A Correlation between Theoretical and Actual Column Shortening and Lateral Sway in a Vertically Asymmetric High-Rise Concrete Building

العلاقة بين النتائج النظرية والقيم الحقيقية لقصر الأعمدة والانزياح الجانبي في مبنى بيتوني عالي غير متناظر شاقولياً

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Abstract

The consideration of columns shortening in high-rise buildings becomes more complex and needs more attention when the building is vertically asymmetric. The inherent complexity is attributed to the dramatically unequally loaded vertical members due to mass shifting after the separation floor (the floor after which the plan is significantly reduced), which consequently leads to building rotation toward the higher side causing more lateral and vertical displacements.

The gravity loads induced sway and settlement of a 360m height vertically asymmetric building in Dubai are investigated in this research. The columns and core walls elastic and time-dependent shortenings are predicted using the ACI 209R-92 model considering all the compensation measures taken, the construction method adopted, and the site conditions revealed during the construction of the tower. Sophisticated calculations including all the influencing factors of this model were performed using an Excel sheet to provide a simple interface for calculating the elastic and time-dependent columns shortening. The building was also analyzed by finite element method software, Etabs where the columns shortening and settlement were predicted using CEB-FIB 90 model for time-dependent effects which was built-in the software. The results of the two models were evaluated by comparing them to site survey readings conducted each five floors during the tower construction. It was found that both methods overestimated settlements in all floors compared to actual ones. Whilst the average overestimation of the developed Excel sheet based on the ACI 209R-92 model was 630%, Etabs analysis based on the CEB-FIB 90 model had more accurate results with average overestimation of 258%.

The lateral sway induce by gravity load was predicted by the same Etabs model using two different analyses, linear and nonlinear staged construction analysis. The sway results of the two models where compared to each other to get a comprehensive overview of this behavior. Further investigation was done on a modified building model where the vertical asymmetry was removed and the building was re-analyzed by the two analyses again. The advantages and disadvantages of each analysis were provided. It was found that the linear analysis

significantly overestimated the lateral sway for the original model, whereas the two analysis had close results for the modified model. The analyses results clearly evidenced that nonlinear staged construction analysis is essential to capture the real behavior of vertically asymmetric buildings.

الملخص

يعتبر قصر الأعمدة في الأبنية العالية من الأمور المعقدة والتي تحتاج لمزيد من الاهتمام عندما يكون المبنى غير متناظر شاقولياً. ويعزى هذا التعقيد إلى التحميل الغير متساوي بشكل كبير للعناصر الشاقولية بسبب انزياح الكتلة بعد طابق الفصل (الطابق الذي يتناقص بعده مسقط البناء بشكل كبير)، والذي يؤدي بالتالي إلى دوران المبنى باتجاه الجانب الأعلى مسبباً مزيداً من الانزياحات الجانبية والشاقولية.

في هذا البحث تتم دراسة الهبوط والانزياح الناتجان عن الأحمال الشاقولية لمبنى عالي بارتفاع 360 متر غير متناظر شاقولياً في مدينة دبي. تم تقدير القصر المرن وطويل الأمد للأعمدة والجدران باستخدام نموذج (أي سي آي 209 آر-92) مع أخذ بعين الاعتبار جميع تدابير تعويض قصر الأعمدة التي تم تطبيقها وطرق البناء التي تم اعتمادها وظروف الموقع التي سيطرت خلال عملية إنشاء المبنى. وتم إجراء عمليات حسابية معقدة تشمل جميع العوامل المؤثرة لهذا النموذج باستخدام ورقة إكسل لتوفير واجهة بسيطة لحساب قصر الأعمدة المرن وطويل الأمد. بالإضافة لذلك، تم تحليل المبنى باستخدام برنامج (إيتابس) الذي يعتمد نظرية العناصر المحدودة حيث تم تقدير قصر وهبوط الأعمدة باستخدام نموذج (سي إي بي- إف آي بي 90) للتأثيرات طويلة الأمد والذي هو جزء من البرنامج. وتم تقييم نتائج النموذجين عن طريق مقارنتهم مع قراءات في الموقع تم أخذها كل خمسة طوابق أثناء بناء البرج. وقد تم استنتاج أن كلا النموذجين بالغا في تقدير الهبوط في كل الطوابق مقارنة بالقيم الحقيقية. في حين بلغ متوسط مبالغة تقدير الهبوط لورقة الإكسل المبنية على نموذج (أي سي آي 209 آر-92) حوالي 630%، فإن تحليل برنامج إيتابس المعتمد على نموذج (سي إي بي- إف آي بي 90) قدم نتائج أكثر دقة بمتوسط مبالغة في تقدير الهبوط بلغت 258%.

تم تقدير الانزياح الجانبي الناتج عن الأحمال الشاقولية باستخدام نفس نموذج إيتابس وبتطبيق نوعين من التحليل: التحليل الخطي وتحليل التحميل المتتابع اللاخطي. وتمت مقارنة نتائج التحليلين مع بعضهما للحصول على نظرة شاملة عن طبيعة هذا الانزياح الجانبي. وقد تم إجراء مزيد من دراسة الانزياح على نموذج معدل للمبنى متناظر شاقولياً بحذف الطوابق الأخيرة المسببة لعدم الانتظام الشاقولي وتم تحليله مجدداً بنوعي التحليل السابقين. وتم تقديم مزايا وعيوب كل نوع من أنواع التحليل. وقد تم استنتاج أن التحليل الخطي بالغ بشكل كبير في تقدير الانزياح الجانبي للنموذج الأصلي، بينما كلا التحليلين قدما نتائج متقاربة للنموذج المعدل. وقد أثبتت نتائج التحليلين بشكل واضح أن تحليل التحميل المتتابع اللاخطي هو أساسي لتمثيل السلوك الحقيقي للأبنية الغير متناظرة شاقولياً.

DEDICATION

I dedicate this work to my father and mother who raised me to believe first in Allah and then in myself to pursue my goals in this life and to have the confidence and faith to achieve them. This work is the outcome of dedicating their life to cradle the way of mine.

Thank you a lot for all your support, doaa and encouragement.

All the credit goes back to you.

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Writing this dissertation was a great challenge to me. I would like to express my profound gratitude to all those who offered me the support and help that I needed to complete my study.

First and foremost, I would like to raise my doaa for mercy on the spirit of the late, Engineer **Ahmed Raad Hajjar** and present my warm condolences to his family and his loved ones. I am deeply gratitude to his efforts and help with starting this research and providing all the information needed to continue this work. His enthusiasm and encouragement in the short period I knew him had a great effect in me to complete what he had dreamed of. His memory will remain as a model for dedication, devotion and pursuit of ambition and achieving goals in this life.

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Last but not least, I must confess that this thesis would have never been possible without the love, support and patience of my loving wife. I am deeply grateful to her for bearing me through all the stressful moments and taking a good care of our family to provide me with the warm and passionate atmosphere to finish my study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SYMBOLS

A	Area of column section
Ec	Elasticity modulus
Ect	Elasticity modulus at age t
H_n	Height of story n
L	Column Length
L_n	Actual constructed column length prior to adding slab at stage n
P	Applied load
P_k	Applied load from adding floor k
S_e	Elastic column shortening
$S_{i,n-1}$	Shortening of column in floor i caused by adding floor n-1
S_{ih}	Shortening of a column in floor (i) caused by the instantaneous and time-dependent effects of adding one single floor h
TS_{kj}	total shortening of a column in floor (k) below floor (n)
$f'c$	Specified concrete strength
$(f'c)_t$	Specified concrete strength at age t
$(f'c)_{28}$	Specified concrete strength at age 28 days
h	Average member thickness
s	Concrete slump
v_t	Creep coefficient
v_u	Ultimate creep coefficient
Δ_{n-1}	Total elastic and inelastic displacement of column in story n-1
Δ_{nj}	Total displacement of a column in floor (n) after casting floor (j)
ε_e	Elastic strain
ε_c	Creep strain
ε_{sh}	Shrinkage strain
γ_c	Product of correction factors for creep
γ_{sh}	Product of correction factors for shrinkage
γ_λ	Corrective factor for ambient relative humidity
γ_{vs}	Corrective factor for volume-surface ratio of member
γ_{la}	Corrective factor for loading age
γ_s	Corrective factor for slump
γ_Ψ	Corrective factor for fine aggregates percentage
t_{la}	Loading age
λ	Relative humidity
Ψ	Percentage of fine aggregates to total aggregates
$(\varepsilon_{sh})_t$	Shrinkage strain at time t
$(\varepsilon_{sh})_u$	Ultimate shrinkage strain

Chapter 1

INTRODUCTION

1.1 Introduction

In reinforced concrete buildings, the difference between the initial column length and the in-service column length is referred to as column shortening which includes three major constituents, elastic, creep and shrinkage shortening. Where the first two components occur under loading (instant for elastic and sustained for creep), shrinkage shortening takes place with no relation to loading. Unlike the instantaneous elastic strain, creep and shrinkage shortenings occur over a period of time, hence called time-dependent effects. To distinguish between steel and reinforced concrete column shortening, the former exhibits only elastic shortening where the later experiences all the three shortening components.

With increased height of buildings, the effects of column shortening become significant and need careful consideration in both design and construction. Those effects are attributed mostly to the differential shortening between columns and core walls. Those differential shortenings are caused by the different reinforcement ratio, higher stress of columns than walls and the difference in volume-surface ratio. The accumulation of those shortenings will cause slabs and beams to tilt along with rotation of partitions walls and distortion of services pipes and ducts. Thus, a compensation of columns lengths during the construction is needed by predicting them earlier in the design.

Predicting time dependent effects on reinforced concrete is a complicated task influenced by many uncertainties such as:

- The inelastic response of reinforced concrete.
- Non-homogeneity of concrete structures because of construction stages.
- Contribution of reinforcement to time-dependent effects.
- Restraint between structural members.
- The effect of loading history.
- Environmental conditions.

Hence, the prediction of those effects is dependent on formulas based on empirical test results accompanied with actual results taken from monitoring of real structures during construction and service life.

1.2 Research Significance

The accumulation of elastic and time-dependent effects due to sequential loading during the construction of tall buildings leads to considerable columns shortening which affects the overall serviceability of the building and may destruct the nonstructural members such as services ducts, finishes and curtain walls which are installed prior to end of construction.

In tall buildings, the difference in the applied loads and the axial stiffness between vertical members is significant leading to considerable differential shortening between those members, more precisely between columns and shear walls. Ignoring this deferential shortening in tall buildings compromises in addition to the non-structural members, the structural elements due to the induced additional forces in the connecting horizontal members.

The problem is magnified when the building is vertically asymmetric. That is when the higher part of the building has much less mass on one side of the building than the other causing the building to rotate and sway toward the higher part. During the service life of such buildings, the lateral loads add more serious effects which lead, in addition to non-structural member's destruction, to collapse of structural members as well. Thus, early prediction of this behavior in the design provides a realistic insight into the overall behavior of the building during the different stages of the construction and during the building lifetime. An account for those effects should be taken during the design by predicting the total absolute and deferential columns shortening at each stage of the construction and propose the compensation measures to be taken during the construction.
This study provides a simple and easy-to-use interface using Excel sheet to predict the elastic, time-dependent and total column shortening. The prediction depends on information available during the design for practicing engineers, so the effects of this phenomena can be accounted for in the design and proper measures and compensations can be specified.

Gravity load induced sway is another important behavior of vertical asymmetric high-rise buildings that needs to be considered and studied earlier in the design. The significant difference in columns loads due to different number of floors above will lead to considerable differential shortening which consequently leads to building rotation and side sway toward the higher side. This unique behavior is investigated in this research showing the different methods of analysis and recommending the best procedure which is able to accurately provide the deformation shape and sway values.

1.3 Research Challenge

Although the prediction of column shortening behavior is sophisticated and accompanied with much uncertainties, a good prediction can be based on estimated information during the design stage. Creep and shrinkage, elastic modulus, construction method and environmental conditions are all affecting the accuracy of columns shortening prediction.

A sequential analysis based on the construction method and schedule rather than the total loading conventional analysis is essential to predict this behavior more accurately and realistically. For this purpose, the proposed Excel sheet is developed to predict the elastic, creep and shrinkage shortening of any concrete column or wall during a particular construction stage (after casting a certain floor) using the ACI 209R-92 method for time-dependent effects prediction.

It's essential to this research, in addition to provide column shortening prediction individually, to present the results of settlement in the same way that were provided in the presented case study building records to compare and assess those values. That is where the settlement is surveyed each five floors at chosen levels during the construction. Thus, the column shortening is incorporated with complex effects of the previous and the following floors which were considered in the developed excel sheet.

1.4 Research Objectives

This research intends to obtain the following targets:

1. Prediction of columns shortening effects in high-rise buildings generally and in vertically asymmetric high-rise buildings particularly to allow for practicing engineers to consider this behavior in different buildings as well as for construction engineers to adopt the proper measures to compensate those effects.
2. To develop an excel sheet adopting the ACI 209R-92 model to calculate both elastic and time-dependent column shortenings based on information that can be available at the design stage.
3. To assess the accuracy of ACI 209R-92 model in predicting the time-dependent effects by comparing the theoretically calculated values for a case study building with actual site readings taken during the construction of that building.
4. To provide a simple procedure for engineers to predict the columns shortening at early stage of the design.
5. To investigate the sway behavior of vertically asymmetric high-rise buildings due to significant mass shifting which causes eccentricity in the vertical loading on the whole building.

1.5 Case Study

In order to evaluate the theoretical results of the considered ACI 209R-92 method, a case study of 360m high vertically asymmetric building was considered to compare the site readings of columns shortening taken during the tower construction with the theoretical results. The building is a 71 floors office tower located in Jumeirah Lake Towers in Dubai, UAE. The typical plan shapes into two intersecting ellipses which, after floor 52, only one ellipse continues to floor 64. That significant shifting in plan for the last 12 floors caused the vertical asymmetric to the building. A reinforced concrete central core wall with peripheral frame connected by spine beams at each floor form the main structural systems of the tower. The floor is hollow core slab with 320 mm thickness and 80 mm topping slab. A typical structural plan is shown in figure 1. Configurations of the building along with structural drawings are shown in appendix A.

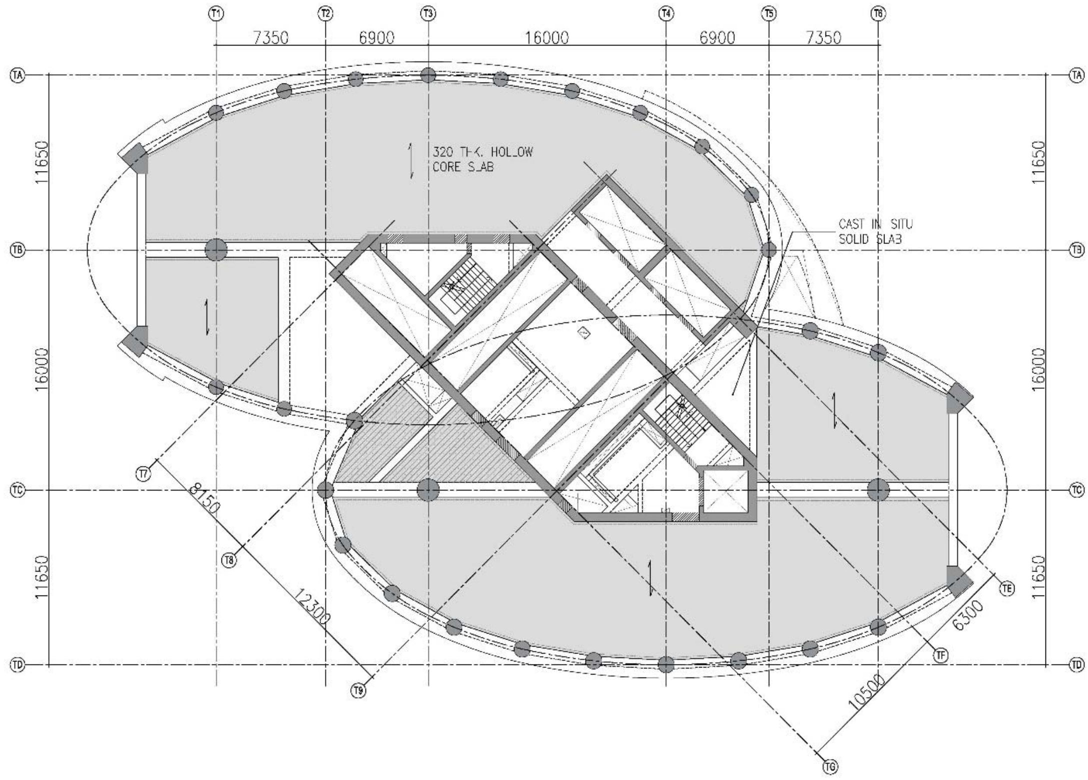


Fig.1 Typical structural plan of the tower

A monitoring system was specified to allow for site readings of the column movement during the construction work. The monitored points were set at each floor for lateral movement and at different floors at peripheral columns and the core wall to monitor the vertical movement. The survey was done by laser device with reference to a benchmark located outside the building. Reading results was done after each 5 floors construction. The survey results for a peripheral column and the core wall which are used in this research are presented in chapter 4. Full detailed site readings and survey charts are shown in appendix B

Chapter 2

LITERATURE REVIEW

2.1 Introduction

A concrete column under sequential construction loading exhibits two types of shortening, elastic due to immediate loading and inelastic as a result of creep and shrinkage effects. Prediction of elastic effects includes less variables than those of time-dependent (creep and shrinkage) since it's related directly to the applied load and modules of elasticity which can be directly predicted by experimental tests on specimens taken from the casting concrete. On the other hand, predicting creep and shrinkage effects is highly affected by the prediction model.
To achieve the objectives of this research, it's instructive to review the previous work of researchers in developing elastic and time-dependent prediction models. This chapter aims to provide background information for this research which will be carried out by reviewing the prediction models of both elastic and time-dependent effects on reinforced concrete which were set by pioneering researchers and adopted in the international codes. The review is extended to cover the shortening and deformation of axially loaded concrete columns generally and in tall buildings particularly.
The differential shortening and its effects on tall buildings construction are also reviewed in this chapter. Each section reviews the historical researches of each subject, discusses the various factors and methods adopted, and evaluates the results and conclusions for each literature.

