UDC 539.3

# AN ANALYSIS OF RAFT THICKNESS IN HIGH-RISE BUILDINGS - CASE STUDIES

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**Abstract.** This study shows that the raft thickness is depended on foundation system, Young modulus of soil right under the raft and number of floors of superstructure, and explains very well the case of thick raft of ICC Tower, thin raft of Dubai Tower and reasonable raft thickness of Incheon Tower.
**Keywords:** Piled raft, Raft, Pile group, Soil-structure interaction, Case study, Settlement.

## 1. Introduction

While designing ofthe superstructure, in practice the structural engineers neglect the behaviour of foundation system, they assume that the raft should be absolute rigid. On the other hand, the geotechnical engineers in designing of the foundation system, only take internal forces from the superstructure design to analyse the foundation, they may not care about the behaviour of superstructure after its designing. Meanwhile, one of targets of foundation design is displacement, especially differential displacement - the one of fixed conditions of superstructure to the foundation. The differential displacement (also called deformation of raft) is the reason in redistribution of internal forces of the superstructure, this had changed the condition of the fixity of the structural engineers. The changed internal forces in superstructure at column feet had also changed the displacement as calculated by geotechnical engineer. Therefore, it is necessary to control the raft deformationin order to maintain the fixed conditions. Niandou & Breysse [1] recognized thatdesigning of superstructure, the raft should be infinitelyrigid in comparison with the superstructure, on the other hand the raft is more or less flexible as compared with the subsoil, the model in this case is when $h^3/k_0$ ($h$ - raft thickness, $k$ - pile stiffness). For the design of piles, the geotechnical engineerassumes that the load from superstructure is evenly distribute for all piles, in this case $h^3/k_\infty$.One can recognize that thetwo cases as mentioned above are of course not compatible, in designing of superstructure and foundation system.

GB 50007 - 2002 stated that the raft thickness is designed based on the criteria of the bending and punching capacity, and usually depended on superstructure. Tomlinson [3] proposed that the raft thickness should be designed as rigid slab under point forces from piles. Poulos [3] give four criteria for the raft design, there are: maximum moment, maximum shear force, maximum contact pressure and local displacement under the raft. Fig. 2 illustrates the relationship between the raft thickness and number of floors of 31 statistic buildings constructed in Vietnam and over the World. It can be recognized that the thicknesses of rafts are very large, it varies from 1.5 to 8 m. With the thickness, the bending and punching of the raft is very large, but the construction cost is also large. Therefore the question is, how the raft thickness should be designed rationally, so it can satisfy the fixed condition of the superstructure and the flexible condition in designing of the raft.

There are a lot of researches for the effect of pile group on the raft thickness, for example: Tan et al (1996), Maybaum et al (200), Poulos (2001), Chow et al (2001), Oh et al (2006), Rabiei (2009), Vasudev & Unikrisnan (2009), Ziaie – Moayed et al. (2010); Or the effect of subsoil on the raft thickness as: Thangaraj & Ilamparuthi (2009), Oh et al. (2006), Nandou & Breysser (2005); Or the effects of superstructure on the raft thickness, as: Meyerhof (1947), Sommer (1957), Grasshof et al. (1957), and Thangaraj & Ilamparuthi (2009). From the researches, one can recognize that the raft thickness is depended on three groups of factors: superstructure (number of floors, stiffness, distance between columns, etc), pile group (length, diameter, amount, configuration and so on), subsoil (Young modulus at the tip and top of piles).

