-11302

[13] EN 1998–5, "Eurocode 8: Design of structures for earthquake resistance-Part 5: Foundations, retaining structures and geotechnical aspects.," vol. 1, no. 2005, 2004

[14] JSCE 15, "Standard Specifcations for Concrete Structures - design JSCE 15. Tokyo: Japan Society of Civil Engineers," 2007

[15] PS92 Règles de construction parasismique (1995) AFNOR NF P 06-013, 1995 (https://www.icab.fr/guide/ps92/) Déc, 1995

[16] American Society of Civil Engineers (2022), Minimum

Design Loads for Buildings and Other Structures.

[17] Gcr, N. (2012). Soil-structure interaction for building structures. National Institute of Standards and Technology (NEHRP).

[18] Road, Housing and Urban Development Research Center (2014), Iranian code of practice for seismic resistant design of buildings.

[19] T. B. I. Tall Buildings Initiative, Guidelines for Performance-Based Seismic Design of Tall Buildings, University of California, Berkeley, C.A, USA, 2010

[20] ACI-318, Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary, Farmington Hills, MI.: American Concrete Institute, 2011