2.2 Prediction of Modulus of Elasticity

Elastic shortening of a column takes place instantaneously by the applied load and is directly dependent on the material properties and the column size as expressed in Eq.1.

$$S_e = \frac{P}{E\text{c} * \text{A}} * L \qquad (1)$$

Where S_e: Elastic column shortening, P: the applied load

A: column section, Ec: Modulus of elasticity, L: length of column

Predicting the modulus of elasticity accurately is a major factor in calculating the elastic strain. Although the prediction methods for the modulus of elasticity are empirical formulas dependent on laboratory controlled tests different from those of real structure, a reliable prediction of modulus of elasticity can be based on one of those formulas because of the fact that elasticity modulus is related directly to the strength of the concrete which can be verified by specimens taken directly from the casting concrete.

The most used formula by practicing engineers is that proposed by (Pauw 1960) and adopted by ACI 318-08 for normal weight concrete, Eq.2.

$$Ec = 5000\sqrt{f'c} \qquad (2)$$

Where Ec modulus of elasticity

$f'c$ Specified concrete strength in MPa

As expressed by Eq.2, modulus of elasticity is directly linked to concrete strength, however it has no recognition of the range of concrete strength which is a matter of question for high strength concrete. The comparison conducted by ACI 363R-92 between experimental results of elasticity modulus and values calculated by Eq.2 evidenced that the ACI 318 formula provides accepted prediction of elasticity modulus for concrete strength up to 40 MPa where the values beyond that range becomes overestimated.

Below, Eq.3 is a refinement of ACI 318 expression which was proposed by (Martinez, Nilson and Slate 1982) and adopted by ACI 363R-92 to go in line with the experimental values for high-strength concrete.

$$Ec_t = 3{,}320\sqrt{(f'c)_t} + 6{,}900 \text{ MPa} \qquad (3)$$

Where $(f'c)_t$ Specified concrete strength at age t in MPa

Ect Elasticity modulus at age t

In fact, Eq.3 is consistent with a certainty that in high-strength concrete, modulus of elasticity will have less multiplier of concrete strength than that used for normal strength concrete. However, Eq.3 was reported by (Saucier et al. 1965; Pfeifer et al. 1971; Russell and Corley 1978) to give less values of modulus of elasticity than experimental ones. That confirms the fact that modulus of elasticity is in relation to other factors than concrete strength such as, properties and proportions of coarse aggregates.

According to (Teychenne et al. 1978), modulus of elasticity is dependent on four factors, concrete compressive strength, aggregates type, aggregate proportion to cement and concrete age at time of test. Despite the evidence provided by ACI 363R-92 for high strength concrete, the latest ACI 318-14 code still has not endorsed nor adopted the ACI 363R-92 formula. The concrete compressive strength used in Eq.3 is determined using ACI 209R-92 expression (Eq.4) for predicting compressive strength at different ages for cement type I using moist curing.

$$(f'c)_{t} = \frac{t}{4+0.85t}(f'c)_{28} \qquad (4)$$

Where t age in days

$(f'c)_{t}$ Specified concrete strength at age t

$(f'c)_{28}$ Specified concrete strength at age 28 days

Thoman and Raede (1934) reported values for elasticity modulus (29 to 36 GPa) for different high strength concrete grades (69 to 76 MPa). The values were taken as slope of strain-stress chart tangent at 25% from the maximum stress. By applying Eq.2 & Eq.3 to the same range of concrete strength, it is notable that both equations overestimate the elasticity modulus for lower concrete strength of 69 MPa (41 and 34 GPa for Eq.2 and Eq.3 respectively) while for higher strength of 76 MPa, Eq.2 still overestimates the value (43 GPa) but Eq.2 predicts the modulus of elasticity accurately (36 GPa). That confirms the statement of ACI 363R-92 that Eq.2 is inappropriate in predicting elasticity modulus in high-strength concrete and Eq.3 is a good replacement. Hence, for reliable results consistent with the previous statement, Eq.3 is used in this research for predicting the elastic column strain.

2.3 Prediction of Creep and Shrinkage Effects

A distinction between creep and shrinkage strain was early reported by Glanville and Thomas (1933) that the former occurs under sustained load, while the later takes place with or without load applied to concrete. The prediction of time-dependent effects on concrete members is a complex procedure accompanied with different interacting factors of this unique phenomena (Bažant and Baweja 1995). Creep prediction was firstly proposed by Ross (1937) who set the first creep curves giving the researchers an indication of creep prediction. He defined the major factors affecting the creep prediction including age at loading, temperature, applied stress, relative humidity, water/cement ratio, specimen size, cement class and aggregates type and proportions. Since then, many formulated models for quantifying creep and shrinkage effects were reported by literatures based on wide range of experimental data. ACI 209R-92 model, firstly introduced by Branson and Christiason (1971) then adjusted by committee 209 of ACI (1982) and (1992) provides a direct and simple model for predicting creep and shrinkage effects which requires basic information such as, cement type, volume-surface ratio, age at loading, relative humidity and curing method. The main principle of this model is based on determining an ultimate value which represents the asymptote of a hyperbolic creep and shrinkage curves. The desired result at any time is extrapolated from that curve by modifying the ultimate value by a time factor. The ultimate value and time factor depends on proportions of concrete mixture, relative humidity, age at loading and ambient temperature. In the comparison study provided by ACI committee 209 (2008) based on (Gardner 2004) charts, the unconformity between this model values and the experiments measures in RILEM TC 107 (Muller et al. 1999) creep and shrinkage databank evidences the inaccuracy of this model, which was initially base on limited experimental data. It is worth mentioning that since ACI 209R-92, the model was not modified to the RILEM databank (ACI committee 209 2008). Nevertheless, the simplicity of this method led to wide adoption by practicing engineers who mostly have limited information during the design stage. This model will be used in detailed calculation for the case study presented in this research. Another widely recognized prediction model is CEB-FIB 90 model which was proposed by Muller and Hilsdorf (1990) to predict the average behavior related to time-dependent effects for a concrete element. With comparison to ACI 209R-92 model, the CEB-FIB 90 model has the same concept including prediction of hyperbolic curve which changes with time and providing an ultimate values modified by the environmental conditions and concrete proportions. Despite the preference of this model by some engineers to the ACI 209R-92 model, ignoring the concrete curing method and conditions by the CEB-FIB 90 model affects its reliability in predicting shrinkage and creep effects. The continuous work of (Bažant 1972; Bažant and Panula 1978, 1984; Bažant et al. 1976, 1992; Bažant and Kim 1991, 1992; Bažant, Kim and Panula 1991) led to the B3 model (Bažant and Baweja 1995, 2000) for time-dependent effects. The latter method considers all the factors that affects the creep and shrinkage prediction, however applying this model may be more complicated than the other models and needs data not normally available for designers, such as the proportions of concrete mix. That could be an obstruction to practicing engineers who prefer to apply simpler with less input data model like the GL2000 model which Gardner and Lockman (2001) originally proposed and Gardner (2004) modified later. The GL 2000 model requires only data that available at the design stage. Illston and England (1970) studied the time-dependent effects on the structural behavior of concrete buildings. Trying to provide a guidance for designers on which method is suitable for design, the latter study reviewed two simple methods of analysis, creep rate and effective modulus. In the first method, the creep strain is predicted by finding first a product of the imposed stress and the specific creep rate and then integrating that product over the imposition period of the stress. In the second method, creep strain is calculated by using an effective creep modulus which equals the divisor of the stress by the total (elastic and creep) strain. The two methods were evaluated under different types of members and loading, axial load, bending moment, cracked and uncracked members and under elevated temperatures. It was recommended that considering a method of analysis for creep and shrinkage is related to the circumstances that rule the design, such as loading, temperature and member type. The rate of creep method was considered more suitable where loading on the building is constant and temperatures are uniform. The latter study showed that creep and shrinkage effects are adequately analyzed using simple method when properties of concrete and loading are essentially known. In his correspondence to the latter study, Russell (1971) used the approach of this study to investigate its accuracy in predicting the time-dependent effects (creep and shrinkage). That approach was applied on four years monitored multi-story building to predict the strain of four selected stories. The strain prediction included three deformation component, elastic, creep and shrinkage. The total elastic deformations were taken as the summation of strains for each incremental load considering the appropriate age-based modulus of elasticity which was taken from extensive laboratory tests. Creep prediction was based on modifying the measured creep of plain concrete cylinders specimens to account for member size and reinforcement. In a similar manner, shrinkage strain was predicted by correcting the shrinkage of 6 in. diameter cylinders. By comparing the theoretically predicted strains to the actual measured ones, the latter study was able to predict in reasonable accuracy the effects of creep and shrinkage. It confirmed that measured settlement of real building can be predicted accurately using the proposed approach. A remarkable conclusion of that study was that the majority of column settlement occurred in the construction period of 570 days. No doubt that the reliability of this study was based on comparing the predicted values to the actual site readings of strains over four years accompanied with extensive laboratory tests to determine accurately the concrete properties used to construct that building. Another simple procedure for predicting time-dependent effects in reinforced concrete was reported by Sharma, Maru and Nagpal (2004) who compared three proposed methods by applying them on three different frame buildings, 40, 60 and 80 stories. The study focused on the stiffness of the beams and their effect of column deformation. No major conclusions were reported by the latter study, however it highlighted the very important factor of restraining effect of horizontal members which affects the column settlement considerably. Lu et al. (2013) also adopted the age-adjusted effective modulus in predicting time-dependent effects in reinforced concrete buildings. The method was applied in their study to predict the time effects of a 632m tower. The latter study stated that the significant shortening of the tower confirmed the fact that this behavior can't be ignored during the design of super tall structures and length compensation during the construction should be considered and provided in the design stage prior to starting the construction work. Despite that the latter study provided valuable information about time effects and a method to predict those effects, the complexity of the finite element formulations and approach is a reason for many practicing engineers to avoid such a method in their designs if and adopt much simpler methods with no much less accuracy.

2.4 Comparison of Creep and Shrinkage Prediction Models

Considering time-dependent effects in the structural analysis is highly affected and varied by the selected prediction model. The variety of results obtained by different models are dependent on the various factors and their sensitivity to effect the considered model. A comparison between those models is reported by researchers to evaluate the applicability and sensitivity of one model to another. Brooks, Gamble and Ghouman (1992) compared the predicted results of five models to experimental values of specimens observed over a period of eight months. The comparison revealed inconsistency between the predicted and the measured values. The ACI 209R-82 method was concluded as the best method for creep and shrinkage prediction over the other compare methods which all overestimated the creep strain. Although the latter study was based on measured values, the number of specimens were limited and the comparison falls short of the other comparisons based on significant data extracted from creep and shrinkage databases such as the RILEM TC 107 (Muller, Bazant and Kuttner 1999) and NU-ITI (Bazant and Li 2008) databases. The two databases were the references to a recent study by (Al-Manaseer and Prado, 2015) who compared statistically six creep and shrinkage prediction methods using those databases. The study concluded that ACI 209R-92 method is the best prediction model for both creep and shrinkage followed by the B3 and GL 2000 models, which is a similar conclusion to (Brooks, Gamble and Ghouman 1992) who reported the ACI 209R-92 model as the best for both individual and total deformations of creep and shrinkage among all the five compared models. On the contrary, the comparison by (Bazant and Li, 2008) based on NU-ITI database considered the ACI 209R-92 method the worst in creep and shrinkage prediction where the best is B3 model followed by GL 2000 model, which also disagrees with the conclusion of (Gardner, 2004; Goel, Kumar and Paul, 2007) who used only the RILEM database in the comparison and recommended the GL2000 model as a better model in predicting time-dependent effects. The inconsistency of results between literatures may be attributed to the different statistical methods and the databases used in the comparison, especially for (Al-Manaseer and Prado, 2015) who combined the results of five statistical methods to rank the compared models. The study by (Usibe, Etim and Ushie, 2012) is another proof of the effect of the selected database and statistical methods in comparing different models. The latter study revealed that B3 model predicted creep and shrinkage most accurately. A different type of conclusion of all the previous studies was reported by (Howells, Lark and Barr, 2005) whose study revealed identical creep and shrinkage strains between the CEB-FIB 90 and Eurocode 2 1992 models. The unsurprising conclusion is a result of the similar formulates and parameters adopted by the two models where the other models had scattered results due to different formulates and parameters. The latter study compared the results of nine models between each other rather than comparing them to experimental values. While some studies (ACI committee 209 2008; Gardner and Zhao 1993; Gardner 2004) showed that ACI 209R-92 method underestimated the experimental values of creep, it resulted in acceptable accuracy in the study provided by (Pan, Lü and Fu, 2011) who compared measurements taken from high strength concrete specimens to four prediction models. The insensitivity of the ACI 209R-92 method to concrete strength is a possible reason of the consistency of the results provided by the latter study for high-strength concrete while this model underestimated creep strain in the other studies which were provided for normal strength concrete.