## 2. Analysis of the effects on raft thickness

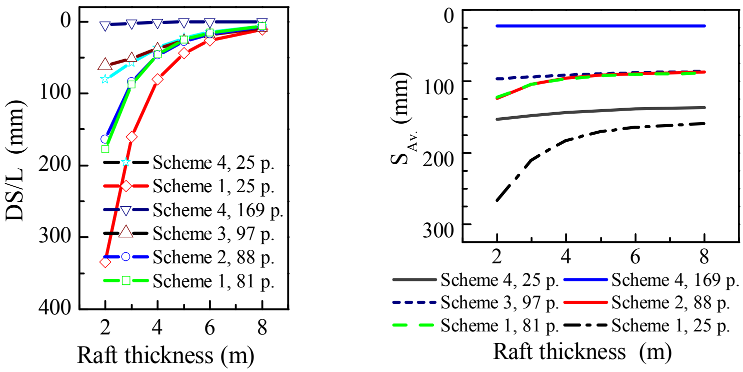
This study usedcomputer code PRABS (Piled Raft Analysis with Batter piles), wrote by Kityodom P. &Matsumoto T [4] to analyse a model of high-rise building, in comparision with the statistical data from 26 buildings constructed in Vietnam and over the World. The detail was described in Chau Ngoc An & Cao Van Hoa [5].

### 2.1 The effect of foundation structure

Settlement of subsoil, displacement of foundation system are related with the displacement and deformation of the raft, they have the same value at the bottom surface of the raft. It is recognized that there are average displacement and differential displacement. But the differential displacement is related with the deformation and the bending moment of the raft. In analysing of raft, the differential displacement is the main target.

The analysis of the effect of the foundation system, the superstructure of the model is keeping unchanged while the pile configuration and the raft thicknessis putting changed, similar to [6].

Fig. 1(a) shows the relationship between the differential displacement with the raft thickness, what isincreasing from 2 m to 8 m, in cases of various pile configurations (Scheme 1 to Scheme4) and various pile diameter. It can be recognized that with increasing of the raft thickness, the differential displacement at all scheme of pile configuration and pile diameter tend to decrease to zero value. The raft thickness at all pile configuration schemes can reduce the differential displacement strongly, it can be compensated for error pile schemes, pile defect and other error. As the more rational pile configuration sheme, the more homogenious subsoil, then the raft thickness do not effect significantly on the differential displacement [1]. Fig. 1(b) shows that the raft thickness do not affect on the average displacement.




(a) (b)

Fig. 1. Effect of raft thickness on displacement

Inshort, thelargethicknessofraftcanreducethe differential displacement whenever the rational pile configuration scheme is impossible.

**2.2 Theeffectofsuperstructure**

The effect of number of floors (load) on displacement is mentioned by many authors such as: Tran&Diep (1990), Tomlinson (1994), Diep T.T. (1995) [7]. In order to verify the effect, PRAB is used to calculate the displacement at raft's level of the above models, being equivalent to building of 30, 40, 50 and 200 floors. In this analysis, our concern is about the differential displacement, is not average displacement, therefore there is no need to re-design any pile group and raft, meaning that we keep the pile group stiffness against average displacement of the foundation.

The curve in Fig. 2 shows the relationship of raft thickness and number of floors of statistics buildings. It clearly shows that the superstructure affects greatly on the number of floors of a building.

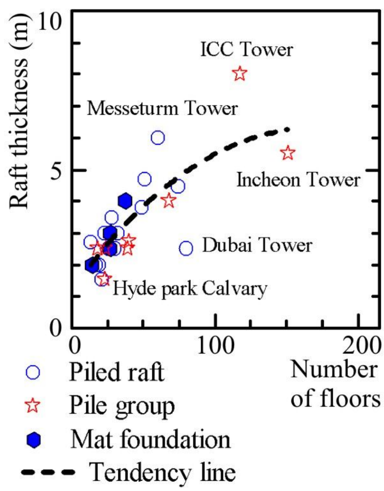



Fig. 2. Relationship between raft thickness and number of floors from 26 statistic buildings

Fig. 3(a) shows that the higher a building, the greater displacement. If we cannot choose a suitable pile's configuration, it is necessary to design a thick raft in order to meet the allowable displacement. The result in Fig. 3(b) shows the relationship of number of floors and raft thickness with allowable displacements of 0.2% and 0.05% accordingly. Curves in both Fig. 2 and Fig. 3(b) are relatively the same, show that the raft thickness increases when number of floors increase.

