EARTHQUAKE-RESISTANT DESIGN OF TALL BUILDINGS WITH BASEMENT AND DEEP FOUNDATION ON SOFT SOIL

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Abstrack

The actual dynamic response of tall buildings on soft soil against earthquake loading is a very complicated one. The desire to have in-elastic responses of the superstructure's structural elements while maintaining the response of the underground structural system remain elastic is not easy to model even with the current advances achieved in available non-linear dynamic structural analysis commercial software. Thus, in this study a parametric study of dynamic behavior of tall structural tower on soft soil are presented which used four type of soft soils configuration representing the condition in Jakarta and Surabaya. The soil structure interaction option using elastic vertical and lateral spring constants were utilized to account for the dynamic contribution of the soft soils on the lateral resistant of the deep foundation system. The result were used to derive the indication on what should be the problem encountered. The conclusion were then used to formed necessary basic concept on the design of earthquake-resistant of tall building with basement and deep foundation on soft soil. The use of available Non-Linear Soil-Structure Interaction Software should be tempered with caution. At best the result will only give indication on the actual behavior of the structure and depend heavily on the accuracy of the non-linear characteristic of the material and elements considered and assumed for the analysis. While the result shows that ground fixity level provide conservative result for the superstructure, the reverse is true for the deep piling foundation system. Large lateral deformation of the foundation system were observed indicating the possible significant reduction to the actual load carrying capacity of the piles. Mass dan rigidity of the basement seems to play an important part of the load transfer capability of the whole structure and hence should be carefully review together with the architects.

Keywords: Tall building, soft soils, earthquake-resistant, performance based, level of fixity, lateral deformation of the roof, lateral deformation of the foundation base, reduction of load carrying capacity of piles, practical guidelines of design steps for practicing engineers.

Abstrak

Respon dinamik aktual dari bangunan tinggi pada tanah lunak terhadap beban gempa merupakan masalah yang rumit. Keinginan untuk mendapatkan respon *in-elastik* dari bangunan atas sementara respon dari bangunan bawah tetap elastik merupakan hal yang sulit untuk dimodelkan sekalipun menggunakan perangkat lunak canggih yang terbaru. Dalam studi parametrik ini, perilaku dinamik dari struktur tower tinggi pada tanah lunak dipresentasikan dengan menggunakan empat tipe dari tanah yang mewakili kondisi tanah di Jakarta dan Surabaya. Opsi interaksi *soil-structure* digunakan dengan menggunakan kekakuan vertikal dan lateral yang dipakai untuk memperhitungkan kontribusi dinamik pada tanah lunak di dalam ketahanan lateral dari sistim pondasi dalam. Hasil yang ada akan digunakan untuk menunjukkan indikasi problem yang terjadi pada struktur. Kesimpulan perlu diambil untuk mendapatkan konsep dasar yang perlu dalam merencanakan bangunan tinggi tanah gempa dengan basemen dan pondasi dalam pada tanah lunak. Penggunaan dari *non linear soil structure* interaksi harus dipakai secara hati-hati. Hasil maksimal hanya akan memberikan perilaku aktual dari struktur dan hal ini tergantung sekali terhadap keakuratan dari karakteristik non-linier dari material dan elemen yang dipakai serta asumsi analisis. Hasil analisa menunjukkan bahwa *ground fixity level* memberikan hasil yang konservatif pada struktur atas, kebalikannya benar untuk sistem pondasi dalam. Deformasi lateral yang besar pada sistem pondasi yang diamati memberikan hasil kemungkinan reduksi dari gaya aktual pada pondasi. Massa dan kekakuan dari *basement* sepertinya menunjukkan hal yang penting dalam mentransfer gaya ke seluruh struktur dan harus direncanakan secara hati-hati bersama-sama dengan arsitek.

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Kata kunci : Bangunan tinggi, ketahanan gempa, *performance based*, *level of fixity*, deformasi lateral pada atap, deformasi lateral pada pondasi, reduksi dari gaya terhadap kapasitas tiang, *practical guidelines of design steps for practicing engineers*

1. INTRODUCTION

The actual dynamic response of tall buildings on soft soil against earthquake loading is a very complicated one. The desire to have in-elastic responses of the superstructure's structural elements while maintaining the response of the underground structural system remain elastic is not easy to model even with the current advances achieved in available non-linear dynamic structural analysis commercial software.

For structural engineers, the common available design practices started with the assumption that the fixity level of the superstructure maybe assumed at ground level. Design of the superstructure was then carried out using the standard procedure of strength design method for live safety design concept of earthquake-resistant building. Design of the basement and the supporting foundation system were then carried out by applying the adjusted load from the superstructure assuming that the system should remain elastic to exclude the possibility of excessive structural damages on below ground structural elements. In the case of soft supporting soils, one of the most common questions pop up in the structural engineer's mind is whether it is still safe to treat the basement and deep foundation separately from the total structural system and each element may still be designed accordingly.

