Identifying the Fixed Base Location of Building Structures under Seismic Excitation

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Abstract: ***The identification of the location of the fixed base at the bottom of a typical structure with a constant stiffness over its height in an earthquake zone is of extreme importance in the design of building structures. Few seismic design codes and investigators have suggested procedures that determine the location of the fixed base (the zero displacement position); these suggested methods are rather simplified and don't give the designers accurate values for the location of the base shear and maximum moment positions on the basement of a structure; this location is very important especially when using static lateral force methods for evaluating structural loads. This work provides a procedure that allows designers to locate the fixed base when subjected to seismic excitation considering the type of the soil surrounding basements. It also gives an upper and lower limit for the structure that should be chosen considering the soil-structure flexibility.***

Keywords: location of the fixed base; seismic forces; soil bearing capacity; zone acceleration factor; zero displacement; soil-structure flexibility factor.

1. Introduction

An earthquake is an oscillatory movement produced by the release of accumulated strain energy stored within the earth's crustinto seismic waves as per Shearer, (2009) and as per Stein and Wysession (2009). All buildings, big or small can be made to withstand earthquakes of a particular magnitude by considering code requirements. During an earthquake the lower portion of a building tends to vibrate as it is indirect contact with the ground and the forces of inertia tend to preserve the stability of the structure. Mitigation works: Earthquake (2014) mentions that "Earthquakes do not injure or kill people. Poorly built manmade structures injure and kill people".

The structural system designed to carry vertical loads may not have the capacity to resist lateral loads or even if it has, the design for lateral loads will increase the structural cost especially with increase in the number of stories. Considering basements in high rise buildings and the surrounding soil which is usually backfill material, the location of the base shear and the maximum moment at the bottom of the structure can significantly affect the corresponding forces applied to the above structure. In buildings that consist of various numbers of typical underground levels basement stories, the location of the fixed base or the location where the displacement just starts in the basement under lateral loads can vary depending on the soil type, substructure and superstructure rigidities or what is known as soil-structure interaction.

The objective of this research is to evaluate the effect of the interaction between basements and the surrounding soil on the estimated earthquake forces. This is done by identifying the location of the fixed base or the height of the location of zero displacement for a variety of soil types and number of underground levels. This height is the distance measured from the top of the foundation level to the location in the basement where the lateral deformation of the building starts.

2. Background

Locating the position where the lateral displacement starts in the basements locates the static base shear and maximum moment positions; these forces are needed to design the lateral load resisting elements in the structure in order to choose an adequate earthquake resistant construction method to withstand seismic activity as per Reitherman (2012). Identifying the location of the fixed base also provides information about the structural behavior and its interaction with the surrounding soil as related to global stiffness and mass.

Few seismic design codes and investigators have suggested procedures to determine the location of the fixed base; those however give simple assumptions and suggestions that are mostly based on engineering judgment. According to UBC97(1997), Section 1629.8.3, "structures having a flexible upper portion supported on a rigid lower portion where both portions of the structure considered separately can be classified as being regular, the average story stiffness of the lower portion is at least 10 times the average story stiffness of the upper portion and the period of the entire structure is not greater than 1.1 times the period of the upper portion considered as separated structure fixed at the base". Section 12.2.3.2 of ASCE/SEI 7-10(2010)applies provisions similar to UBC, and in addition, the upper and lower portions shall be designed as separate structures using the appropriate values of R (response modification coefficient) and ρ (redundancy factor). Also, the reactions from the upper portion shall be those determined from the analysis of the upper portion amplified by the ratio of R/ρ of the upper portion over R/ρ of the lower portion; this ratio shall be greater than 1.NEHRP (2009), Section C12.2.3.1also provides more stringent seismic design parameters in order to prevent the use of mixed systems that could concentrate inelastic behavior in lower stories. Kelly (2009)however, mentions that the base should be located where seismic forces enters and exit the building and if there is a doubt the base should be located at the lower elevation.

The French seismic code PS92(1995), on the other hand, is the only code that explicitly defines the location of the fixed base; it gives a location relative to three soil categories. If H_0 is the height of the superstructure, H_1 is the height of the substructure and H is the design dimension then PS92 gives:

- $H=H_0$ if the structure is constructed on high mechanical resistance category "*a*" soil.
- $H=H_0 + H_1/2$ if the structure is constructed on medium mechanical resistance category "*b*" soil.
- $H=H_0 + H_1$ if the structure is constructed on a low mechanical resistance category "*c*" soil.