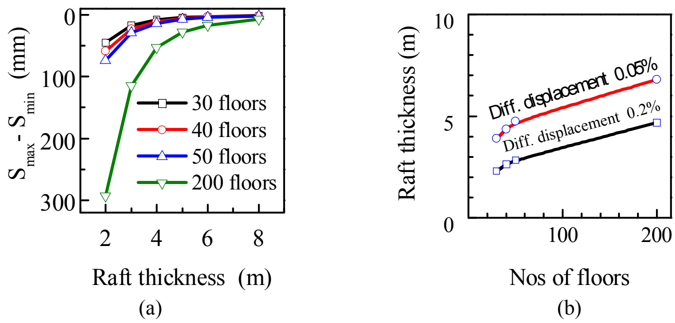



Fig. 3. Relationship between raft thickness and number of floors

In short, the raft thickness is depended on number of floors, as with conclusions of Tran & Diep (1990), Diep T.T. (1995), Tomlinson (1994). When number of floors increase from 30 to 200, the raft thickness increases around 2.5 times.

**2.3 The effect of Young modulus of soil**

During the calculation of pile internal forces and soil pressure around piles by PRAB, it can be recognized the exist of a neutral plane somewhere between top and tip of piles, see Fig. 4. This conclusion is matching well with Fellenius research [8].

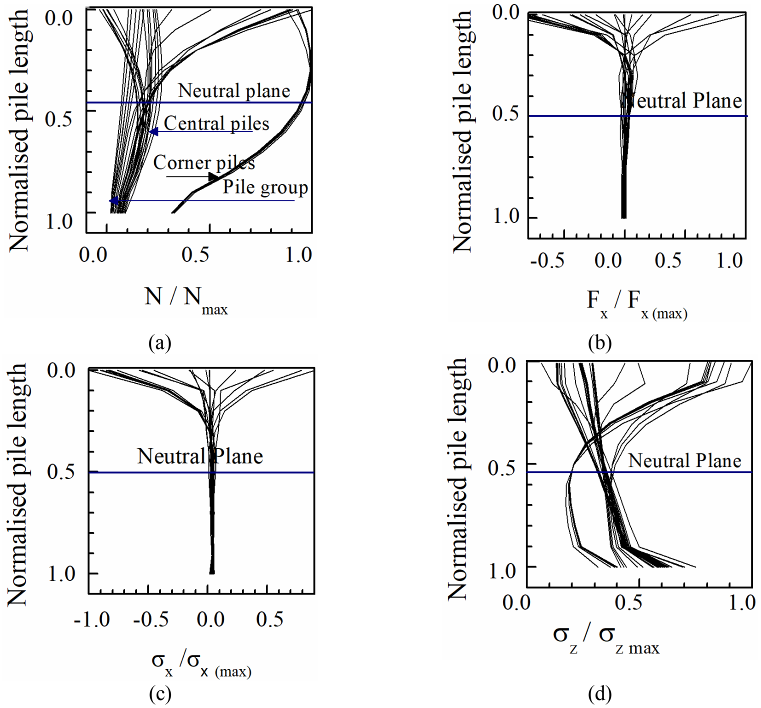
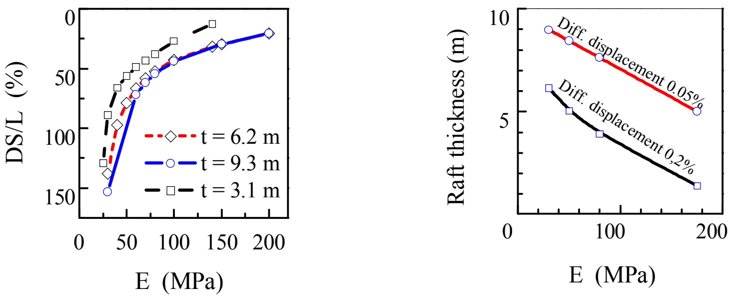