2.5 Axial Column Shortening

In reinforced concrete buildings, the effects of columns shortening increase in high-rise buildings and hence, need special attention during the design and construction. Columns shortening is a cumulative procedure of elastic and inelastic strains which are produced during the construction and extend over the life time of the building. The prediction of columns shortening is a complex task including the elastic and time-dependent strains with all the influencing factors. The deformation of axially loaded vertical members due to time dependent effects takes place from the moment the member is cast for shrinkage effects and the moment it is loaded for creep effects. It was reported (Glanville and Thomas, 1933; Fintel, Ghosh and Iyengar, 1987; Swamy and Arumugasaamy 1978) that creep and shrinkage effects have the most proportion of the total effect (represented as column strain) occurs during the first few months of the member age. As well, creep effects due to loads applied at later ages have much less effects than those applied at early age. As a consequence, the consideration of columns shortening in tall buildings during the construction stage is of higher concern compared to those caused by sustained loads applied at later stages (imposed loads). Fintel and Khan (1969) firstly originated a model to quantify the axial shortening of a concrete column. The model was proposed in (Fintel, Ghosh and Iyengar, 1987) as the PCA method for prediction and compensation of columns shortening in tall buildings. The method is based on numerous tests and formulations to calculate the elastic and inelastic post-slab installation deformations caused by the sequence of tall buildings construction. In the proposed procedure, it was suggested that columns shortening can be accurately predicted during the preliminary design while the designer has some control over the specifications and enough information about the construction sequence. Although that procedure suggests a compensation work by adjusting the slab form vertically, it has no limits to the columns shortening or slabs tilt due to differential shortening at which the slab cambering is cost effective and convenient. The method presented by (Ghosh 1996) is a refinement of (Fintel and Khan 1969) method which gives according to (Jayasinghe and Jayasena, 2005) almost the same results. Swamy and Arumugasaamy (1978) researched the complexity of reinforced concrete columns behavior in buildings by observing the movement of an eight-story building during construction and six years later in service. During that period, the estimation of stress history was obtained using stress meter embedded into the observed columns. The study was based on separating the three components of the total strain, elastic, shrinkage and creep strains. The elastic strain was computed by knowing the stress history and the elastic modulus from laboratory control tests. The shrinkage and creep strains were predicted using tests on unreinforced concrete specimens which were under the same environmental conditions of the building. The time-dependent strains were then corrected to account for age at loading, size effects and reinforcement. The good agreement between measured and predicted values reflects the accurate and precise procedure of the latter study utilizing controlled experiments on specimens of the same concrete where the same environmental conditions are applied. Indeed, the method provided an accurate prediction for purpose of study and further research, however it’s not a practical method for designers who need to predict the strains in the design stage much earlier than construction where tests take place. That shortcoming was rectified by a following study (Swamy and Arumugasaamy, 1981) where a simple method was developed to predict time-dependent deformations occurring during service life up to 50 years. The proposed method was based on a creep factor chart which includes reinforcement percentage, age at loading, member size and relative humidity. And to ensure reliability of the proposed method, it was applied on two reinforced concrete structures whose movements were monitored in the site under incremental loading. The method showed excellent agreement with the measured values with error factor of 11% at all ages. The latter method can hence be applied by practicing engineers with available information in the design stage such as, the expected loading history and cubic strength at 28 days. A good agreement between measured and predicted values of time-dependent effects was also reported by (Pan, Liu & Bakoss 1993) who created a method for column shortening prediction in tall buildings. Kim and Cho (2004) perceived the importance of comparing the calculated column shortening to field measurement to assess the varying results of different prediction models. In their study, the strain in a 256m high concrete building was measured for 21 months and compared to three models results, ACI 209R-92, CEB-FIB and PCA. While the ACI 209R-92 model overestimated the strain, the measured values showed good agreement with the strain curve pattern but not with results of the strain calculated using PCA and CEB-FIB models. Although Kim and Cho (2004) concluded that the difference between measured and calculated values are related to the complicated behavior between concrete and the imbedded steel column, no accurate method or a modification to the prediction models to incorporate the characteristics of the steel embedded column were provided. Seol et al. (2008) presented an analytical and experimental studies on the shortening of two types of concrete columns, reinforced concrete (RC) and steel reinforced concrete (SRC). The study was focused on moisture diffusion inside the concrete section and its different routes which are more obstructed by the steel section in the steel reinforced concrete columns. The study compared the theoretical results obtained using CEB-FIB model to the experimental results obtained by measurements of real structure columns shortening. It was concluded from the comparison that CEB-FIB model overestimates the shortening of steel reinforced concrete columns, where it shows good agreement to reinforced concrete columns. That difference is an expected result where the steel section inside the concrete column obstructs the moisture diffusion and hence reducing moisture run out keeping shrinkage and creep effects lower than reinforced concrete columns. In matter of fact, the high percentage of steel in a steel reinforced concrete column reduces the total shortening of the column considerably since the steel section undergoes only elastic shortening causing the normal prediction model to overestimate its shortening. The fact that embedded steel section reduces the column shortening is presented in the design of Taipei 101 Tower, a 507 m height building (Shieh, Chang and Jong, 2010). Using ACI 209R-92 model, the maximum calculated deformation in Taipei 101 Tower was 2.1 cm at 284m height, which is relatively small for such a super tall building compared to normal reinforced concrete columns. The prediction of axial shortening of a 300 m height building was studied by (Kumagai, 2002) who considered the effect of steel reinforcement on the axial shortening by conducting creep tests on reinforced concrete columns rather than plain concrete. Because the theoretical values showed a good agreement with the actual test results, that method was used in the prediction of overall columns shortening of the 300 m height reinforced concrete building. The study concluded that no significant tilt in the slab due to vertical displacement of peripheral columns and core shear walls. In the latter study, the accuracy of the proposed method was of high level because the creep test was done under heat curing which simulates the hydration heat of a real structure concrete. Vafai et al. (2009) also calculated the axial shortening of shear walls and columns in a 45 stories concrete building. The main feature of the latter study was the nonlinear behavior in staged construction analysis. The effect of construction rate (days per story) was considered by comparing different rates and the corresponding settlements. It was found that the higher the construction rate the more column shortening. The relative humidity was also considered by comparing different values of humidity and its effect on columns shortening. It was found that increasing the relative humidity decreases the time-dependent effects. Although the staged construction analysis was presented in the latter study, the results stands to reason and are implied in the nature of creep and shrinkage and the concept of sequential loading analysis where the building is loaded floor by floor and increasing the construction time between two floors will consequently increase the column shortening. Moragaspitiya et al. (2010) also adopted the construction sequence method to develop a numerical procedure to calculate columns shortening. However, a more complex procedure combining time history analysis with construction sequence using finite element method was presented in the latter study. The results indicated the ability of that method to incorporate the geometric complexity of the structure as well as the influence of outrigger and belt walls included in the considered building. It showed that creep and shrinkage effects can be captured accurately using more complex and detailed analysis which, in fact, time and effort consuming work compared to conventional construction sequence analysis. Such as in (Waghmare et al. 2015) study who presented a procedure to calculate the elastic and inelastic deformations of 40 story reinforced concrete building using staged construction analysis. The study revealed that around 60-75 % and 70-85% of the total shortenings of columns and walls respectively are caused by time-dependent effects. The previous fact that creep and shrinkage affect walls more than columns is included in all the prediction models formulas where creep and shrinkage effects will increase when volume-to-surface ratio is decreased such as in walls. Construction staged analysis was also investigated by (Kim et al. 2012) to calculate the column shortening. However, a different procedure was adopted in the latter study called lumped construction sequence, where each group of floors is lumped in one step and all floors of each group are supposed to be constructed simultaneously. Kim et al. (2012) compared the values obtained by that procedure to those of conventional (floor-by-floor) construction sequence analysis for an 80 stories reinforced concrete frame. It was concluded that the resulting total shortening curve of the lumped model revealed a good agreement to the exact one. Indeed, the lumped construction sequence model reduces the computation time compared to that of exact model especially for tall buildings where repetitive analysis is required consuming more design time. In addition, it gives a good estimation in the early design stage where the method of construction, loading age and many factors are undetermined. However, the overestimation of results of that method is expected due to applying the dead load of many floors at one time. Consequently, the impact on the final design is dependent on the lumping rate which at the end has to be compared to an exact model to be used in the final design. Maru et al. (2003) explored the restraining effect of horizontal members and steel reinforcement on column shortening in high-rise buildings. Although the precise and complicated procedure provided by Maru et al., considering the restraining effects of beams and reinforcement independently in different steps is a matter of question of the soundness of the proposed method which falls short of the method proposed by (Kim 2013) that instantaneously considers the effects of beams and steel reinforcement. Kim concluded that differential shortening is reduced by considering the restraining effect while more beam stiffness results in more differential shortening reduction. Kang et al. (2011) developed a procedure to estimate time-dependent deformations of a 258m reinforced concrete building. The study included field measurements on columns and walls axial shortening by embedding vibrating wire strain gauges into selected columns before casting concrete. The predicted long-term values were based on both ACI 209.2R-08 and PCA models. A consistence between predicted and measured values was reported by the latter study, thus, it's possible to predict column shortening in high-rise buildings with good accuracy using the available time-dependent prediction models. In addition to column shortening, a very recent study (Hamed and Lai, 2016) investigated the effects of creep on the whole behavior of RC columns including geometric nonlinearity, cracking and aging. A combination of material and geometrical nonlinearity of time-dependent effects was included in an analytical model developed by the latter study where a numerical model was created to magnify the internal stresses and deformation of RC columns. The study concluded that a failure of an RC column can occur under sustained load that are much less than the elastic capacity. The nonlinear creep analysis conducted in the latter study revealed the importance of considering the nonlinearity for both material and geometric in concrete columns long-term deformations and opened a way to more future researches to fully understand and clarify the various phenomena encountered due to creep in RC columns.

2.6 Differential Columns Shortening

In reinforced concrete buildings, the distribution of stresses between vertical supporting members (walls and columns) are not equal, due to the unification system adopted for columns sizes for practicality of design and construction, or where the walls are designed to resist lateral loads resulting in bigger sections than required for vertical loading. The difference between vertical members' axial stiffness and stresses leads consequently to different shortening of those members as the stress is the primary cause of both elastic and creep shortening. The effects of differential column shortening are of higher interest in high-rise buildings where applied loads are huge leading to considerable shortening and overall building settlement and sway. When the building is symmetric horizontally and vertically, the problem is restricted to slab tilt which induces additional moments in horizontal members affecting the nonstructural elements, finishes, services, partition walls and cladding which are installed before the most portion of columns shortening takes place i.e. completion of construction. In this case, the prediction of this behavior is accompanied with special details allowing a relative movement of those elements to the structure without cracking or visible distortion. However, ignoring the effects of differential shortening caused failures in buildings which can be found in many examples. Plewes (1977) reported crushing of cladding in a tall building due to frame movement causing the cladding supports to rotate at both ends and distort the cladding. The problem of columns shortening gets more serious in asymmetric vertical buildings where the deferential shortening causes the building to laterally sway due to higher mass of one part of the building compared to the others. Scanning the many literature on columns deferential shortening in tall buildings , it can be obviously noted that all of them are considering the differential columns shortening in symmetric vertical buildings, where the gravity load and creep and shrinkage induced sway was not discussed earlier. Jayasinghe and Jayasena (2004) studied the differential shortening of seven different symmetric buildings variated in height and concluded from the results that the number of stories has no effect on the magnitude of differential shortening between two neighboring columns. In fact, because the study was based on maximum of 40 stories building, the stresses between members are not of high difference making the latter conclusion relatively right for buildings of such height. However, in tall buildings, the significant difference between stresses causes the differential shortening to be directly proportional to building height, i.e. increasing the building height will not only increase the absolute shortening but also the differential one, especially when high-strength concrete is used and the columns sizes are decreased. Song and Cho (2002) used a probability analysis and a deterministic theory to analyze the differential column shortening. The compared results were in good range of agreement. In their study, Huang et al. (2007) also used the probability theory as a tool to predict the differential column shortening. Chowdhary and Sharma (2009) investigated numerically the differential shortening between shear walls subjected to elastic and inelastic shortening and steel frames which have only elastic shortening. By increasing the shear walls reinforcement percentage in the latter study, the differential shortening between columns and shear walls was decreased. It confirmed the fact that reinforcement reduces the shortening of columns since the reported decrease in differential shortening is a result of the decrease in the wall absolute shortening due to reinforcement increase. To compensate the differential shortening, different methods were proposed such as, absolute, uniform, lumped and optimal compensation. Each of them is different with the number of floors at which the shortening is compensated. Serror and El-Din (2012) studied the differential shortening of 12 different models of three buildings, 20, 40 and 60 stories. Each building was modeled in two different structural systems, shear walls and shear walls with outrigger walls and each of them was studied with and without reinforcement. The variety of the proposed models led to definite facts that first, increasing reinforcement will reduce the absolute shortening but not necessarily the differential one. Second, including outrigger walls in high-rise buildings reduces the differential shortening between walls and columns which was also confirmed by (Kamath, Rao and Shruthi, 2015) who reported 34% reduction in differential shortening by adding an outrigger at an optimum level at floor 35 of a 60 story building. Additional reduction of 14% was found by adding another outrigger at floor 45. Kim and shin (2014) used the same two methods, reinforcement and outrigger wall in reducing the differential shortening of an 80 story building and succeeded. Woo, Choi and Park (2013) proposed a practical method for differential shortening compensation by applying moving average correction technique. The procedure is based on dividing the building stories into groups where every story in that group utilizes the same average compensation amount. The method provided a practical solution to differential shortening reducing the time and effort to calculate the compensation value at each floor of a tall building. However, its accuracy is highly dependent on the number of stories in each group.

Chapter 3

RESEARCH METHODOLOGY

This chapter describes the approach of this research and the procedure adopted to achieve its purpose. It provides a step by step process to explain the procedure of the chosen methods and models of prediction. Moreover, it provides guidelines for comparing the theoretical results with the actual site readings of the presented case study.

3.1 Research Approach

The literature review presented in this research is an evidence of the complexity of predicting elastic and time-dependent effects on reinforced concrete buildings. The quantitative work of those pioneering researchers has created methods and formulas for using in design and further future researches. As such, a quantitative methodology is implemented in this research in a way to continue upon the methods and formulas that have been already developed. In specific, many factors used in this research are extracted from the findings of the previous models. Some of those factors are based on realistic information available about the case study presented in this research and some are estimated where information is not available. The quantitative procedure allowed this research to investigate and evaluate those models numerically by comparing their results to actual site reading taken during the construction of the building presented as a case study in this research.

This investigation is based on case study research method. The particular case presented in this study is used to focus on the settlement and sway phenomena in vertically asymmetric tall buildings. The data on the presented case were collected from the site operation office by consultant who was responsible for the construction of the case building and had an access to the project information and records. That information includes detailed drawings, construction statement, materials properties and site survey readings. The focus on the case study is then narrowed to column shortening in tall buildings caused by elastic and time-dependent strains and how they affect the overall settlement and sway of tall buildings. By applying the chosen model on the case study, the findings are used to challenge the accuracy of that model by comparing them to the case study records. That represents the main purpose of this research.

3.2 Research Strategy

The main purpose of this research is to quantitatively investigate a correlation between theoretical and actual columns shortening in tall buildings. The effects of this phenomenon are investigated by carrying out a boarder analysis to determine the overall settlement and sway of a vertically asymmetric tall building. The quantitative analysis will be carried out on a specific tall building located in Dubai and constructed in 2008. The results of this case study building will be compared to those taken from site readings during the construction. Upon the comparison, the prediction model will be assessed in its ability to provide realistic results.
The strategy adopted in this research to achieve its objectives is based on the following steps:

- Providing the steps by which the columns shortening are predicted and how accumulated to provide column settlement.
- Extracting the required formulas from ACI 209R-92 which are needed to predict the three shortening components, elastic, creep and shrinkage.
- Applying the columns shortening procedure and the extracted formulas in a developed excel sheet to calculate column shortening and settlement at any age caused by any stage of loading.
- Presenting the actual site readings of the presented case study and providing the settlement charts associated with those readings.
- Using the developed excel sheet to predict the shortening components of a certain column in 9 floors to study and compare the shortening behavior of those columns.
- Calculating the monitored column and wall settlement caused by adding groups of floors in a similar style of the actual results using the developed excel sheet.
- Analyzing the building using Etabs software to calculate columns settlement using the CEB-FIP method for time-dependent effects.
- Comparing all the three sets of results, actual, theoretical and Etabs by plotting them on the same settlement chart.
- Drawing the final settlement charts (actual, theoretical and Etabs) at the end of construction for further comparison.

- From the same Etabs model, the sway results are extracted using two different analyses, linear and nonlinear staged construction.
- Sway charts are plotted and compared for the two analyses.
- Modifying the case study building by removing the last 12 stories which caused the vertical asymmetry, called model-2.
- Analyzing Model-2 using the two previous analyses and comparing the sway results to the original building.
- The results of all comparisons are used to draw a conclusion on the accuracy and reliability of the proposed method in predicting column settlement and sway in high-rise vertically asymmetric buildings.

3.3 Data Collection

The study is associated with collecting data on that particular case through meetings and emails with the site operation office who was responsible for the supervision work on the building. All the information provided were based on the office records taken and kept during the construction of the building. The collected data includes:

- As built structural drawings and details.
- The tower settlement and sway report by (Hajjar 2007).
- Method statement for the survey of the tower during construction.
- Setting out for the construction.
- Standard monitoring record for the movement of the concrete columns and walls until the completion of the last slab.
- Schedules and charts for actual site readings for columns and walls settlement taken during the construction of the building.
- Finite element model (Etabs file) which was developed by the tower designers.

Chapter 4

RESULTS

This chapter describes the numerical procedure of predicting the different components of column shortening and how those components are combined using the superposition method to get the total settlement. It then provides the result of the proposed method used to develop the prediction program. The results are divided into two main parts, actual and theoretical. While the actual part represents a small portion of the results showing the measurements taken during the construction of the case study building, the theoretical results, on the other hand, represent the majority of this chapter where different types of results such as, column shortening, settlement and sway are shown and compared to the actual ones.

4.1 Procedure of Column Shortening Prediction

The procedure adopted in this research to predict the total column shortening is a representation of the actual sequence of the whole construction process, where the considered column is added with the load above story by story. The total column shortening is determined from the accumulation of elastic and time-dependent shortenings induced by slab self-weight for each additional floor. A spreadsheet using Excel was developed for that purpose. To overcome the complexity of the problem, the following assumptions were considered:

- Every applied load produces a continuous deformation component for the considered period of loading.
- The applied load produces no change in stress with time and the resulting deformations over a period of time are cause by creep and shrinkage.
- Although column length changes with time, it's considered to remain constant and equal to floor height when calculating the different components of deformation.
- The influence of age on concrete properties, such as shrinkage strain, creep coefficient and modulus of elasticity is considered.
- Every column is cast up to a pre-determined level, hence all the deformation occurred to columns below before adding that column are ignored.
- Strain component, elastic, creep and shrinkage are independent and additive.

4.1.1 Compensation of Column Length

In the developed program, the slab is considered to be positioned in the exact predetermined elevation rather than the exact column length or story height which is consistent with the compensation measure followed in the construction of tall buildings which called total station elevation. Based on that, the column length in floor (n-1) prior to adding floor slab (n) is calculated as the summation of the story height and the displacement of the column below:

$$L_n = H_n + \Delta_{n-1} \qquad (5)$$

Where L_n The actual constructed column length prior to adding slab at stage n

H_n Height of story n

Δ_{n-1} Total elastic and inelastic displacement of column in story n-1

The procedure for calculating Δ_{n-1} is shown in fig.2 and explained as follows: the column (n-1) is cast up to the real elevation by the proposed compensation method applied in the construction. Hence, the displacement of column (n-1) is only calculated from the load applied by adding floor (n-1) for elastic and time-dependent effect. That is expressed by Eq.6

$$\Delta_{n-1} = \sum_{i=1}^{n-1} S_{i,n-1} \qquad (6)$$

Where $S_{i,n-1}$: the shortening of column in floor i caused by adding floor n-1

The prediction of compensation value Δ_{n-1} is of less importance to this research since the compensation method can be applied at site by the total station elevation technique without the need for this value which is theoretically calculated, and hence that value was not included in the spreadsheet.