Fig. 1 shows the PS92 equivalent model of the soil-structure interaction and the corresponding equivalent height *H*.

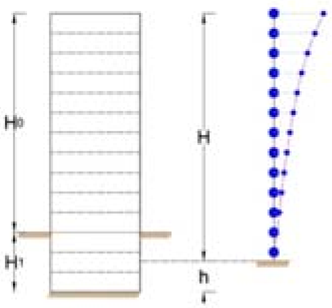


Figure 1: PS92 soil structure interaction - equivalent model

The effect of identifying the location of the fixed base is also observed when performing modal response spectrum analysis or modal time history analysis because if the mass of the substructure is relatively large and stiff (all-around retaining wall system), then it becomes difficult to capture the codes' requirement of 90 percent mass participation with the usual 10 -15 modes; a very high number of modes is then required. This issue was also pointed out by Charney(2006). Consequently, if the location of the fixed base can be identified, then the superstructure can be extended into the substructure to the specified fixed base location and the analysis can be performed from that point upwards assuming that the structure is fixed at the identified base. In addition, the location of the fixed base changes the seismic height of the building which consequently modifies the value of the allowable drift suggested by seismic design codes and by the authors of this article Khouri and Elias (2014).

This study generates a simple and empirical set of equations that can be used by engineers and designers to determine the location of the base by determining the zero horizontal displacement level using various soil and structural properties. It also provides an upper and lower limit for the soil-structure flexibility coefficient which specifies the flexibility of the structure that should be chosen considering soil-structure interaction.

3. Analysis

Finite element calculations were done using Effel software for several models and different soil types with different upper and lower structure heights. The properties used were as follows:

a. Soil bearing capacity factors were taken as follows: 0.5 Kg/cm^2 to 8 Kg/cm^2.
b. All typical Basements and typical story heights are 3m.
c. Underground basements number vary from 2 to 5; note that basements are usually stiffer than the above ground structure however in this work their geometry are modeled with the same vertical projection of the above ground structure because in buildings where the number of stories exceeds 10there is usually large vertical static loads and the basements are separated by joints as shown in Fig. 2.

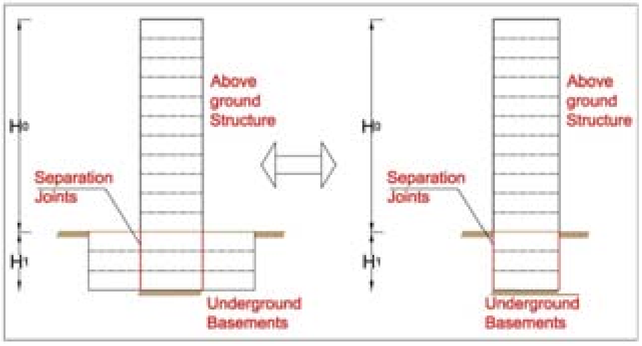


Figure 2: Separated structures

d. Number of stories 15 floors, 20 floors, 25 floors and 30 floors.
e. Shear walls inertia varies progressively from *K*to*16K* by doubling the values using *K,2K,4K…,16k.K* is taken equal to 520 x 10^3 cm^4.
f. Various slab masses were considered with a super imposed dead loads D.L. =0.4T/m^2, 0.8 T/m^2 and 1.2 T/m^2.
g. Seismic zone acceleration of 0.2g was used in the calculations of the finite element models with a seismic response spectrum shown in Fig.3.

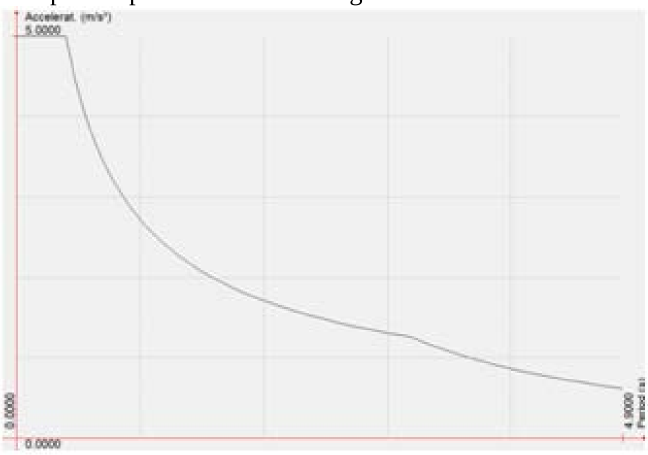


Figure 3: Seismic response spectrum used in the analysis

Note: The above parameters were used to perform the analysis, but in the generated equations the designer can use any value.