Fig. 4. Relationship between internal forces in piles and stress in soil with depth

Fig. 4 shows that there is a neutral plane stay parallel to raft foundation at approximately the middle of pile length. The differentiated value between force in piles and stress in the subsoil on *x* and *z* direction above this plane is relatively large, but the differentiated value below is rather trivial.This means the piles and soil on the neutral plane bearing the great force.

Therefore, it is really necessary to research the effect of soil in this area (between raft and neutral plane), displacement and role of raft. Young modulus of soil underneath the raft foundation in the research is around 30 MPa, which is rather common in the area of district 1, HCM city. However, when the soil is improved, or in other construction area, Young modulus of soil has the greater value, ranging from 50 to 100 MPa (equivalent to the clay soil in Frankfurt). In some buildings in the world, such as Dubai Tower, the soil underneath the raft is limestone, with Young modulus of 1,500 MPa. In order to evaluate generally and understanding the raft thickness of 31 statistic buildings in the world, the Young modulus in this research is ranging from 30 to 175 MPa.




(a) (b)

Fig. 5. Effect of Youngmodulus on raft thickness and displacement

Fig. 5(a) shows that in case of the soil layeris thick 3.1 m (around 10% of the raft width) under the raft has the large Young modulus, the displacement is sharply reduced; in comparison with the thicker soil layer (around 6.2 m and 9.3 m). Fig. 5(b) shows the effect of soil's Young modulus on the raft thickness: if the modulus increases from 30 to 175 MPa, raft thickness can be reduced from 2 to 3 times, depending on the displacement tolerance.

In conclusion, Fig. 5 shows that if Young modulus of soil layer under the raft has thickness of 10 – 20% of the raft width, it can greatly reduce displacement.

## 3. Discusion and Cases study

### 3.1 Dubai Tower

The Dubai Tower is 400 m high, include 74 floors plus 3 basement floors, see Fig. 6. It is founded on very thin raft supported by 163 piles with 22 m and 29 piles 32 m long below the main foundation area. Under the raft there is 15 m limestone with long term Young modulus of 1,500 Mpa. The Dubai Tower is designed as piled raft foundation, meaning that piles are placed in the foundation mainly to reduce the displacement. [9].

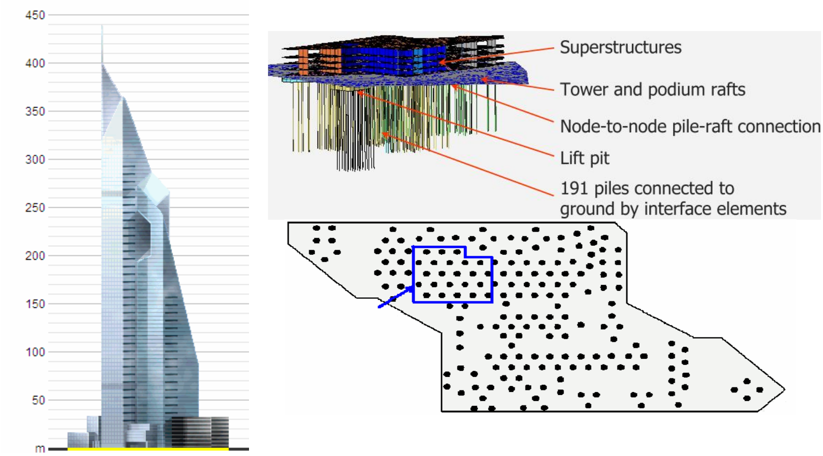
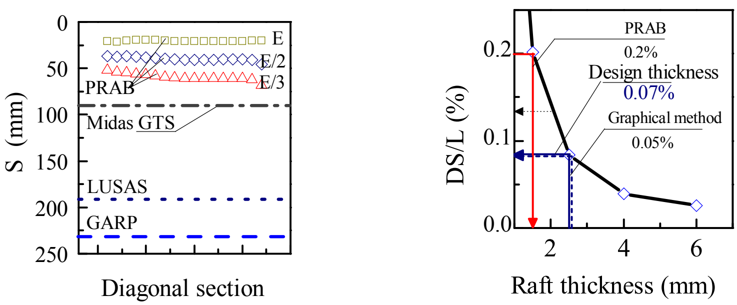