The uncertainty on the most appropriate procedure of how the total building should be modeled and designed started indirectly from the fact that most references available on the subject (Fintel, 1985; Khan, 1985; Derecho et al., 1985; Paulay et al., 1992; Naeim, 2001; Filippou et al., 2004; Bertero et al., 2004; Garcia et al., 1997) assumed that the example buildings are fixed at ground level. The non-elastic nature of the response of the supporting soft soil interaction against the deep foundation elements, the case where significant depth of the upper part of the supporting soils is soils with average N-SPT value $<<$ 15 or average shear wave velocity $<<$ 183 m/s, certainly do not lend to fill the profile of ground level fixed end behavior of the superstructure assumed.

Considering the logic underlying the above standard procedure, the overall design concept seems to be alright. However questions remain on several issues, including the followings:

1. Shouldn't the actual level of fixity of the building dictate the natural period of the building and hence the value of related design base shear? What is the "save" option and how "costly" should it be?
2. What is then the proper limit of the roof lateral deformation, a value commonly used to measure the possible damage level of the superstructure structural elements? This will be a very important issue if we are opting to choose performance based design concept for the whole building.
3. Why can't we just use the available commercial structural design software option of non-linear soil-structure interaction to modeled the dynamic response and designed the whole structure at one go?

This paper submit practical explanation to the above three questions. Recommendation and practical conceptual guidance for practicing structural engineers on how to reasonably counter this complicated problem were also submitted. Caution should be exercised in setting the performance target goals for the case of performance based earthquake design since specific accurate target criteria is still not an easy thing to set. Design after all is a complicated mixture of art and engineering. Thorough understanding of what has been mastered and what is yet to be understood should become the guidance of every decision made. In most difficult cases like this particular subject, no single set of rule may define and accepted as the one and only criteria to the problem. Proper judgments, guided by seasoned related experiences, should rule.

2. CASE STUDIED

In the following the three questions raised earlier will be conceptually discussed and reviewed.

2.1 Level of Fixity of Superstructure

Surono and Hoedajanto (Surono et al., 2006) show that the degree of softness of the supporting soil does significantly alter the position of the possible fixity level of the tall superstructure on soft soil under earthquake loading, see Figure 1. Consequently the value of fundamental period of the building and the base shear at ground level will also be different as shown in Table 1 below.

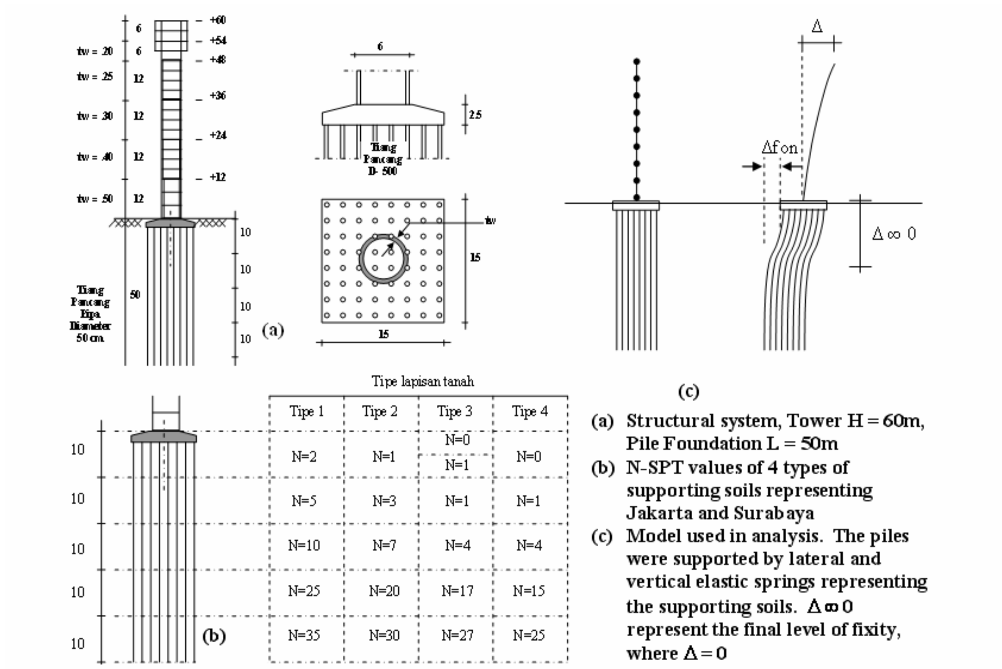

Figure 1. Technical Description of the Case Studied

Table 1. Result of Analysis Assuming Linear Spring Constant for Lateral Soil Resistant

Soil Type	Fundamental Period (s)	Max Internal forces on top of pile			Possible level of fixity (m)	Δ_{found} (mm)	Δ_{roof} (mm)	Depth of very soft top soil (m)
		M (kN.m.)	V (kN)	N (kN)				
1	3.21	139	91.3	675	- 5	47.5	244	10
2	3.31	133	75.0	658	- 8	62.4	254	15
3	4.87	130	25.6	637	- 9	180	246	15
4	8.50	130	19.2	552	- 24	436	150	15

Analysis of the superstructure alone (fixity at ground level) give Fundamental Period T of about 1.38 sec., Base Shear V = 4470 kN (about 93 kN per pile), M = 173000 kN.m, N = 12000 kN, and Δ_{roof} = 270 mm. Upon applying the external forces to the foundation, Δ_{found} for case 1, 2, 3, and 4 are 23.3 mm, 36.6 mm, 123 mm, and 360 mm respectively.