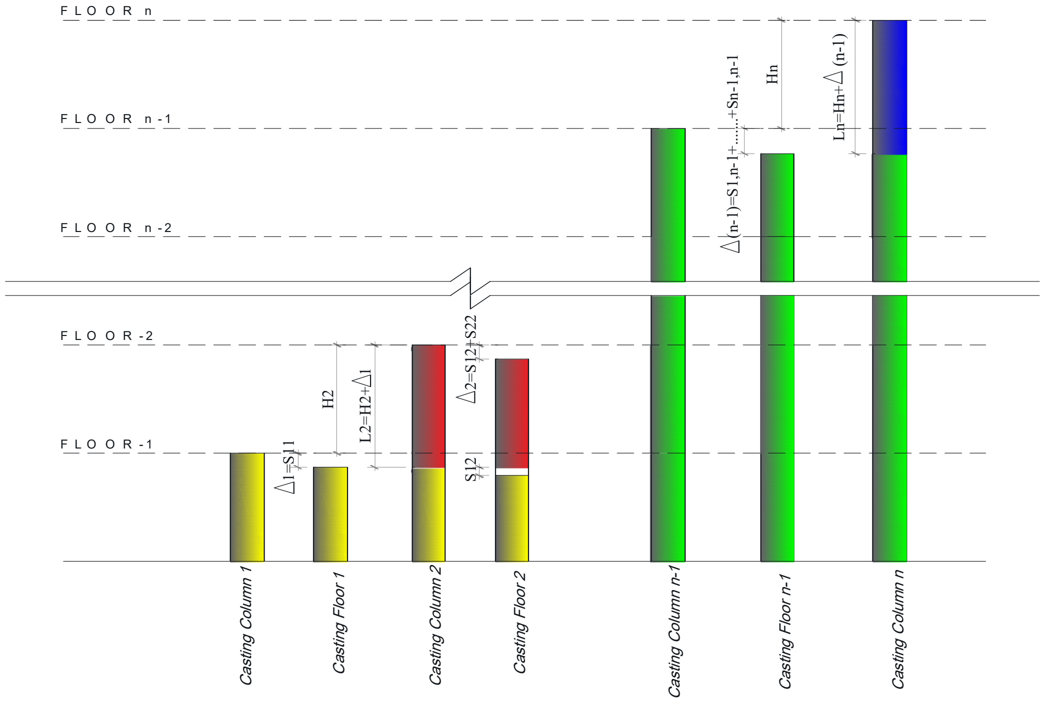


Fig.2 Shortening and compensation technique

4.1.2 Total Column Settlement

Based on the above discussion, it's notable that the total displacement of a column in any floor from the predetermined position is caused only by the floors added after that particular floor, since the column is cast up to that position with no shortening effects of the columns below. Thus, it can be expressed by Eq.7 that the total displacement on the top of a column in a certain floor is equal to the shortenings summation of the columns below caused by adding each floor separately above that considered column up to the last considered floor.

$$\Delta_{nj} = \sum_{k=1}^{n} TS_{kj} \qquad (7)$$

Where Δ_{nj} The total displacement of a column in floor (n) after casting floor (j)

TS_{kj} The total shortening of a column in floor (k) below floor (n) caused by adding number of floors (j-n+1)

The calculation of TS_{kj} is based on the accumulation of column shortening caused by adding each of the considered floors (j-n+1) individually as expressed by Eq.8.

$$TS_{kj} = \sum_{h=n}^{j} S_{ih} \qquad (8)$$

Where S_{ih} Shortening of a column in floor (i) caused by the instantaneous and time-dependent effects of adding one single floor h.

For example, the total displacement of column in floor 3 after adding floor 5 is the summation of columns shortening caused by adding floors 3,4 and 5 considering the time between casting column 3 to casting the 5th floor for time-dependent effect.

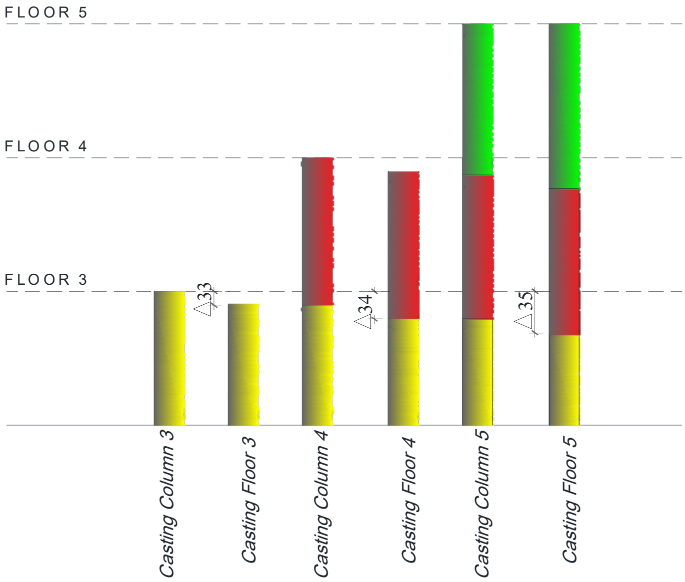


Fig.3 Total column shortening

$$\Delta_{3,5} = TS_{1,5} + TS_{2,5} + TS_{3,5}$$
$$= (S_{1,3} + S_{1,4} + S_{1,5}) + (S_{2,3} + S_{2,4} + S_{2,5}) + (S_{3,3} + S_{3,4} + S_{3,5})$$

Predicting S_{ih} includes the three components of column shortening, elastic, creep and shrinkage. Hence, S_{ih} is not constant and changes with time from casting that particular column to the considered stage k.

$$S_{ih} = L_n(\varepsilon_e + \varepsilon_c + \varepsilon_{sh}) \qquad (9)$$

Where ε_e elastic strain ε_c: creep strain ε_{sh}: shrinkage strain

In fact, the considered column length L_n is not constant and keeps changing with time due to the time-dependent effects. However, to simplify the proposed procedure, it's considered constant and equal to floor height since that will have minimal effect on the predicted values.

4.1.3 Elastic Strain

The prediction of elastic strain is derived from Eq.10 independently for each load induced by additional floor

$$\varepsilon_e = \frac{P_k}{Ec_t\,A} \qquad (10)$$

Where P_k The applied load from adding floor k

A Area of the column surface

Ec_t Elasticity modulus at concrete age (t) at loading calculated from Eq.2 using concrete strength at age (t) from Eq.3

4.1.4 Creep Strain

The procedure for creep strain prediction presented in this paper is a direct application to the ACI 209R-92 model. It's based on finding the creep coefficient (v_t) and then multiplying that coefficient by the elastic strain ε_e of the initial loading to get the creep strain ε_c as shown in Eq.11.

$$\varepsilon_c = v_t * \varepsilon_e \qquad (11)$$

Creep coefficient v_t is calculated from Eq.12.

$$v_t = \frac{t^{0.6}}{10+t^{0.6}} * v_u \qquad (12)$$

Where v_u , the ultimate creep coefficient defined as ratio of ultimate creep strain to elastic strain given in Eq.13 as recommended by ACI 209R-92 where data for conditions and aggregates creep are not available.

t in days, time after loading

It should be noted that (t) used to find $(f'c)_t$ and Ec_t is the concrete age at loading while to find creep and shrinkage effects, t is the loading age.

It's noted from Eq.12 that the required creep strain for a specified time after loading is a proportion of the ultimate strain.

$$v_u = 2.35 * \gamma_c \qquad (13)$$

Where γ_c is the product of corrective factors related to all variables affecting the creep strain.

$$\gamma_c = \gamma_{vs} * \gamma_\lambda * \gamma_{la} * \gamma_\Psi * \gamma_s \qquad (14)$$

Where

γ_{vs} : Corrective factor of volume-surface ratio of member

γ_λ : Corrective factor for ambient relative humidity

γ_{la} : Corrective factor for loading age

γ_Ψ : Corrective factor for fine aggregates percentage

γ_s : Corrective factor for slump

Eqs.15 to 19 are proposed by ACI 209R-92 and used in the Excel sheet to calculate the correction factors for creep strain.

$$\gamma_{la} = 1.25(t_{la})^{-0.118} \quad (15)$$

$$\gamma_{\lambda} = 1.27 - 0.0067 * \lambda \quad (16)$$

$$\gamma_{vs} = \frac{2}{3} * [1 + 1.13 * e^{(-0.0213\, v/s)}] \quad (17)$$

$$\gamma_{s} = 0.82 + 0.00264 * s \quad (18)$$

$$\gamma_{\Psi} = 0.88 + 0.0024 * \Psi \quad (19)$$

Where

t_{la} in days is loading age

λ is relative humidity in percent

h in mm is the average member thickness

s slump in mm

Ψ percentage of fine aggregates to total aggregates

4.1.5 Shrinkage Strain

As recommended by ACI 209R-92, at any time t, the shrinkage strain after shrinkage is considered $(\varepsilon_{sh})_t$ is a proportion from ultimate shrinkage strain $(\varepsilon_{sh})_u$, Eq.20.

$$(\varepsilon_{sh})t = \frac{t}{35+t} * (\varepsilon_{sh})u \quad (20)$$

Where t in days, the time after shrinkage in considered, which is equal to concrete age minus the initial wet curing period (considered as 7 days)

$$(\varepsilon_{sh})u = 780\gamma_{sh} * 10^{-6} \quad (21)$$

$$\gamma_{sh} = \gamma_{\lambda} * \gamma_{vs} * \gamma_{s} * \gamma_{\Psi} \quad (22)$$

Where γ_{sh} the product of correction factors for shrinkage

$$\gamma_{\lambda} = 1.4 - 0.0102 * \lambda \quad (23)$$

$$\gamma_{vs} = 1.2 * e^{(-0.00472\, v/s)} \quad (24)$$

$$\gamma_{s} = 0.89 + 0.00161 * s \quad (25)$$

$$\gamma_{\Psi} = 0.30 + 0.014 * \Psi \quad (26)$$

Calculating shrinkage strain of a column for a certain period is based on the differential shrinkage between the start and the end of that period. For example, the shrinkage strain for a column between 24 and 40 days age is equal to

$(\varepsilon_{sh})40 - (\varepsilon_{sh})24$

Where $(\varepsilon_{sh})40 = \frac{(40-7)}{35+40-7} * (\varepsilon_{sh})u$ and $(\varepsilon_{sh})24 = \frac{(24-7)}{35+24-7} * (\varepsilon_{sh})u$

4.2 Procedure of Excel Sheet Calculation

The above formulas were used to develop spreadsheets in order to predict the final settlement of a considered column in any floor caused by casting floors above as following:

1- An Excel sheet was developed to estimate the total axial shortening (elastic, creep and shrinkage) of any column caused by adding one single floor and get the value S_{ih}.

2- The spreadsheet was prepared to sum up all the column shortenings of that particular column caused by adding a group of floors to get the value TS_{kj} as shown earlier in figure 3.

3- The spreadsheet was replicated to calculate the value TS_{kj} for each column below the considered column caused by adding the same group of floors.

4- Another Excel sheet was prepared to sum all the column shortening values TS_{kj} to get the final value Δ_{nj}

5- Steps 3 and 4 were repeated for each required group of floors to get the final settlement of that particular column after each five floors construction above that column.

6- Displacement charts were constructed to represent the column displacement for each stage similar to the actual site reading charts taken during the construction of the case study building.

Shortening Prediction of Column in Floor (1) by Adding Floors (4 to 8)

Input Data			Output Data	
Floors Data	Considered Column Floor	1	Elastic Shortening Δe (mm)	0.1044
	Floor Height (m)	3.2		
	Casting Floors from	4	Creep Shortening Δc (mm)	0.03
	to	8		
	Rate of Construction (days/floor)	3	Shrinkage Shortening Δsh (mm)	0.058
Elastic Data	$f'c$ (mpa)	70	**Total Shortening TS_{kj} (mm)**	**0.192**
	Column Cross Section (m²)	1.54		
	Load Increment (kN/floor)	320		
Creep & Shrinkage	Column volume/surface (mm)	350		
	Percentage of fine agg. (%)	30		
	Slump (mm)	100		
	Relative Humidity (%)	80		

Input Notes

Considered column floor : the floor at which the column deformation is required

Casting floors: refers to the slab loads causing the considered column shortening

Column in floor (*i*) suports slab (*i+1*)

Column in basement (*i*) input as -*i*

Column in ground floor input as 0

Fig.4 Developed spreadsheet for column shortening prediction

4.3 Case Study Actual Site Readings

As mentioned in chapter 1, the building presented as a case study in this research was monitored during the construction for both settlement and sway.

The survey method was performed as following: (Hajjar 2007)

- Assigning seven levels (3rd, 10th, 21st, 29th, 41st, 50th and 60th) for monitoring called "monitoring floors".
- Assigning designated points on a certain column and wall called "monitored column/wall". The monitored column and wall are shown in figure 5.

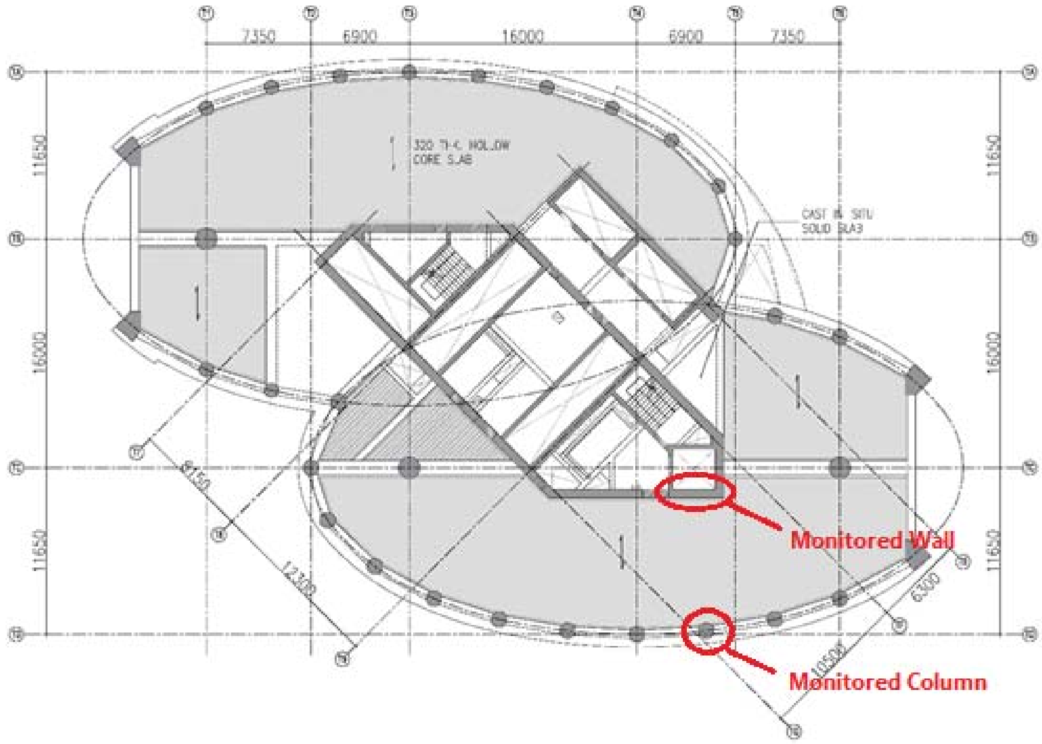


Fig.5 Monitored Column and Wall

- Monitoring the designated point's settlement with reference to a fixed benchmark existed on ground floor.
- The frequency of monitoring survey was at every five stories of the tower construction progress.

The survey results for the monitored column and core wall are presented in Figures 6 & 7 respectively. Each chart represents the settlement of the considered column/wall after casting a certain floor mentioned at the horizontal axis. For example, the settlement of the peripheral column in floor 21 after casting floor 48 is 9mm.

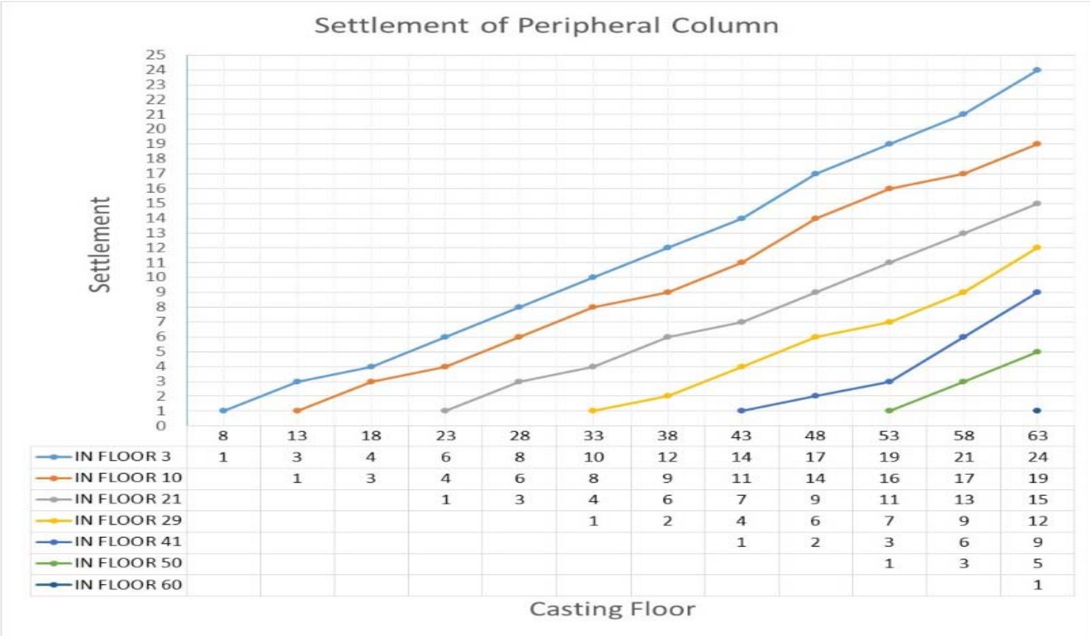


Fig.6 Site readings of peripheral column settlement

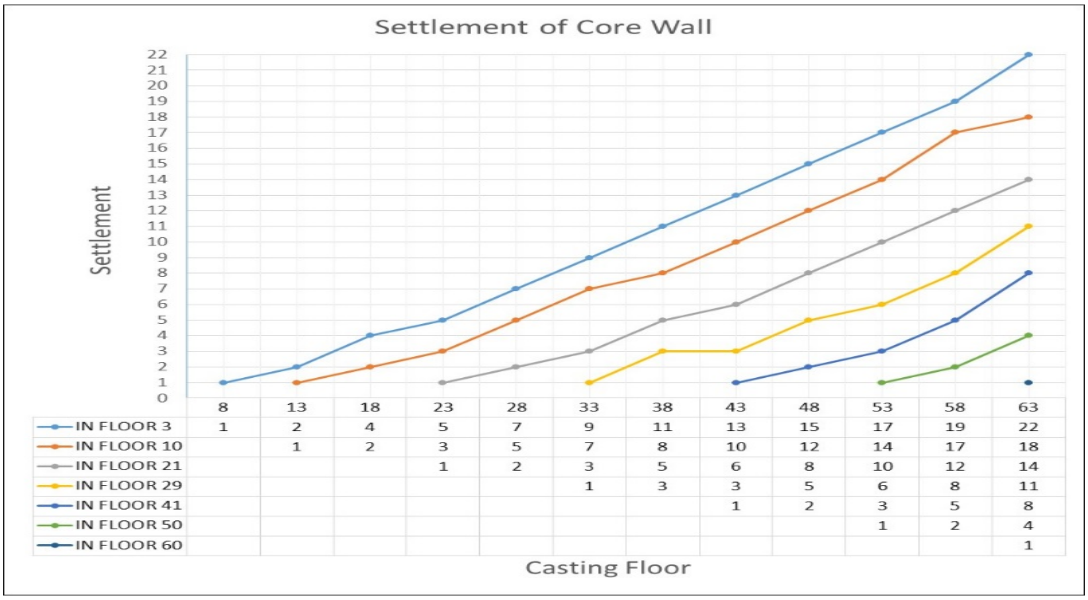


Fig.7 Site readings of core wall settlement

Each survey value in the previous charts for a column/wall in a certain floor involves the shortening of the columns below caused by casting the next five floors and the time effects of the previously casted floors. Hence, the shortening of columns can't be predicted from the survey values since it's included in the settlement value.