Fig. 6.The Dubai Tower




(a) (b)

Fig. 7. Comparison of the displacement by various methods, and optimizing raft thickness by PRAB

The original designed raft thickness is 2.5 m, the differential displacement (raft deformation) of 0.07% calculated by Poulos [9] using GARP. The computed thickness by PRAB is 1.5 m at deformation of 0.2%. Fig. 5(a) shows that the displacement of the Dubai Tower foundation is calculated by various methods by many researchers [9], [10] are matched well with PRABS results. Therefore, using PRABS one can optimize the thickness of the Dubai Tower's raft to meet the allowable different displacement of 0.2% is about 1.6 m. Using graph developed based on 3 factors: Young modulus of soil, number of floors and piles length, as described in [5], we get the raft thickness of 2.1 m. It shows that even with using different methods to attain results with similar value.

We can see that the raft thickness in Dubai Tower is thin because the Youngmodulus of soil under the raft is great.

**3.2 ICC Tower, Hong Kong**

The ICC Tower (HongKong) is 484 m high (with 118 floors + 6 basements), was built in the West of Kowloon Island, on Victoria Coast, Hong Kong. Fig. 6 shows the layout of upper structure and raft foundation of the ICC Tower.

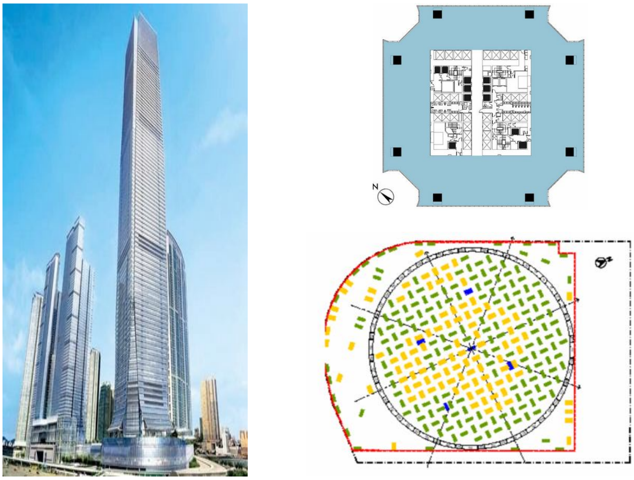


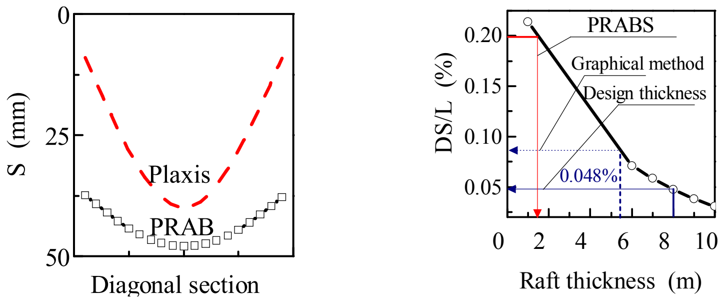
Fig. 8. Layout of upper structure and foundation structure of ICC Tower, Hong Kong [11]

The Tower is designedbythe pile group foundation. The raft thickness is 8m, the raft is placed at level of - 26m. The pile system includes 86 barrette piles of 1.5x2.8 m, and 154 barrette piles of 1.0x2.8 m. Since the rock-head level varies between EL-61m and EL-106 m, the soil hasdifferent bearing capacity, then the pile toe is proposed to place 2m away from the base rock in order to limit the different displacement. The result is that the pile length is the ranging from 35 to 70 m (the largest pile toe elevation is EL-95m). The barrette wall surrounding the perimeter of foundation with dia. 76 m, 1.5 m thick, and is constructed at the elevation of EL-95m.