The case studied showed that:

1. Except for the value of Shear force V acting on the foundation (represent the value of base shear acting on the superstructure), the bending moment and the axial force for all cases considered do not differ too much,
2. The assumed fixity at base gives conservative result for the case of Base Shear V and Total (Roof) Drift Δ_{roof}. While technically this conservative result looks better from the design point of view, it should be carefully considered if consequently it leads to excessive construction cost,
3. Considering the result of the foundation lateral deformation, which represents the possible unfavorable condition for the total foundation system, care should be taken to ensure that no failure of the piling system may occur due to excessive lateral movement of the upper part of the pile. The design of the pile should consider the effect of P-Δ action which may leads to much lower useable axial capacity of the pile.

2.2 Limit of Lateral Roof Deformation

The roof lateral deformation directly represents the level of damage experienced by the building particularly the upper structure. This is an important issue for the case of Performance Based Design where building damages become the main consideration for design target performance. Result of the analysis shows that the common assumption of fixity at ground level leads to a conservative design and hence should be welcome. Caution however should be raised since it underestimates the lateral deformation for the foundation system. The result may become worse if instead of elastic spring constant an in-elastic spring characteristic were used for the analysis. The case need further detail studies and investigations.

2.3 The Use of Available Non-Linear Soil-Structure Interaction Software

While it is true that the advancement achieved in several commercial structural design software is outstanding, the fact remain that at best they are accurate only within the basic assumptions set for non-linear behavior of the materials and elements considered. For the case of the response of soft soil due to ground shaking experiences during earthquake loading, the level of strain experienced during the whole loading dictate the cyclic behavior the response. To date the full understanding of such case is still under study (Irsyam). Limited insight to the case maybe obtained from Chapter 19 of ASCE 7-05 Standard (ASCE 7-05, 2006) on “Soil Structure Interaction for Seismic Design”, pp. 201 - 203.

Considering all the above, the best way a practicing engineer can do is to perform both elastic and in-elastic analysis and try to physically understand the ramification of the whole process of the analysis, especially on setting the assumption for the material properties of the structural elements, including the spring characteristic of the supporting soils. Understanding that the basic concept of structural design in this case is to provide a reasonably safe structure within the current state-of-the-arts of design technology, bracketing the result of the analysis seems to be a safe and reasonable way out. Safety however should be carefully judge and measured to construction and maintenance (including repair) cost. This is where the concept of Performance Based Design can be utilized to its optimum. Target Performance should then be a matter of mutual agreement among all concern, most importantly the owner and potential users of the building.

3. CONCLUSION AND RECOMMENDATION

Based on the above limited studies, the following conclusion and recommendation maybe submitted:

1. The assumption of fixity at base level in most cases give a conservative result for the upper structure but may significantly under estimate the design requirement for the foundation system

as a whole. Since conceptually any kind of failure is not desirable for any part of the structure below ground, it is imperative that a more detailed and thorough studies on this problem should be carried out before a designer settle for his final detailed design. Safety, tempered with caution on its cost implication, should be the prime motivation of his decision.

2. To ensure that good fixity may be obtained at the junction of the upper structure and the basement and foundation system, especially to ensure that enough mass (compared to the mass of the upper structure) and rigidity are present at the basement part of the structure. Structural engineers should help the architects to design the size and the structural system of the basement. One of the important things to do is to decide the size and thickness of the base slabs. This is where the initial transfer of the action from the upper structure to the foundation system happened. The concept of maintaining all of the below ground structural elements remain elastic should be kept in mind at all time.

3. The design of the vertical structural elements of the basement should consider the maximum forces experienced if the level of fixity is not at ground level. In this case the practical practice is to consider the result of the analysis if the level of fixity at basement floor level. Hence if we have 2 basement floor levels, we should also consider fixity at B1 and B2 level. Choose the maximum internal forces to design the element considered.

4. Choosing the proper element and material for the deep foundation system is very important. Lateral rigidity of the pile foundation system should be considered and choosing a more rigid system, in this case larger diameter of piles seems to be the better solution to the problem.

5. The calculation of the actual axial pile capacity should be carefully carried out considering the overstrength capacity of the vertical components of the superstructure at ground level and the possible maximum lateral deformation of the foundation system (P-Δ effect).

6. Detailing of the upper section of the pile should consider confinement requirement set for columns on soft story cases.

7. This study should be used with caution and may not be considers as a final indication of what may happen to the similar cases. It is entirely possible that different structural configuration may leads to significantly different results.

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