4.4 Case Study Theoretical Results

The developed spreadsheet in section 4.2 is used to estimate the columns and walls shortening in each floor and then accumulate them to predict the settlement of the considered column and wall in the same survey results style for comparison between actual and theoretical values. The monitored column and wall properties are presented in table 1.

Table 1. Properties of Monitored Column and Wall

Floors	$f'c$ (MPa)	Column			Wall		
		Size (mm)	Cross Section (m²)	v/s Ratio (mm)	Size (mm)	Cross Section (m²)	v/s Ratio (mm)
B5 to B1	70	Ø 1400	1.54	350	4050x750	3.038	316
G to 2nd	70	Ø 1200	1.13	300	4050x750	3.038	316
3rd to 8th	70	Ø 1100	0.95	275	3900x600	2.34	260
1stS to 9th	70	Ø 1000	0.785	250	3900x600	2.34	260
10th to 14th	60	Ø 1000	0.785	250	3800x650	2.47	277
15th to 21st	60	Ø 1000	0.785	250	3800x650	2.47	277
22nd to 26th	60	Ø 1000	0.785	250	3800x650	2.47	277
2ndS to 27th	60	Ø 1000	0.785	250	3800x650	2.47	277
28th to 33rd	50	Ø 1000	0.785	250	3700x550	2.035	240
34th to 38th	50	Ø 1000	0.785	250	3700x550	2.035	240
39th to 43rd	50	Ø 1000	0.785	250	3700x550	2.035	240
44th to 48th	50	800x1000	0.80	222	3700x400	1.48	180
49th to 50th	40	Ø 800	0.50	200	3700x400	1.48	180
51st to 53rd	40	Ø 800	0.50	200	3700x400	1.48	180
54th to 55th	40	Ø 800	0.50	200	3700x400	1.48	180
56th to 64th	40	Ø 800	0.50	200	3700x400	1.48	180

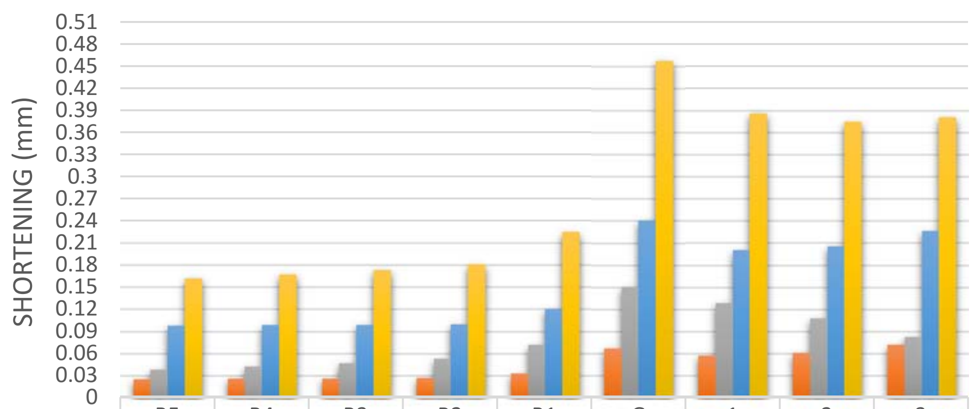
4.4.1 Shortening of Monitored Column and Wall below 4th Floor

The procedure presented in section 4.2 is used to calculate the settlement of the monitored column and wall in 3rd, 10th, 21st, 29th, 4th, 50th and 60th floor. Those column and wall are the ones which were monitored during the tower construction. Below are the steps for the column and wall in 3rd floor and similarly used for other columns floors:

- The added floors are divided into groups, 3rd to 8th, 3rd to 13th, 3rd to 18th, ….., 3rd to 63rd. Each group is used to calculate the shortening of the 3rd floor column and wall after casting this group. The resulted values are similar to those of monitoring points survey used in the case study.
- The developed Excel sheet was replicated to estimate the shortening of each column and wall below 4th floor for each of the twelve groups of floors, 3rd to 8th, 3rd to 13th, 3rd to 18th, ….., 3rd to 63rd.

4.4.1.1 Absolute Shortening of Monitored Column/Wall below 4th Floor

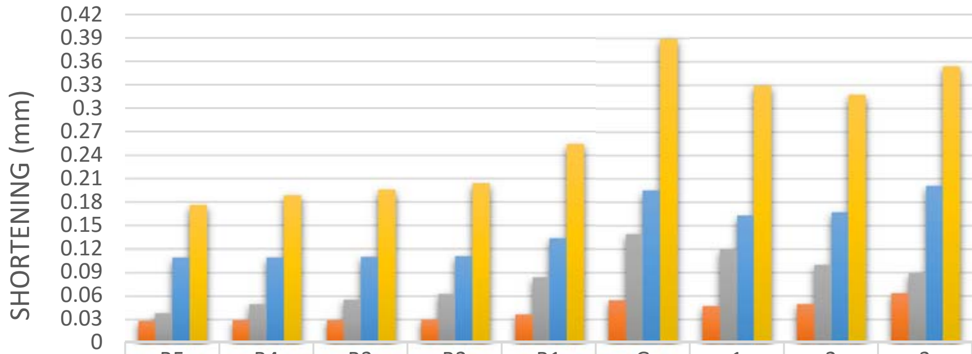
The total shortening of columns and walls below 4th floor for the first floors group (3rd to 8th) are plotted as charts in figures 8 & 9 for each shortening component.



	B5	B4	B3	B2	B1	G	1	2	3
CREEP	0.0255	0.026	0.0263	0.027	0.0329	0.0672	0.0576	0.0613	0.0721
SHRINKAGE	0.0382	0.0425	0.0475	0.0534	0.0719	0.1507	0.1291	0.108	0.083
ELASTIC	0.0986	0.099	0.0996	0.1003	0.1203	0.2402	0.2	0.2056	0.2265
TOTAL	0.1623	0.1675	0.1734	0.1807	0.2251	0.4581	0.3867	0.3749	0.3816

FLOOR

*Fig.8 Shortening of monitored **columns** below 4th floor due to adding floors 4th to 8th*



	B5	B4	B3	B2	B1	G	1	2	3
CREEP	0.0283	0.0287	0.0294	0.0299	0.0365	0.0546	0.0468	0.0499	0.0639
SHRINKAGE	0.0382	0.0499	0.0557	0.0627	0.0844	0.1397	0.1197	0.1002	0.0891
ELASTIC	0.1095	0.11	0.1106	0.1114	0.1334	0.1954	0.1628	0.1674	0.201
TOTAL	0.176	0.1886	0.1957	0.204	0.2543	0.3897	0.3293	0.3175	0.354

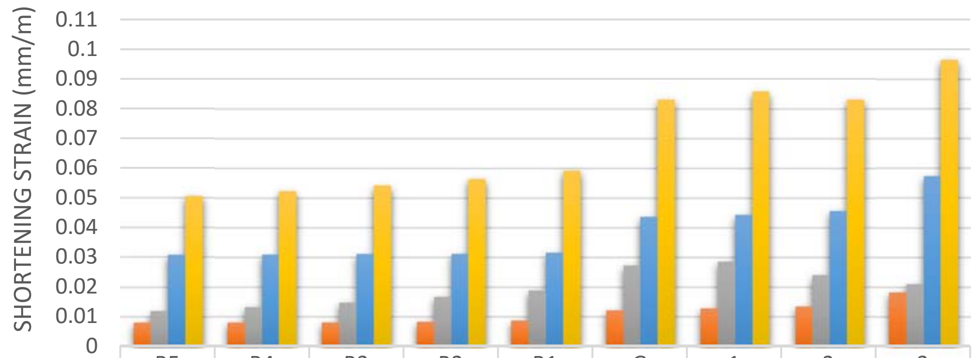
FLOOR

Fig.9 Shortening of monitored ***walls*** *below 4th floor due to adding floors 4th to 8th*

By observing the shortening results in figures 8 and 9, it can be noticed that the three shortening components (elastic, creep and shrinkage) and the total shortening increase steadily with column floor until a sudden increase in the ground floor column for all the shortening components. The shortening components then differ for the 1st, 2nd and 3rd floor. After a decrease in the creep and elastic shortening in the 1st floor, they go back to increase in the 3rd floor. On the contrary, shrinkage shortening continues to decrease until 3rd floor. It's also noticed that there is no difference in pattern between column and wall charts. The wall shortening, however, is less than the column's for all shortening components and for total shortening as well.

4.4.1.2 Strain of Monitored Column/Wall below 4th Floor

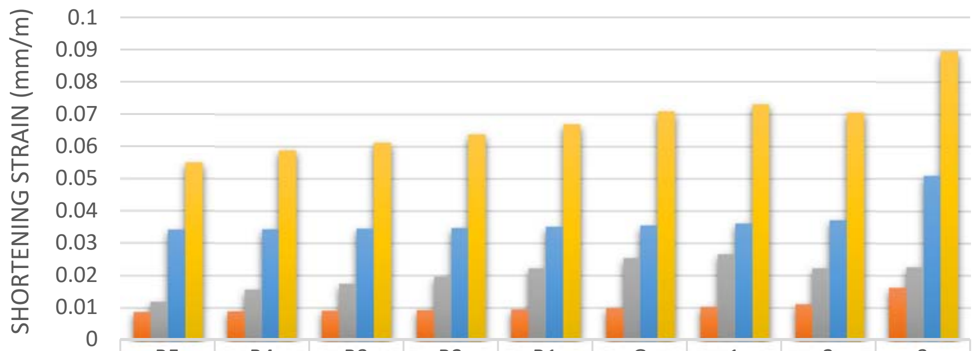
To eliminate the influence of column/wall length on the shortening and for a better understanding of this behavior, the shortening charts are transformed into strain charts by dividing each shortening component on the column/wall length.



	B5	B4	B3	B2	B1	G	1	2	3
CREEP	0.008	0.0081	0.0082	0.0084	0.0087	0.0122	0.0128	0.0136	0.0183
SHRINKAGE	0.0119	0.0133	0.0148	0.0167	0.0189	0.0274	0.0287	0.024	0.021
ELASTIC	0.0308	0.0309	0.0311	0.0313	0.0317	0.0437	0.0444	0.0457	0.0573
TOTAL	0.0507	0.0523	0.0542	0.0565	0.0592	0.0833	0.0859	0.0833	0.0966

FLOOR

Fig.10 Strain of monitored ***columns*** *below 4th floor due to adding floors 4th to 8th*



	B5	B4	B3	B2	B1	G	1	2	3
CREEP	0.0088	0.009	0.0092	0.0093	0.0096	0.0099	0.0104	0.0111	0.0162
SHRINKAGE	0.0119	0.0156	0.0174	0.0196	0.0222	0.0254	0.0266	0.0223	0.0226
ELASTIC	0.0342	0.0344	0.0346	0.0348	0.0351	0.0355	0.0362	0.0372	0.0509
TOTAL	0.055	0.0589	0.0612	0.0638	0.0669	0.0709	0.0732	0.0706	0.0896

FLOOR

Fig.11 Strain of monitored ***walls*** *below 4th floor due to adding floors 4th to 8th*

The strain charts show a more regular pattern than shortening charts when elastic and creep strains keep increasing from B5 to 3rd floor. The shrinkage strain has a peak value in the 1st floor decreasing then for both fresher and older columns. The total strain is thus in line with the dominant pattern by increasing from B5 to 3rd floor except for one decrease in the 2nd floor for both column and wall strains. By examining the elastic strain, it can be noticed that the increase in elastic strain is much less than of creep and shrinkage. For further examination of the results, the changes in strain between floors are expressed as a percentage of the column/wall strain in floor B5 as shown in table 2.

Table 2. Difference between columns/walls strain below 4th floor due to adding floors 4th to 8th

Floor		**B5**	**B4**	**B3**	**B2**	**B1**	**G**	**1**	**2**	3
Creep Per. (%)	Col.	100	101	102	105	108	152	160	170	228
	Wall	100	102	104	105	109	112	118	126	184
Shrinkage Per. (%)	Col.	100	111	124	140	158	230	241	201	176
	Wall	100	131	146	164	186	213	223	187	189
Elastic (%)	Col.	100	100	101	102	103	141	144	148	186
	Wall	100	100	101	102	103	104	106	109	149
Total (%)	Col.	100	103	107	111	116	164	169	164	190
	Wall	100	107	111	116	121	129	133	128	163

By a examining the results in table 2, it's possible to see the leap in all column strains in ground floor (108 to 152 % for creep, 158 to 230 % for shrinkage and 103 to 141 % for elastic) but not for wall whose elastic and creep strains increase steadily from B5 to 3rd floor. However, for the column, the elastic strain revealed a very slight increase until the jump in ground floor whereas for wall, the elastic strain slightly changed from B5 to a leap in 3rd floor.

4.4.1.3 Factors Affecting the Shortening and Strain of Monitored Column/Wall

In order to understand the nature of the results more broadly, the main factors used in predicting the previous column shortening are extracted from the developed Excel sheet and studied for further clarification. Table-3 shows the main contributing factors to shortening and strain difference between the columns from B5 to 3rd floor for the applied loads of floors 4th to 8th and for the period of applying those loads. Those factors are:

- Floor height.
- Average concrete strength at loading age: *f'c* is calculated from Eq.4 at each age when one floor is added. The average is calculated for the five floors.
- Average modulus of elasticity at loading: *Ec* is calculated from Eq.3 at each age when one floor is added. The average is calculated for the five added floors.
- Average age at loading: for each column the age is calculated when one floor is added. The average is taken for the five added floors.
- Applied stress from each floor: the same stress applied to similar column sections where the floor load is constant.
- Shrinkage differential age: an indicative value to express the period of column age when the differential shrinkage strain is calculated, where t1 is the time when shrinkage is considered to start which equals the age of column at loading starts (adding 4^{th} floor) minus the construction rate (3days) minus the curing period (7days), and t2 is the time after casting the 8^{th} floor. The actual shrinkage is then equal to $(\varepsilon_{sh})t2 - (\varepsilon_{sh})t1$.