The soil under the raft consists of alluvium and CDG overlying rock, including medium to coarse gravel, clay to coarse sand, sandstone with modulus under 30 MPa [9].

The designed raft thickness is 8 m at the differential displacement (raft deformation) of 0.048%. Fig. 9(a) shows that the displacement calculated by Plaxis [PdLong] and the result from PRAB are matched well. Then using PRABS to optimize the raft thickness of ICC Tower at Fig. 9(b), one can recognize that the thickness is about 1.5 m at deformation of 0.2%. Raft thickness based on the graph method [5] is 7.1 m at deformation of 0.2%. It shows that the raft thickness attained by using 3 methods above give vastly different value.

In short, the raft thickness of ICC Tower seem to be too large. For this case, this is the case of the pile group foundation, the average displacement should be very small, then the differential displacement is also small. The ICC Tower do not need the thick raft to balance the raft deformation.




(a) (b)

Fig. 9. Comparison of the displacement by various methods, and optimizing raft thickness by PRAB

**3.3 Incheon Tower Poulos 2011,8, Republic of Korea**

The foundation of the Tower is pile group type, include a raft thickness 5,5 m as an intermediate structure with piles under and core of superstructure above. Number of piles, pile configuration and sizes are determined after a numerious repeated analysis, with cooperation between the structural and geotechnical engineers. Pile length and pile diameter are selected based on behaviour and bearing capacity. The target of pile length selection is to control the displacement of tower. From the above analysis, pile tips are proposed to locate in the soft rock layer, instead of lightly weathered rock above. There are two rules for determination of pile length: pile tip should be minimum 2 m in the soft rock and pile tip should be at elevation of EL -50,0 m.

The final pile configuration was proposed to be 172 piles with dia. 2.5m, with length (from raft level) ranging from 36 to 66m. The raft bottom is at EL - 14.6 m.

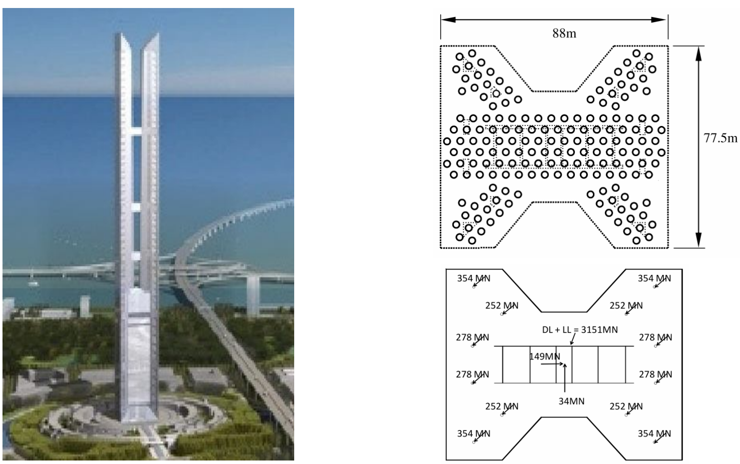
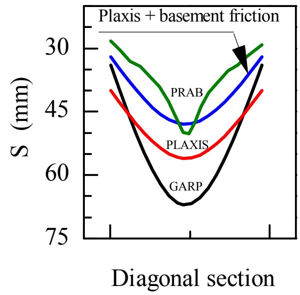