Springs were introduced in the finite element model to reflect the behavior of the soil surrounding the basement walls and the mat foundation as shown in Fig.3; the horizontal K_{sh} and vertical K_{sv} soil rigidities were approximated according to Terzaghi $K_{sv}=120q$, and $K_{sh}=(2/3)K_{sv}$ as described by Bowles (1988). It is important to note that Effel program allows only compression for the lateral springs which is the case when considering the effect of the basement surrounding soil.

Table 1: Parameter variations and total number of finite element models

q	H_1	H_0	$(\frac{1000.M.S}{E.I})$	*Total Number of F.E models*
12 values	5 values	4 values	15 values	3600

3600 finite element 3-D models were analyzed and the lateral displacements were extracted at the shear walls; a typical model is presented in Figs.4-5. The analysis was done for each and every change in the parameters mentioned in Table 1.

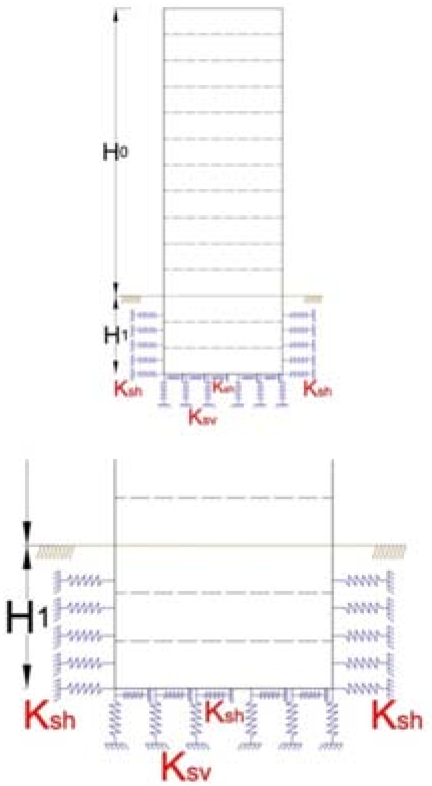


Figure 4: Typical spring model section

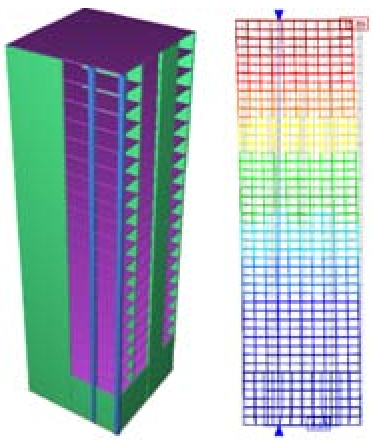


Figure 5: Structure displacement results for a F.E model

3.1 The $(\frac{1000.M.S}{E.I})$parameter and boundary limits

Analysis was done on the output data to determine the zero displacement position and find the equivalent height of the basements structure. The nomenclature used in the equations is:

- Total Mass of each typical slab structure "*M*" in (T).
- Surface of the typical slab of the building "*S*" in (m^2).
- Concrete modulus of elasticity "*E*" in (T/m^2).
- Shear walls inertia in the direction of the earthquake "*I*" in (m^4).
- Bearing capacity of the soil surrounding basement walls "*q*" in (MPA).
- Superstructure height "H_0" in (m).
- Basements total height "H_1" in (m).

The$(\frac{1000.M.S}{E.I})$ factor is a dimensionless parameter that is used in the calculation for two reasons:

1- It simplifies the step-by-step procedure to reduce the number of factors used.

2- It provides an upper and lower limit for the flexibility of the structure; a detailed description of the usefulness of the $(\frac{1000.M.S}{E.I})$parameteris explained in the following sections.