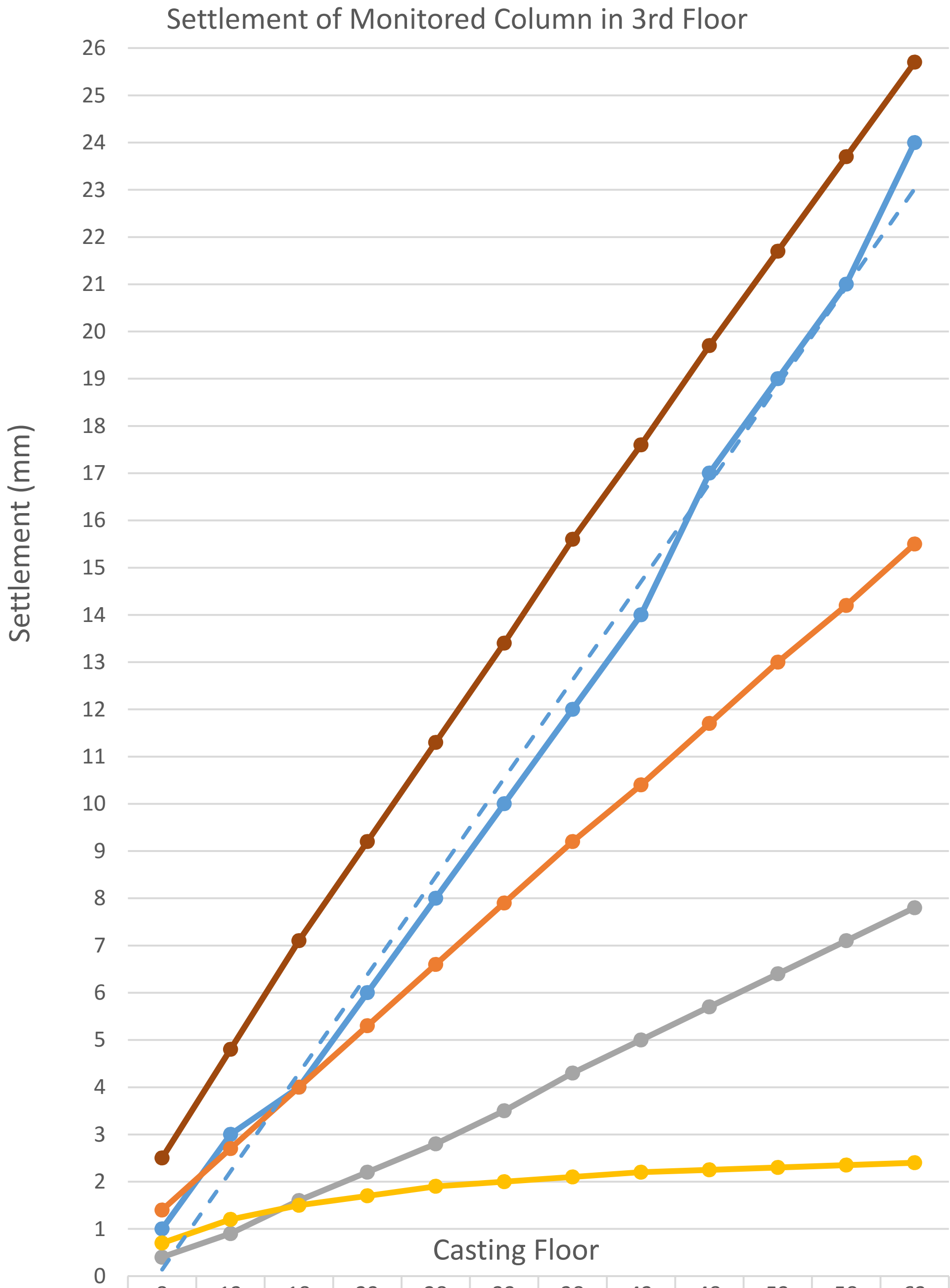
Table 3. Factors Affecting Columns Strain Below 4^{th} Floor By Adding Floors 4^{th} to 8^{th}

Floor		B5	B4	B3	B2	B1	G	1	2	3
Floor height (m)		3.2	3.2	3.2	3.2	3.8	5.5	4.5	4.5	3.95
Average $f'c_{(avg)}$ at loading (MPa)		65	64	63	62	61	59	56	53	47
Average $Ec_{(avg)}$ at loading (MPa)		33711	33554	33363	33128	32826	32428	31875	31041	29590
Average age at loading (days)		33	30	27	24	21	18	15	12	9
Applied Stress from each floor (MPa)	C	0.207	0.207	0.207	0.207	0.207	0.283	0.283	0.283	0.283
	W	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.30
Shrinkage differential age (t2-t1)		22	22	22	22	22	22	21	18	15

It can be seen from table 3 that concrete strength and modulus of elasticity are proportional to column age. The applied stress on the column have increased suddenly in ground floor due to section reduction where for the wall it increased at the 3rd floor. Shrinkage differential age is reduced after ground floor where the upper columns are newer and experience less differential time.

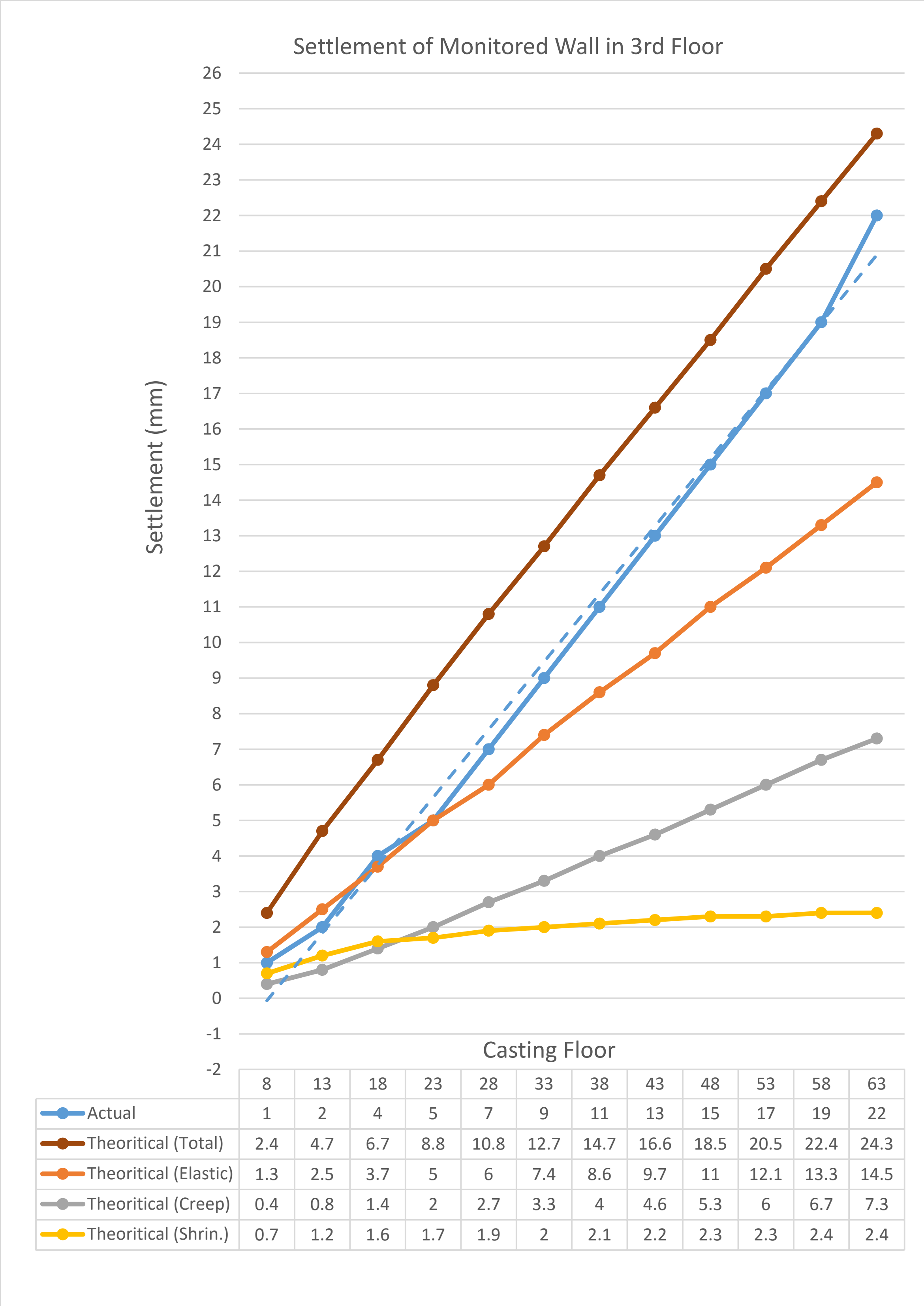
4.4.2 Settlement of Monitored Column and Wall in 3rd Floor

For each group of floors, the shortenings of all the columns and walls below 4th floor were accumulated to get the final settlement of the monitored column and wall in 3rd floor after casting that considered group of floors. The resulted settlements of each added group of floors are used to construct settlement charts similar to those in figures 6 and 7 for comparison between actual and theoretical results.



Casting Floor	8	13	18	23	28	33	38	43	48	53	58	63
Actual	1	3	4	6	8	10	12	14	17	19	21	24
Theoritical (Total)	2.5	4.8	7.1	9.2	11.3	13.4	15.6	17.6	19.7	21.7	23.7	25.7
Theoritical (Elastic)	1.4	2.7	4	5.3	6.6	7.9	9.2	10.4	11.7	13	14.2	15.5
Theoritical (Creep)	0.4	0.9	1.6	2.2	2.8	3.5	4.3	5	5.7	6.4	7.1	7.8
Theoritical (Shrin.)	0.7	1.2	1.5	1.7	1.9	2	2.1	2.2	2.25	2.3	2.35	2.4

Fig.12 Actual & Theoretical Settlement of Monitored ***Column*** *in 3rd Floor*



Casting Floor	8	13	18	23	28	33	38	43	48	53	58	63
Actual	1	2	4	5	7	9	11	13	15	17	19	22
Theoritical (Total)	2.4	4.7	6.7	8.8	10.8	12.7	14.7	16.6	18.5	20.5	22.4	24.3
Theoritical (Elastic)	1.3	2.5	3.7	5	6	7.4	8.6	9.7	11	12.1	13.3	14.5
Theoritical (Creep)	0.4	0.8	1.4	2	2.7	3.3	4	4.6	5.3	6	6.7	7.3
Theoritical (Shrin.)	0.7	1.2	1.6	1.7	1.9	2	2.1	2.2	2.3	2.3	2.4	2.4

*Fig.13 Actual & Theoretical Settlement of Monitored **Wall** in 3rd Floor*

By studying all the charts individually, it can be observed that elastic and creep charts tend to have linear relation between settlement and adding floors. In contrast, shrinkage chart starts linear after adding the first few floors, then the effect of shrinkage starts to disappear in the horizontal segment of the chart. It's obvious that elastic settlement is highly overestimated before casting the 28th floor since it exceeds the actual settlement which includes the three settlement components. The elastic settlement is then deviated decreasingly from the actual settlement chart till the end of construction. By comparing the total theoretical settlement chart and the actual chart, it can be seen that in all construction stages the settlement is overestimated, however a consistent relation is maintained by the parallelism between the theoretical chart and the approximated linear line of the actual chart. The percentage of theoretical results overestimation is tabulated in table 4.

Table 4. Difference between theoretical and actual settlement of 3rd floor column/wall

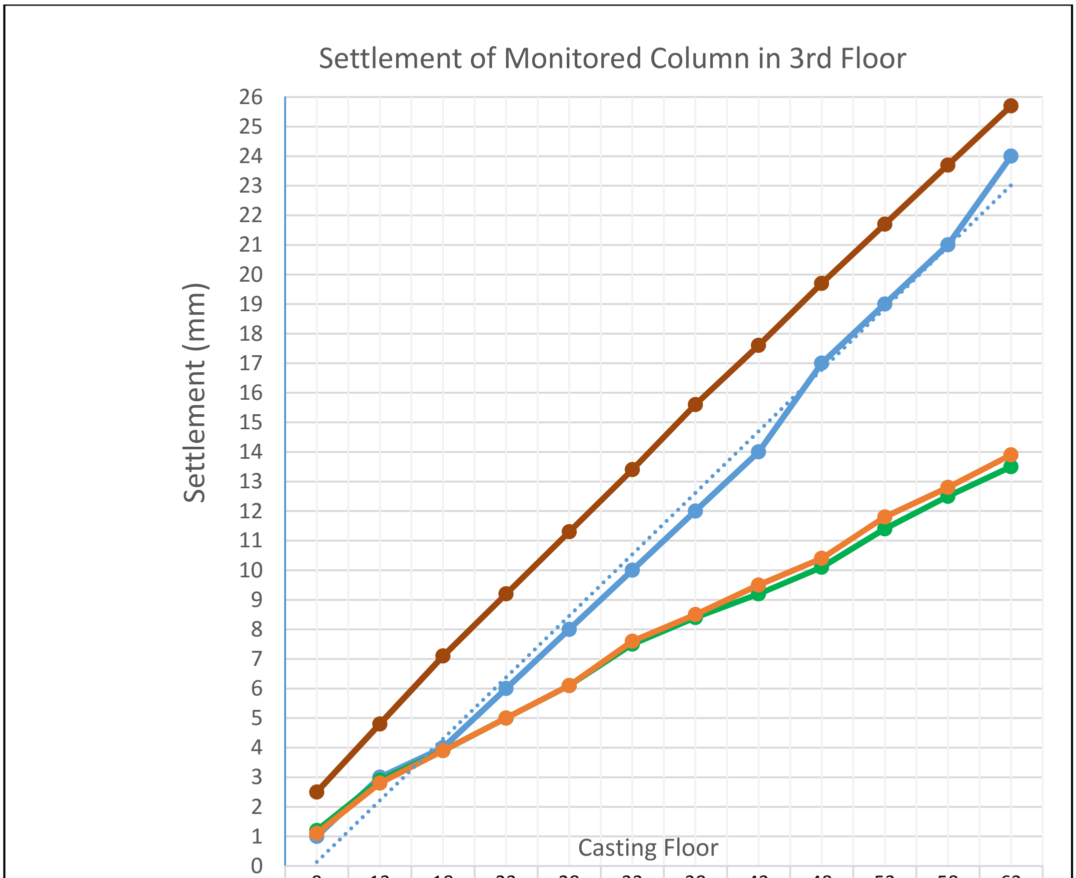
Casting Floor		8	13	18	23	28	33	38	43	48	53	58	63
Actual (%)		100	100	100	100	100	100	100	100	100	100	100	100
Theoretical (%)	**c**	250	160	177	153	141	134	130	126	116	114	113	107
	w	240	235	168	176	154	141	134	128	123	121	118	110

By a careful examination of the results in table 3, it's possible to notice the significant variation for both column and wall settlement in the early ages. The variation is then reduced with the construction progress until the theoretical settlement approaches near to the actual one in the end of building construction.

4.4.3 Settlement of Columns in all Monitored Floors

The procedure presented in 4.4.1 and 4.4.2 to predict the total settlement of monitored column and wall in 3rd floor is repeated for the same monitored column and wall in the other considered floors, 10th, 21st, 29th, 41st, 50th and 60th. The building was analyzed using Etabs software as a 3D finite element model using the CEB-FIB 90 model to predict the time-dependent settlement and the results were compared with the previous ACI model results and the actual site readings as well.

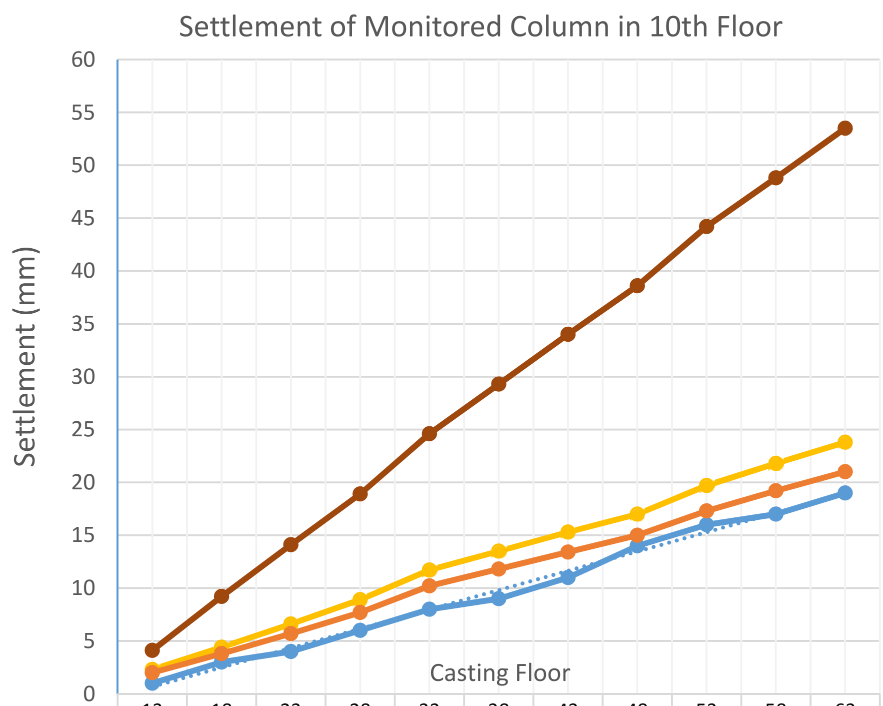
The same inputs for the developed excel sheet are used in the Etabs model considering two models, one with the columns unreinforced and the other where the columns are composite columns using the steel embedded section and the reinforcement used in the construction of the columns. The monitored column and wall settlement charts are plotted for both ACI and CEB-FIP model (with and without reinforcement) with the actual settlement chart.