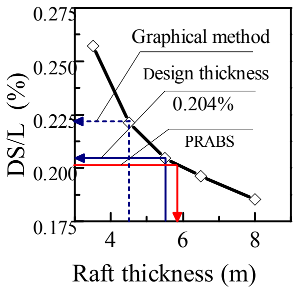

Fig. 10. Layout of upper structure of Incheon Tower

Soil in this area is mainly a mixture of sand and mud, near sea coast, and constantly flooded by tide. Geological section included: The surface is lost sand and sandy silt with 8 m thick; the second layer is upper marine deposits (UMD), with soft to firm marine silty clay, with 20 m thick; the third layer is lower marine deposits (LMD), with medium dense to dense silty sand, with 2 m thick; the fourth layer is highly weathered rock, with low pressure bearing capacity, under it is a layer of lightly weathered rock with greater pressure bearing capacity; the fifth layer is base rock, with two minor layers: softer stone located onEL-50m, and harder stone located under EL -50m.[11], [12].

The designed raft thickness is 5.5 m at the differential displacement (raft deformation) of 0.204%. Fig. 11(a) shows that the displacement calculated by Plaxis and GARP [11] and the result from PRAB are matched well. One can recognize that the results from Plaxis with consideration or without consideration of friction of basement wall can be neglected. That mean that computer program like PRABS, GARP can be used for evaluation of the pile raft foundation. Then using PRABS to optimize the raft thickness of Incheon Tower at Fig. 11(b), one can recognize that the thickness is about 5.8 m at deformation of 0.2%. The raft thickness from graph (Fig. 9) is 7.75 m at deformation of 0.2%. The raft thicknesses calculated by the three methods are matched well.




(a)




(b)

Fig. 11. Comparison of the displacement by various methods, optimizing raft thickness by PRABS

In short, the raft thickness of the Incheon Tower is designed reasonably. This is a good practice that the structural engineers and geotechnical cooperate in optimizing the raft thickness before designing rebar and concrete.

## 4. Conclusion

It proves that there is no agreed method for designers to use when choosing raft thickness at the moment, as well as the need for choosing reasonable raft thickness has not been put into the thought.

The research records 3 important elements that need to be focus on when analyzinga reasonable raft thickness. They are: number of floors, Youngmodulus of soil, and pile configuration (especially pile length). The actual raft thicknesses in all statistic building are larger than optimizing results from PRABS show that,it is necessary to choose the larger raft thickness than the reasonable one, in cases of damaged pile, uneven ground throughout the pile's body, soil under the pile's head.

Raft thickness of The Dubai Tower and the Incheon Tower are reasonable, raft thickness of the ICC Tower seem to be larger than required.

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**AN ANALYSIS OF RAFT THICKNESS IN HIGH-RISE BUILDINGS - CASE STUDIES**

From the observation of rafts of 31 high-rise buildings constructed in Vietnam and over the world, it can be recognized that they have very large thickness. So, the questions are, what is the role of the raft (it's thickness) in a especially foundation system, and in the whole upper-structure – raft – soil and pile group's interaction in general? And why does the raft thickness in some building seem to be very large (e.g. ICC Tower is 484 m tall, has raft of 8.0 m thick), while the others have relatively thinner raft (e.g. Dubai Tower is 400 m tall, has raft of 2.5 m thick ).

This study shows that the raft thickness is depended on the foundation system, Young modulus of soil right under the raft and number of floors of superstructure. This analysis explains very well the case of thick raft of ICC Tower, thin raft of Dubai Tower and reasonable raft thickness of Incheon Tower.