For example by fixing a value of $(\frac{1000.M.S}{E.I})$to 35.95for a building structure 10 m height (3 Floors), 15 m basements height (5 Basements) and a specified soil bearing capacity of 0.1 MPA, the finite element model shows that the position where displacement starts in the structure is equal to 5.79 meters measured from the foundation level.

This procedure was done for all the models and parameters described in Table 1 for different $(\frac{1000.M.S}{E.I})$parameters and the zero displacement output results of these models were extracted to proceed with the step-by-step method.

On the other hand, for all the models, a variation of the $(\frac{1000.M.S}{E.I})$parameter was done in order to limit the zero displacement position of the structure between the foundation level and the natural ground level; this allows a flexible soil-structure interaction behavior of the building from which the boundary limits of this factor were determined and shown in Table 2. This is why this parameter is named the soil-structure flexibility parameter.

3.2 The step-by-step procedure

The steps that were followed to generate the step-by-step procedure are presented as follows:

By changing the bearing capacity, the zero horizontal displacement level h varies linearly with q:

$$h = 10.a.q + b \tag{1}$$

By changing the total height of the basements H_1, the coefficients "a" and "b" of Eq.(1) varies linearly with H_1 as shown in Eqs.(2) and (3):

$$a = \alpha . H_1 + \beta \tag{2}$$

$$b = \gamma . H_1 + \delta \tag{3}$$

By changing the superstructure height H_0, the coefficients "α" and "β" of Eq.(2) vary with H_0as shown in Eq.(4) and Eq.(5):

$$\alpha = \alpha_1 . {H_0}^{\alpha_2} \tag{4}$$

$$\beta = \beta_1 . {H_0}^{\beta_2} \tag{5}$$

By changing the dimensionless parameter$(\frac{1000.M.S}{E.I})$, the coefficients "α_1" and "α_2" of Eq.(4) varies linearly with $(\frac{1000.M.S}{E.I})$ as shown in Eq.(6) and Eq.(7) below.

$$\alpha_1 = 0.0327.\left(\frac{1000.M.S}{E.I}\right) + 0.2515 \tag{6}$$

$$\alpha_2 = 0.0225.\left(\frac{1000.M.S}{E.I}\right) - 0.6431 \tag{7}$$

The coefficient "β_1"of Eq.(5) varies linearly with $(\frac{1000.M.S}{E.I})$ as shown in Eq.(8):

$$\beta_1 = -0.3066.\left(\frac{1000.M.S}{E.I}\right) + 0.1893 \tag{8}$$

The coefficient "β_2" of Eq.(5) varies to the logarithmic with $(\frac{1000.M.S}{E.I})$ as shown in Eq.(9):

$$\beta_2 = 0.2524.\ln\left(\frac{1000.M.S}{E.I}\right) + 0.0559 \tag{9}$$

The coefficients "γ" and "δ" of Eq.(3) vary logarithmically with H_0 as shown in Eq.(10) and Eq.(11):

$$\gamma = \gamma_1 . \ln(H_0) + \gamma_2 \tag{10}$$

$$\delta = \delta_1 . \ln(H_0) + \delta_2 \tag{11}$$

The coefficient "γ_1" of Eq.(10) varies exponentially with $(\frac{1000.M.S}{E.I})$ as shown in Eq.(12):

$$\gamma_1 = 0.137.e^{0.0943.(\frac{1000\,MS}{EI})} \tag{12}$$

The coefficient "γ_2" of Eq.(10) varies linearly with $(\frac{1000.M.S}{E.I})$ as shown in Eq.(13):

$$\gamma_2 = 0.1225.\left(\frac{1000\,MS}{EI}\right) + 0.1627 \tag{13}$$

The coefficient "δ_1" of Eq.(11) varies logarithmically with $(\frac{1000.M.S}{E.I})$ as shown in Eq.(14):

$$\delta_1 = 0.2633.\ln\left(\frac{1000\,MS}{EI}\right) + 0.8108 \tag{14}$$

The coefficient "δ_2" is a constant as shown in Eq.(15):

$$\delta_2 = -5.9244 \tag{15}$$

These equations were found using a numerical method based on the correlation between the output collected data of the zero horizontal displacement level h obtained from the analyses of the 3600 models that take the form of a dynamic three-dimensional spring mass system as shown in Fig. 1 and mentioned by Clough and Penzien (1993).