Casting Floor	8	13	18	23	28	33	38	43	48	53	58	63
Actual	1	3	4	6	8	10	12	14	17	19	21	24
Theoritical (ACI)	2.5	4.8	7.1	9.2	11.3	13.4	15.6	17.6	19.7	21.7	23.7	25.7
ETABS (CEB WO/R)	1.2	2.9	3.9	5	6.1	7.5	8.4	9.2	10.1	11.4	12.5	13.5
ETABS (CEB W/R)	1.1	2.8	3.9	5	6.1	7.6	8.5	9.5	10.4	11.8	12.8	13.9

Fig.14 Actual, Theoretical and ETABS Settlement of Monitored Column in 3rd Floor

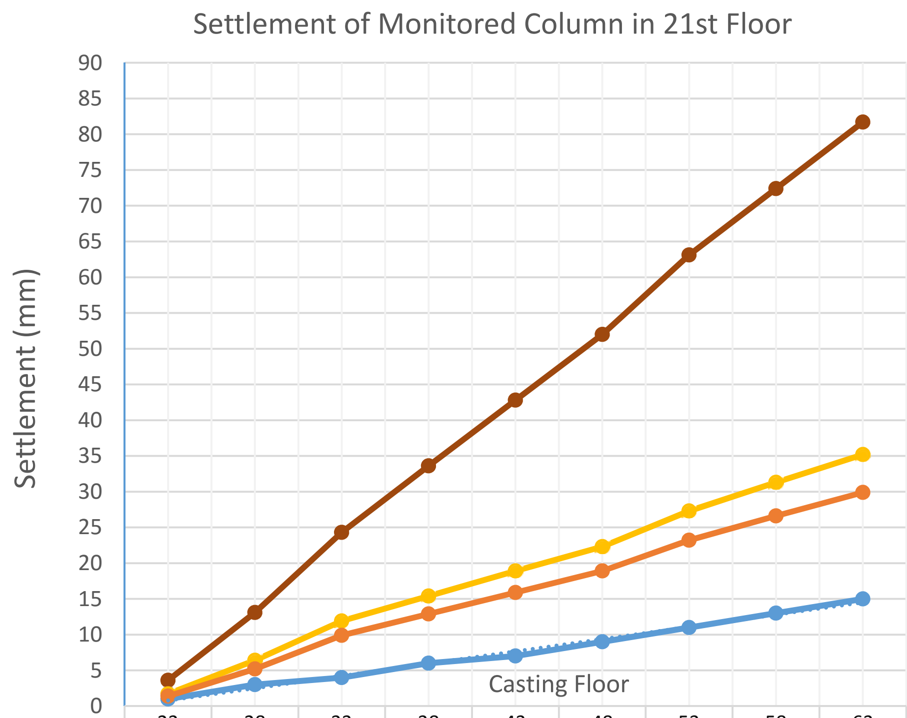
The CEB-FIP model results extrapolated from the Etabs model analysis for both with and without reinforcement show identical results to the actual ones in the first casted 20 floors. After that, the results start to deviate continuously underestimating the settlement until the end of construction where the Etabs settlement becomes around 57 % of the actual one. No major effect of considering reinforcement was found in the total settlement where the results of the two Etabs models are matched or too close. Unlike the ACI model chart, the CEB-FIP charts show inconsistent relation with the actual chart where parallelism is maintained between the ACI and actual charts but not between CEB-FIP and actual charts. However, overestimation by the ACI model is maintained during all construction stages.



	13	18	23	28	33	38	43	48	53	58	63
Actual	1	3	4	6	8	9	11	14	16	17	19
Theoritical (ACI)	4.1	9.2	14.1	18.9	24.6	29.3	34	38.6	44.2	48.8	53.5
ETABS (CEB WO/R)	2.3	4.4	6.6	8.9	11.7	13.5	15.3	17	19.7	21.8	23.8
ETABS (CEB W/R)	2	3.8	5.7	7.7	10.2	11.8	13.4	15	17.3	19.2	21

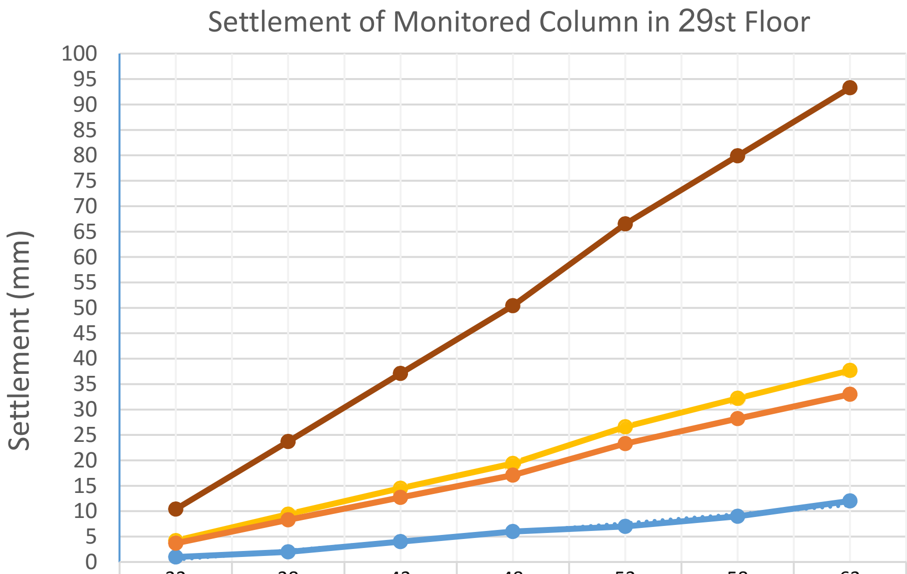
Fig.15 Actual, Theoretical and ETABS Settlement of Monitored Column in 10th Floor

By studying the 10th floor column settlement, it can be noticed that both models (CEB and ACI) overestimate the settlement in all construction stages. However, considering composite column in the second Etabs model affected the results considerably by reducing the total settlement to closer values to the actual ones. On the contrary to 3rd floor, the ACI chart gradually varies from the actual chart until the end of construction where the theoretical settlement reaches 280% of the actual one. In the contrast, the Etabs charts now are, unlike the 3rd floor, parallel to the actual chart with average overestimation of 120% and 150% for models with and without reinforcement respectively. The continuous linear charts of the Etabs model (CEB-FIP method) represent the consistency with the actual results despite the overestimation of the total settlement.



Casting Floor	23	28	33	38	43	48	53	58	63
Actual	1	3	4	6	7	9	11	13	15
Theoritical (ACI)	3.6	13.1	24.3	33.6	42.8	52	63.1	72.4	81.7
ETABS (CEB-FIB)	1.7	6.4	11.9	15.4	18.9	22.3	27.3	31.3	35.2
ETABS W/Steel	1.4	5.2	9.9	12.9	15.9	18.9	23.2	26.6	29.9

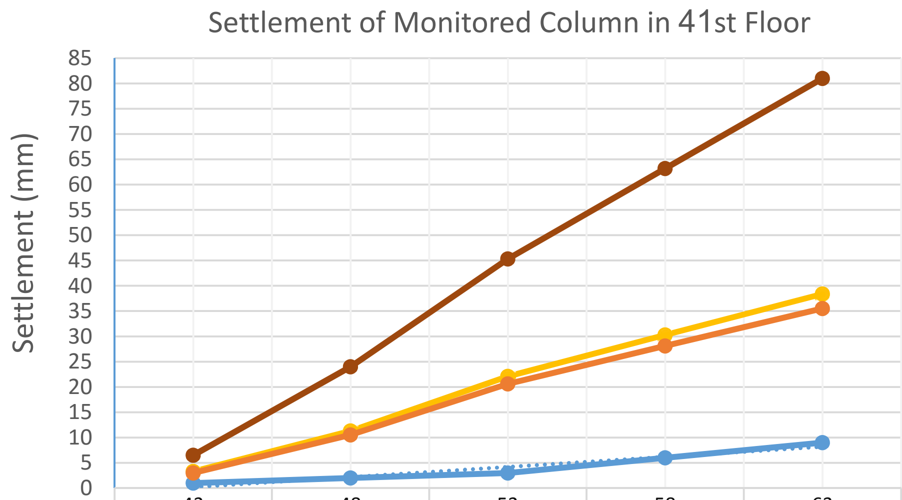
Fig.16 Actual, Theoretical and ETABS Settlement of Monitored Column in 21st Floor



	33	38	43	48	53	58	63
Actual	1	2	4	6	7	9	12
Theoritical (ACI)	10.4	23.7	37.1	50.4	66.5	79.9	93.3
ETABS (CEB-FIB)	4.2	9.4	14.5	19.4	26.6	32.2	37.7
ETABS W/Steel	3.7	8.3	12.7	17.1	23.3	28.2	33

Casting Floor

Fig.17 Actual, Theoretical and ETABS Settlement of Monitored Column in 29th Floor



	43	48	53	58	63
Actual	1	2	3	6	9
Theoritical (ACI)	6.5	24	45.3	63.2	81
ETABS (CEB-FIB)	3.3	11.3	22.1	30.3	38.4
ETABS W/Steel	3	10.5	20.6	28.1	35.5

Casting Floor

Fig.18 Actual, Theoretical and ETABS Settlement of Monitored Column in 41st Floor

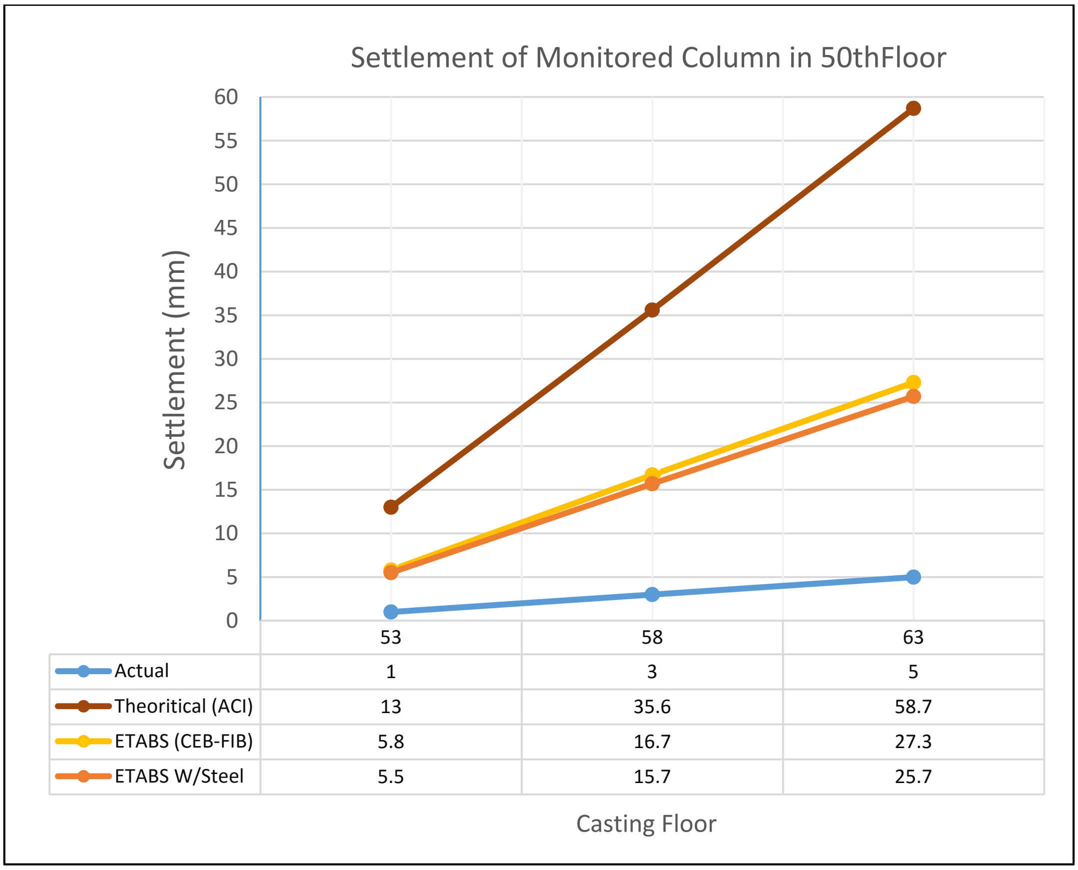


Fig.19 Actual, Theoretical and ETABS Settlement of Monitored Column in 50th Floor

By examining the charts for the other floors (21st, 29th, 41st and 59th) it can be noticed that both charts (ACI and CEB-FIP) start to deviate significantly from the actual chart reaching 1174 % and 546 % for ACI and CEB-FIP charts respectively for the total settlement of the 50th floor column after casting the 63rd floor. Another notice from the previous charts is that both models charts start close to the actual charts, that is with the first additional floors and then the different inclined slope represents the significant difference between the actual measurements and the predicted values.

4.4.4 Final Settlement of Monitored Column and Wall

The final settlement of the monitored column and wall after completion of construction work (after casting floor 63) are derived from the previous charts and plotted on charts for theoretical, actual and Etabs results. It should be noted that Etabs results are derived from the with-steel model considering the composite steel-concrete column.

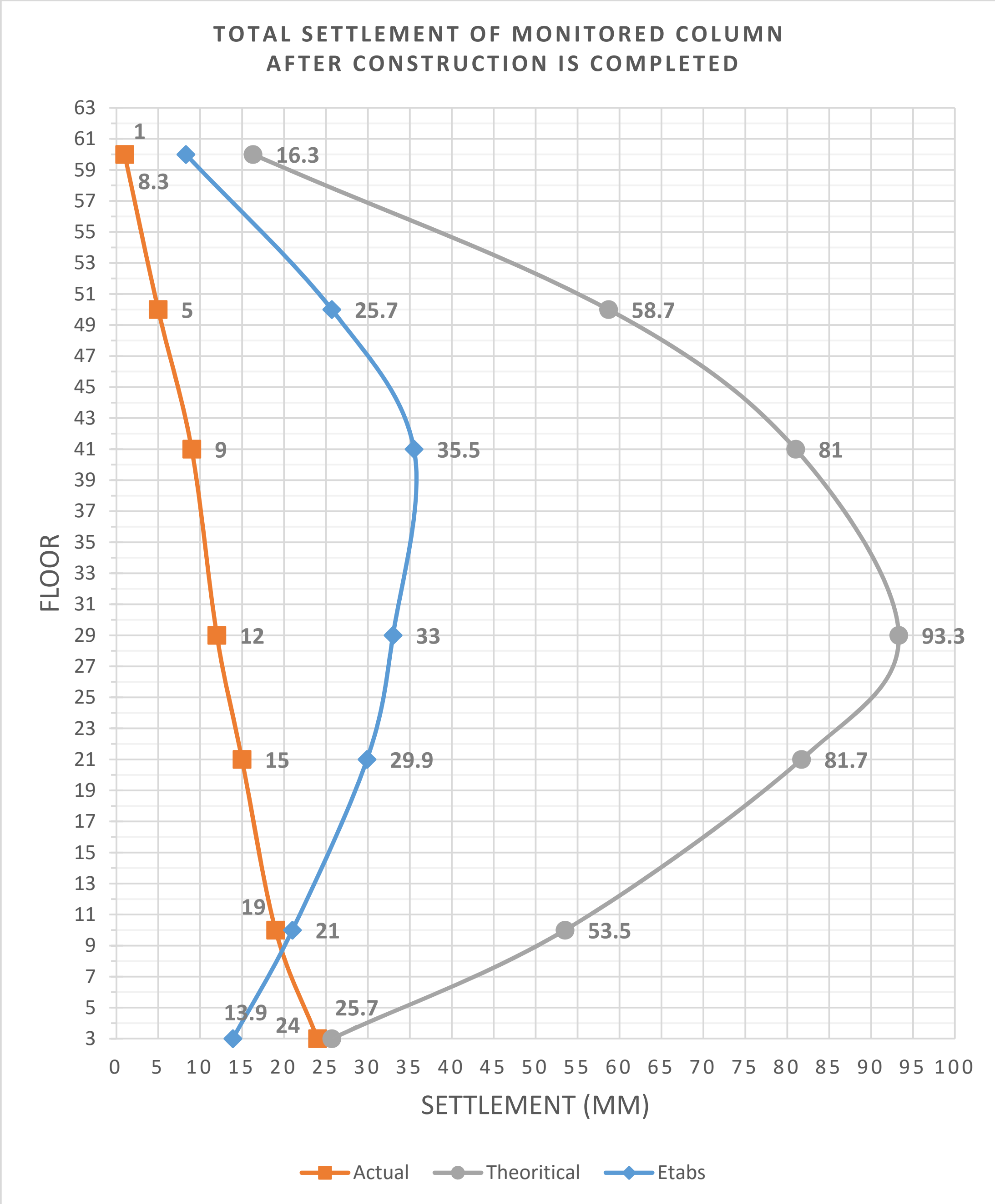


Fig.20 Total settlement of monitored column after completion of construction

In the total settlement actual chart, the settlement has almost a linear relation with floors decreasing continuously from 24mm in the 3rd floor to only 1mm in the 60th floor. Both theoretical and Etabs charts show a totally different relation between floors and total settlement where the settlement increases when going up in floors until it reaches a maximum value near the building mid height and then decreases until the last floor. Where the actual and theoretical (ACI) settlement of 3rd floor are too close (24 & 25.7 mm), the other floors settlement differ significantly except for one intersection which reveal identical settlement between the two intersecting charts (actual and Etabs in the 9th floor as 20mm). In general, the theoretical settlements are the highest, the actual settlements are the least where Etabs settlements are between those values.