**Keywords:**Piled raft, Raft, Pile group, Soil-structure interaction, Case study, Settlement.

*Као Ван Хоа, Нгуен Анх Туан*

**АНАЛІЗ ТОВЩИНИ ФУНДАМЕНТНИХ ПЛИТ ВИСОТНИХ БУДІВЕЛЬ - ПРИКЛАДИ ДОСЛІДЖЕННЯ**

По вивченню товщини фундаментних плит 31 висотного будинку, побудованого у В'єтнамі і в усьому світі, можна визнати, що вони мають дуже велику товщину. Отже, питання полягає в тому, яка роль фундаментної плити (її товщини) в системі фундаменту, і в цілому у взаємодії верхньої конструкції плити-грунту і свайне групи? І чому товщина плити в деяких будівлях виявляється дуже великий (наприклад, вежа ICC висотою 484 м, має фундаментну плиту товщиною 8,0 м), в той час як інші мають відносно більш тонкі фундаментні плити (наприклад, товщина фундаментної плити Дубайської Вежа висотою 400 м становить 2,5 м).

Це дослідження показує, що товщина плити залежить від конструкції фундаменту, модуля пружності грунту, що знаходиться безпосередньо під плитою і кількості поверхів будівлі. Цей аналіз дуже добре пояснює випадок потовщеною плити вежі ICC, більш тонкої плити Дубайської вежі і оптимальної товщини плити в башті Інчхон.

**Ключові слова**: Пальовий фундамент, пальове поле, взаємодія грунт-структура, приклади дослідження, поселення.

*Као Ван Хоа, Нгуен Анх Туан*

**АНАЛИЗ ТОЛЩИНЫ ФУНДАМЕНТНЫХ ПЛИТ ВЫСОТНЫХ ЗДАНИЙ - ПРИМЕРЫ ИССЛЕДОВАНИЯ**

В результате изучения фундаментных плит 31 высотного здания, построенных во Вьетнаме и во всем мире, можно признать, что они имеют очень большую толщину. Итак, вопрос заключается в том, какова роль фундаментной плиты (её толщины) в системе фундамента, и в целом во взаимодействии верхней конструкции плиты–грунта и свайной группы? И почему толщина плиты в некоторых зданиях оказывается очень большой (например, башня ICC высотой 484 м, имеет фундаментную плиту толщиной 8,0 м), в то время как другие имеют относительно более тонкие фундаментные плиты (например, толщина фундаментной плиты Дубайской Башня высотой 400 м составляет 2,5 м)?

Это исследование показывает, что толщина плиты зависит от конструкции фундамента, модуля упругости грунта, находящегося непосредственно под плитой и количества этажей здания. Этот анализ хорошо объясняет случай утолщенной плиты башни ICC, более тонкой плиты Дубайской башни и оптимальность толщины плиты башни Инчхон.

**Ключевые слова**: Свайный фундамент, плот, Свайное поле, взаимодействие грунт-структура, примеры исследования, поселение.

УДК 539.3
*Као Ван Хоа, Нгуен Анх Туан.* **Аналіз товщини фундаментних плит висотних будівель - приклади дослідження** / Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2019. – Вип. 102. – С. 13-24. – Англ.

*Досліджено залежність товщини фундаментних плит багатоповерхових споруд від конструкції фундаменту, модуля пружності грунту, що знаходиться безпосередньо під плитою і кількості поверхів будівлі.*

Табл. 0. Іл. 11. Бібліогр. 12 назв.

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*Cao Van Hoa, Nguyen Anh Tuan.* **An analysis of raft thickness in high-rise buildings - case studies** / Strength of materials and theory of structures: Sci.&Tech. Collected Artcl. – K.: KNUBA, 2019. – Issue 102. – P. 13-24.

*The dependence of the thickness of the raft foundation of multistoried buildings on the structure of the foundation, the modulus of elasticity of the soil, located directly under the stove and the number of floors of superstructure, is investigated.*

Tabl. 0. Fig. 11. Ref. 12.

УДК 539.3
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*Исследована зависимость толщины фундаментных плит многоэтажных сооружений от конструкции фундамента, модуля упругости грунта, находящегося непосредственно под плитой и этажности здания.*

Табл. 1. Ил. 5. Библиогр. 25 назв.

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