Table 2: Boundary limits for the soil-structure flexibility parameter $(\frac{1000.M.S}{E.I})$

		q=0.5 Kg/cm2		q=1 Kg/cm2		q=2 Kg/cm2		q=4 Kg/cm2	
	H0 (m) =	(1000MS/EI) Lower Limit	(1000MS/EI) Upper Limit	(1000MS/EI) Lower Limit	(1000MS/EI) Upper Limit	(1000MS/EI) Lower Limit	(1000MS/EI) Upper Limit	(1000MS/EI) Lower Limit	(1000MS/EI) Upper Limit
H1 =6m	5	39.267	40.751	44.21	45.135	50.44	50.93	57.33	57.56
	10	39.775	40.859	47.06	47.57	54.85	55.08	62.4	62.53
	15	41.835	42.626	50.16	50.49	58.4	58.54	65.96	66.017
	20	43.971	44.567	52.8	53.04	61.154	61.246	68.509	68.54
	25	45.957	46.419	55.04	55.21	63.35	63.42	70.45	70.478
	30	47.758	48.127	56.96	57.1	65.17	65.22	71.98	72
	35	49.388	49.689	58.63	58.73	66.69	66.73	73.22	73.24
	40	50.866	51.117	60.09	60.18	68	68.04	74.24	74.26
	50	53.445	53.628	62.56	62.63	70.11	70.14	75.83	75.84
	60	55.629	55.767	64.57	64.62	71.76	71.78	76.99	77
	70	57.508	57.618	66.25	66.29	73.08	73.1	77.87	77.88
	80	59.15	59.239	67.67	67.7	74.16	74.17	78.56	78.57
	90	60.6	60.674	68.89	68.92	75.05	75.06	79.11	79.11
H1 =9m	5	36.05	38.025	39.73	41.12	44.78	45.61	50.7	51.14
	10	35.32	36.96	41.6	42.48	48.77	49.18	55.93	56.11
	15	36.64	37.95	44.29	44.88	52.21	52.46	59.55	59.66
	20	38.31	39.36	46.74	47.17	54.95	55.12	62.21	62.28
	25	40	40.84	48.89	49.21	57.177	57.3	64.25	64.3
	30	41.61	42.31	50.76	51.01	59.03	59.12	65.88	65.92
	35	43.12	43.69	52.41	52.61	60.6	60.68	67.22	67.25
	40	44.52	44.99	53.88	54.04	61.96	62.02	68.33	68.36
	50	47	47.36	56.38	56.5	64.19	64.23	70.1	70.11
	60	49.16	49.44	58.45	58.54	65.95	65.99	71.42	71.438
	70	51.04	51.26	60.19	60.27	67.38	67.41	72.45	72.46
	80	52.71	52.89	61.69	61.75	68.56	68.59	73.27	73.28
	90	54.19	54.34	62.99	63.03	69.56	69.58	73.94	73.95

H1 =12m	5	34.13	36.47	36.88	38.67	40.89	42.07	45.87	46.55
	10	32.54	34.64	37.95	39.19	44.48	45.09	51.2	51.48
	15	33.27	35.06	40.25	41.12	47.79	48.17	54.91	55.08
	20	34.53	36.03	42.49	43.14	50.49	50.759	57.65	57.76
	25	35.94	37.2	44.51	45.01	52.72	52.91	59.77	59.85
	30	37.35	38.4	46.32	46.72	54.59	54.74	61.48	61.53
	35	38.71	39.6	47.95	48.27	56.199	56.31	62.88	62.93
	40	40	40.77	49.39	49.66	57.59	57.68	64.07	64.1
	50	42.37	42.95	51.9	52.09	59.89	59.96	65.95	65.98
	60	44.46	44.91	54	54.14	61.73	61.789	67.39	67.41
	70	46.33	46.69	55.78	55.89	63.24	63.28	68.53	68.55
	80	47.99	48.28	57.32	57.41	64.5	64.54	69.45	69.46
	90	49.49	49.73	58.67	58.74	65.57	65.606	70.2	70.22
H1 =15m	5	30.53	33.09	34.88	37.01	38	39.52	42.06	43.01
	10	30.63	33.12	35.29	36.87	41.2	42.03	47.48	47.88
	15	30.88	33.11	37.22	38.39	44.37	44.9	51.26	51.49
	20	31.79	33.74	39.25	40.15	47.02	47.39	54.06	54.21
	25	32.93	34.62	41.15	41.85	49.23	49.51	56.24	56.35
	30	34.14	35.6	42.88	43.44	51.11	51.32	58	58.09
	35	35.35	36.6	44.46	44.92	52.73	52.9	59.47	59.53
	40	36.54	37.63	45.88	46.26	54.14	54.28	60.71	60.76
	50	38.76	39.6	48.37	48.65	56.5	56.6	62.69	62.73
	60	40.78	41.44	50.48	50.69	58.4	58.48	64.22	64.25
	70	42.6	43.13	52.28	52.45	59.97	60.03	65.44	65.466
	80	44.24	44.68	53.85	53.99	61.29	61.34	66.43	66.45
	90	45.74	46.1	55.23	55.34	62.42	62.46	67.26	67.27

4. Design Procedure

In order to proceed with the design, the first step is to determine the soil structure flexibility parameter $(\frac{1000.M.S}{E.I})$. This parameter defines the type of the structure's displacement function. It can be used to provide lower and upper limits of soil-structure flexibility. As shown in Table 2, this parameter increases when the soil bearing capacity factor increases which indicates that the more the soil is rigid the more the building structure should be flexible to allow structural movements without any failures when an earthquake occurs.

This makes $(\frac{1000.M.S}{E.I})$parameter not only simplifies the step-by-step procedure to find the location of the fixed base, but also it is useful in selecting an adequate structural design depending on its mass "*M*", slab surface "*S*", modulus of elasticity "*E*" and shear wall inertia "*I*". A range of soil-structure flexibility parameter can be identified for any structure; the actual parameter $(\frac{1000.M.S}{E.I})_{actual}$for any building should have the following range:

Lower Limit for $(\frac{1000.M.S}{E.I}) < (\frac{1000.M.S}{E.I})_{actual} <$ *Upper Limit for* $(\frac{1000.M.S}{E.I})$ (16)

Table 2lists the range for any structure by providing upper and lower limits for the soil-structure flexibility parameter as a function of the soil bearing capacity *q*, the height of the substructureH_1 and the height of the superstructure H_0. It is important to note that part of the results was not listed in Table 2 due to the fact that inter values can be interpolated and outer values can be extrapolated keeping in mind that all the results of the 3600 runs were considered in generating the equations.

When $(\frac{1000.M.S}{E.I})_{actual}$does not fall within the acceptable limits given in Table 2, the design should be rejected and a variation in the properties of the building structure is required to allow a flexible behavior. This variation can either be by changing the mass *M*of the typical slab (changing its thickness or its super imposed dead loads), orby changing the shear walls inertia *I* in the direction of the earthquake. Also if architecturally allowed, changing the slab surface area *S* can change the value of the flexibility factor.

After finding the $(\frac{1000.M.S}{E.I})_{actual}$within the acceptable limits, and given H_0, H_1 and *q*, the procedure to find the zero horizontal displacement level or the location of the fixed base can be presented as follow:

<u>*Step 1:*</u> Check if the ratio $(\frac{1000.M.S}{E.I})$ satisfies the boundary conditions given by the Eq.(16) where the values of *Lower Limit for*$(\frac{1000.M.S}{E.I})$ and *Upper Limit for* $(\frac{1000.M.S}{E.I})$ are given in the tables that can be found in the Table 2.

<u>*Step 2:*</u> Find the coefficients $\gamma_1, \gamma_2, \delta_1$ and $\delta_2$from Eqs. (12)–(15), respectively.

<u>*Step 3:*</u>Find the coefficients γ and $\delta$from Eqs. (10) and (11), respectively.

<u>*Step 4:*</u> Find the coefficients $\alpha_1, \alpha_2, \beta_1$ and β_2 from Eqs. (6)–(9), respectively.

<u>*Step 5:*</u> Find the coefficients α and $\beta$from Eqs. (4) and (5), respectively.

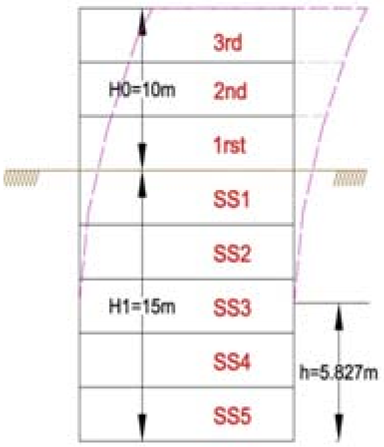
<u>*Step 6:*</u> Find the coefficients a and b from Eqs. (2) and (3), respectively.

<u>*Step 7:*</u> Find zero horizontal displacement level *h* from Eq. (1).

An example presented in Table 3 of a building containing three stories above ground level H_0=10 meters, five basements below ground level H_1=15 meters surrounded by a soil with a bearing capacity equal to 0.1 MPA = 1 Kg/cm^2, this building has a typical floor surface equal to 400 m^2 and four shear walls 3m x 0.25 m each in the direction of the earthquake in a 0.2g seismic; this example shows that the result of the zero horizontal displacement level is equal to 5.82 meters which is similar to the output of the example shown in Section3.1.

Table 3: Example applying the design procedure

Slab Thickness(m)=	0.22				
D.L (T/m2)=	0.7	Total Load(T/m2)=	1.728		
L.L (T/m2)=	0.5				
M (T)=	691.2				
S(m2)=	400				
fc28(MPA)=	30				
Ec(T/m2)=	3417956				
Thickness of Shear Walls(m)=	0.25				
Width of Shear Walls(m)=	3				
Number of Shear Walls=	4				
Inertia of Shear Walls(m4)=	2.25				
1000.MS/EI=	35.95				
Super Structure H0(m)=	10				
Lower Structure H1(m)=	15				
Soil Bearing Capacity(Kg/cm2)=	1				
α1=	1.427107962	α=	2.0906	a=	-67.452
α2=	0.165804561				
β1=	-10.83337281	β=	-98.81		
β2=	0.960038605				
γ1=	4.065084538	γ=	5.011	b=	73.2795
γ2=	-4.349189883				
δ1=	1.75398421	δ=	-1.886		
δ2=	-5.9244				
Equivalent Basement Displacement Position (m) h= a.q+b			5.8275	m	



5. Conclusion

Due to the fact that the location where displacement starts in the basement was not explicitly considered by researchers and seismic codes, the objective was to come up with a design procedure that can calculate the location of the fixed base for any building sitting on any number of underground levels. Consequently, the dynamic effect of the surrounding soil on the basement structure was investigated in order to determine the location of the fixed base or the location where the displacement starts in the sub-structure.

A modeling campaign was done on various models. Variations were done on number of underground levels, number of stories, mass of a typical slab and its area, lateral stiffness of the buildings and the soil type surrounding the basements.

Evaluation of the results showed that:

- The position of the displacement of the building *h* tends to increase from zero to H_1 when the soil bearing capacity increases; this shows that for a rigid soil $h \rightarrow H_1$ and the sub-structure behaves like having a box-effect similar to what is described in UBC97 designers' assumptions.
- When the structure's height H_0 increases, the position of the displacement of the building *h* tends to decrease to a lower level in the substructure; this means that an increase in the flexibility of a structure pushes the zero horizontal displacement level to a lower level closer to the foundation level.
- When the basement height H_1 increases, the zero horizontal displacement level *h* increases to a higher level in the sub-structure towards the natural ground level; this is due to the fact that the soil and the basement structure behave as one rigid unit leading to an increase in the zero horizontal displacement level far from the foundation level.
- The sub-structure flexibility has a significant effect on the tower response to earthquake loading. Results show that the soil-structure interaction could have a significant effect on the location of the fixed base as well on the

structure drift which can significantly modify the value of the allowable drift suggested in seismic design codes.

Designing structural engineer can make use of this procedure to evaluate his structure and determine the corresponding location of the fixed base; one can also check if the structure under consideration falls within the upper and lower limit of the soil-structure flexibility parameter suggested in this work. Finally, the step-by-step procedure and the flexibility parameter suggested by the authors can serve as a starting point from which the designing engineer would understand the behavior of his structure and check if it falls within the allowable flexibility limits in order to achieve a better design.

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