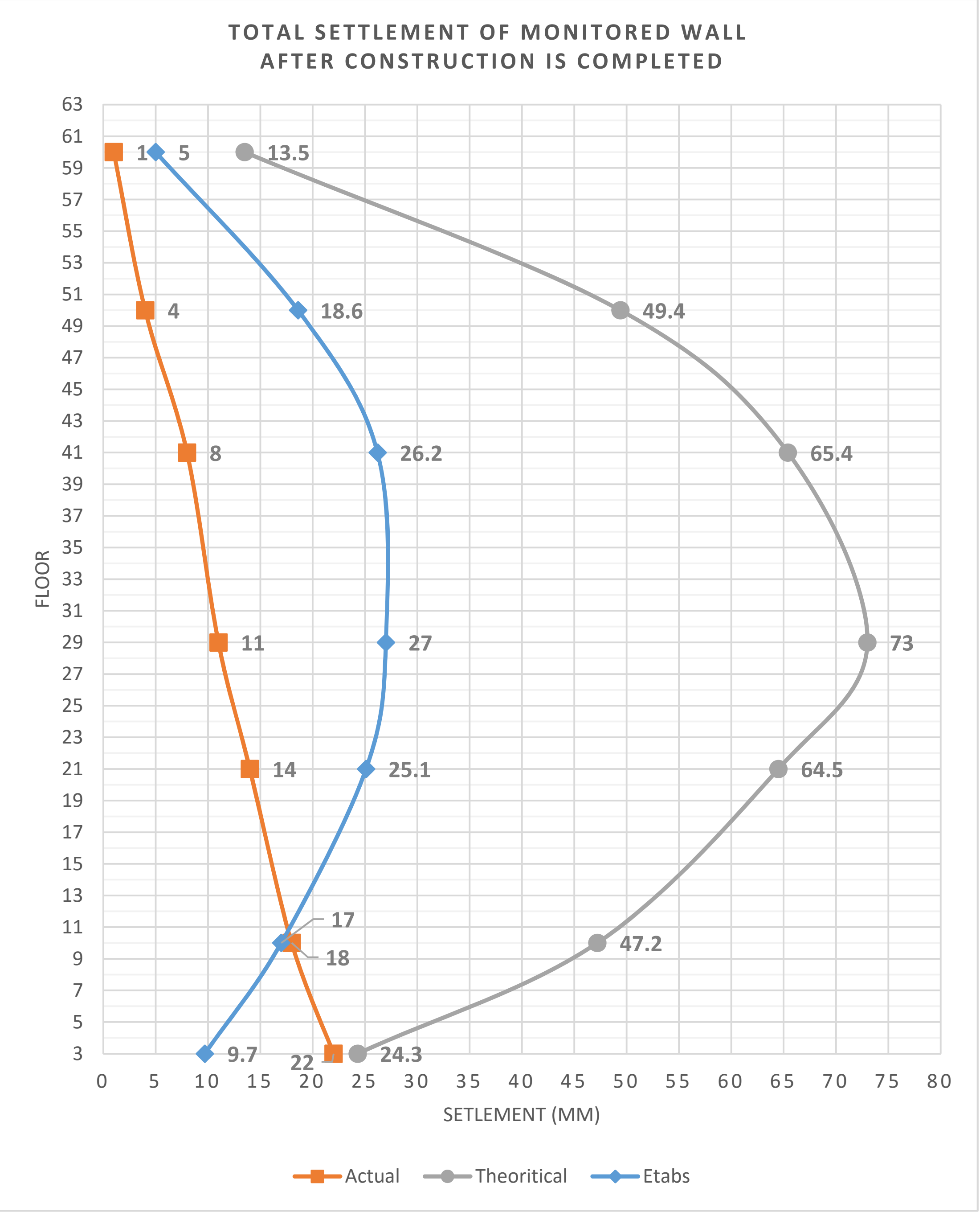


Fig.21 Total settlement of monitored wall after completion of construction

Wall settlement charts show a very similar behavior to column chart in the shapes of charts and the differences between the three presented charts. Settlement values are the only difference between column and wall settlement which are presented later as differential settlement.

4.4.5 Differential Settlement between Monitored Column and Wall

The difference in stresses between border columns and core wall leads to cumulative differential shortening which causes the slab and connecting beams to tilt and the partitions to rotate if they installed during the construction as shown in figure 22 (Fintel et al. 1987).

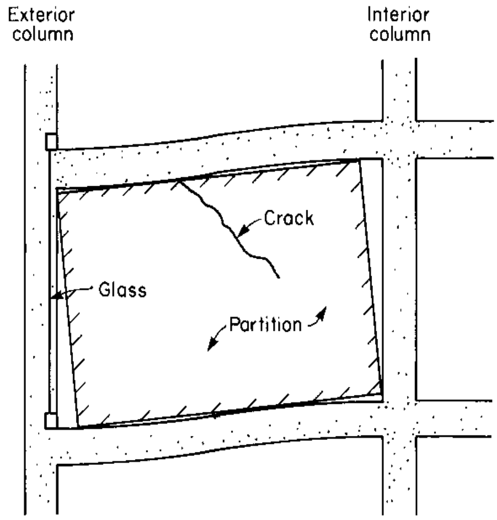


Fig.22 Effects of tilted slab

(Adopted from: Fintel et al. 1987)

The effects of those differential shortenings can be avoided by providing special details that allow columns and walls to deform without distorting the partitions, finishes or cladding. However, such details can't

prevent the additional stresses in horizontal members induced by the differential shortening. Thus, providing length compensations to columns during the construction is essential by knowing already the values of differential shortening during the design. In this section, the deferential settlement of the monitored column and wall is presented for the three measures, actual, theoretical and Etabs. The values shown in deferential charts are calculated as the settlement of columns minus wall settlement after the construction is completed i.e. settlement charts in figure 20 minus settlements charts in figure 21.

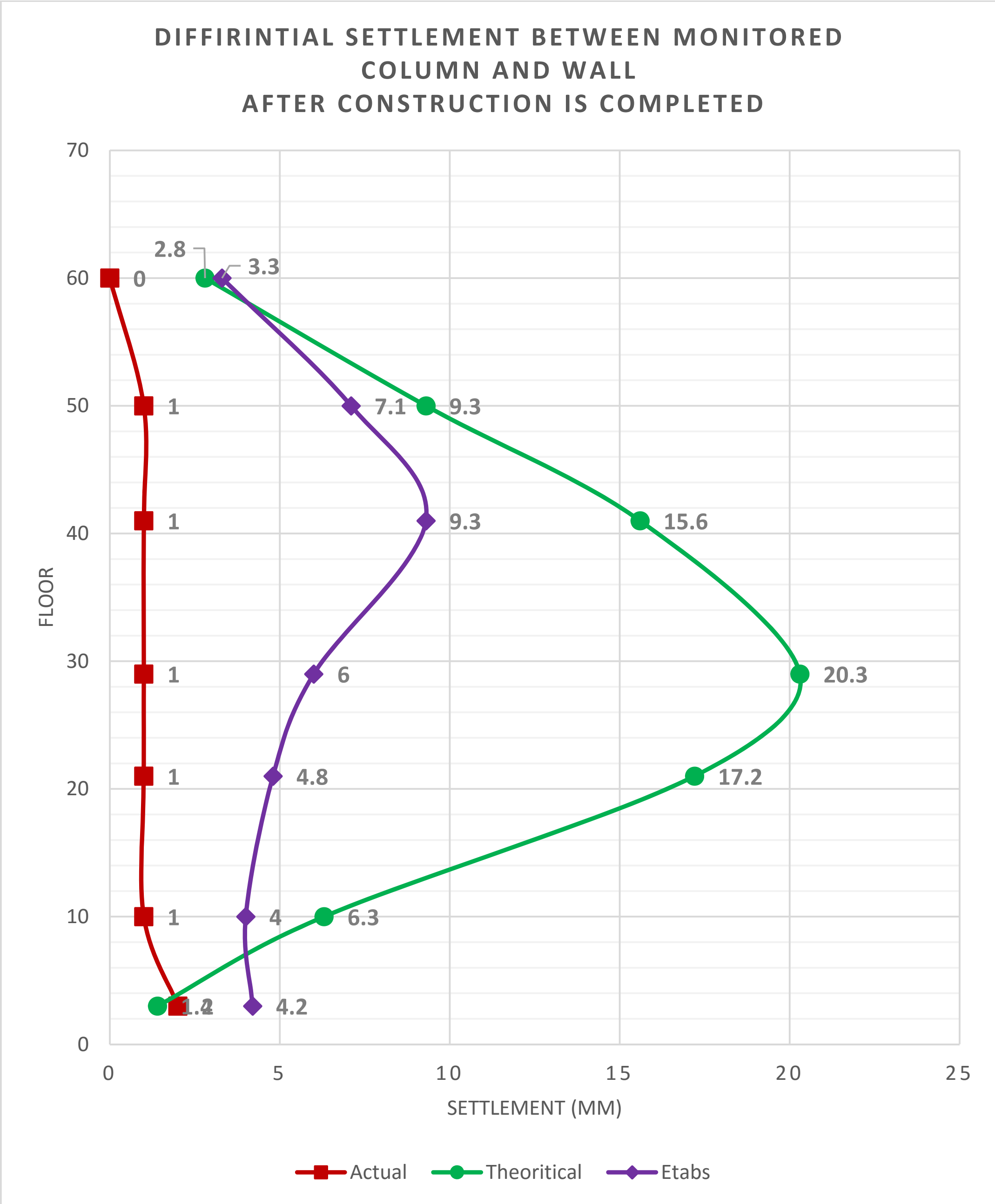


Fig.23 Differential settlement between monitored column and wall

All the differential settlement charts show a totally different behavior from each other. A value of 1mm differential settlement is maintained for almost all floors in the actual chart. However, the theoretical chart is similar to that of absolute settlement where the chart starts with minimum value at the lowest floor increasing until a maximum value in the mid-height and then the minimum value appears again in the last floor. Etabs chart shows scattered values with no clear pattern or relation to floors. In general, theoretical values are the highest, actual values are the lowest and Etabs values are in between.

4.5 Lateral Sway

In the presented case study, the building typical plan which consist of two intersecting ellipses is reduced after the 52nd floor to one ellipse only till the last floor as shown in figure 24.

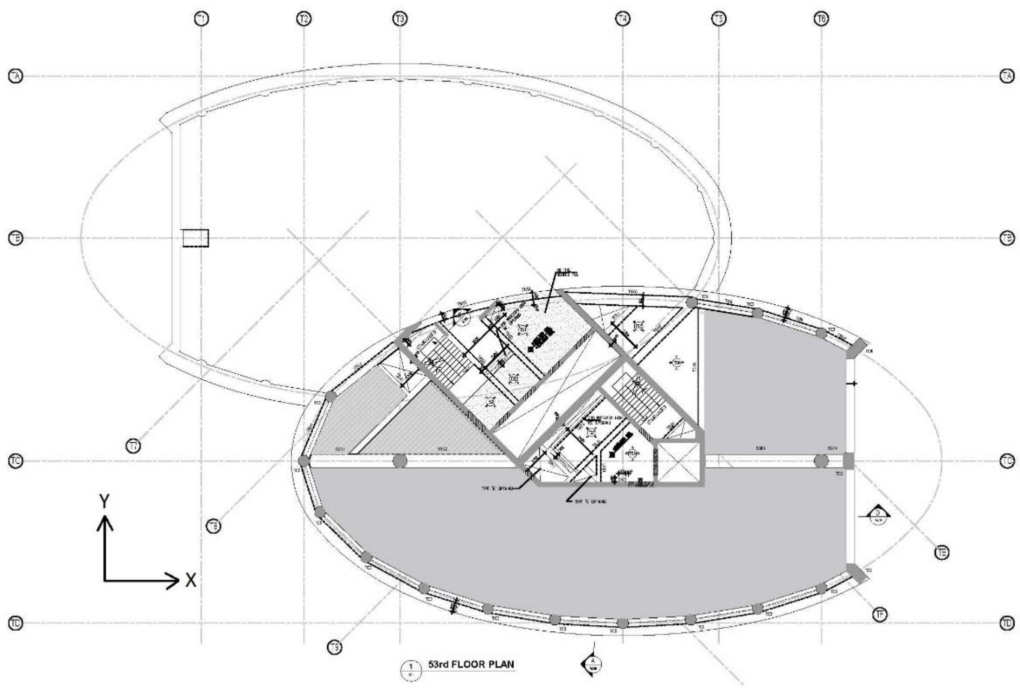


Fig.24 Typical structural plan of the tower after the 52nd floor

The significant mass shifting after the 52nd floor (called the separation floor) will normally cause the building to rotate toward the higher side causing lateral sway after each added floor. That sway was compensated in the construction by adjusting the column form for a vertical alignment. The residual sway represents the final sway of the building upon completion of construction and thus it's investigated in this research. The method of vertical alignment is shown in figure 25.

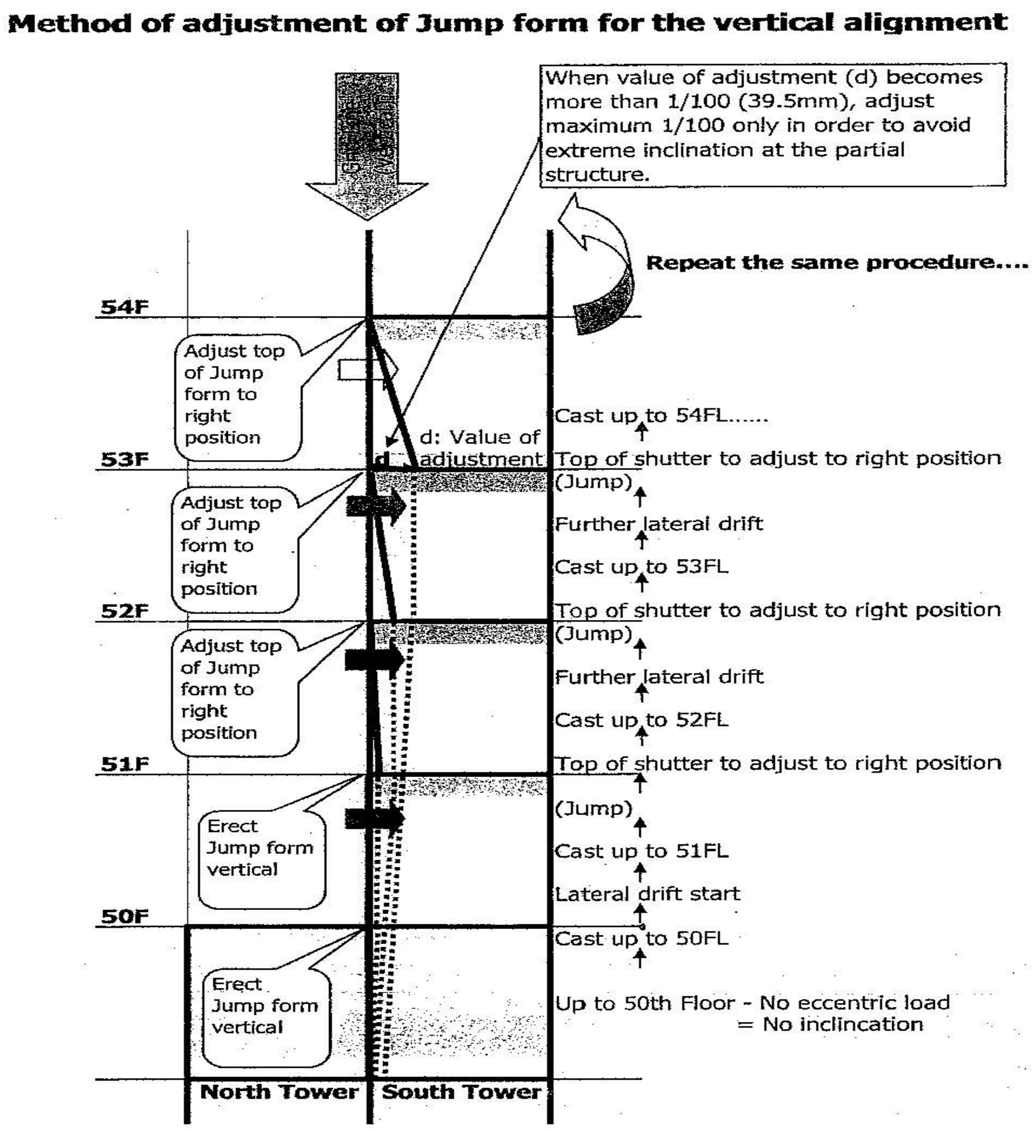


Fig.25 Method of vertical alignment used in the tower construction
Adapted from (Hajjar 2007)

In the developed Etabs model, an account for the vertical alignment was considered in the sequential loading analysis approach where every new joint (top of column) is added to the exact pre-determined location. The lateral sway induced by gravity load is calculated from the Etabs model considering two approaches:

- The normal (linear) analysis procedure where the model is fully build in the software and then loaded instantaneously without any settlement or sway compensation.

- The sequential loading analysis, where the building is automatically modeled and loaded floor by floor and the compensation for both settlement and sway is taken into consideration by adding every new joint to its correct coordinates representing the compensation techniques done during the construction of the building.

The study is provided in two parts. The first part includes analysis of the case study where the building is vertically asymmetric, and the second part is a modification to the building where the last twelve floors are removed and the building became vertically symmetric. The model of the modified building is called model-2. In the first part, in order to investigate this behavior in more depth, the results are presented in two sets. First the total sway of all floors resulted from the two analysis approaches, and second the sway of the separation floor resulted from the sequential analysis where above floors are added and loaded step by step with inherent sway compensation of each additional floor.

4.5.1 Total Sway of all Floors

The results of the two analysis procedures are shown on two different charts, one for normal linear analysis and the other for sequential loading analysis. Each chart includes the lateral sway induced by the own weight of the building in two orthogonal directions named X & Y. The more concerning direction is Y direction where most of the mass shifting occurs, however two directions are plotted for further comparison. The displacement shown in the charts represents the maximum story displacement where it occurs in the furthest points on the ellipse in the two directions. The behavior of the building under this vertical asymmetry is investigated by comparing the results of those two analysis approaches and checking the serviceability of the building under this behavior.

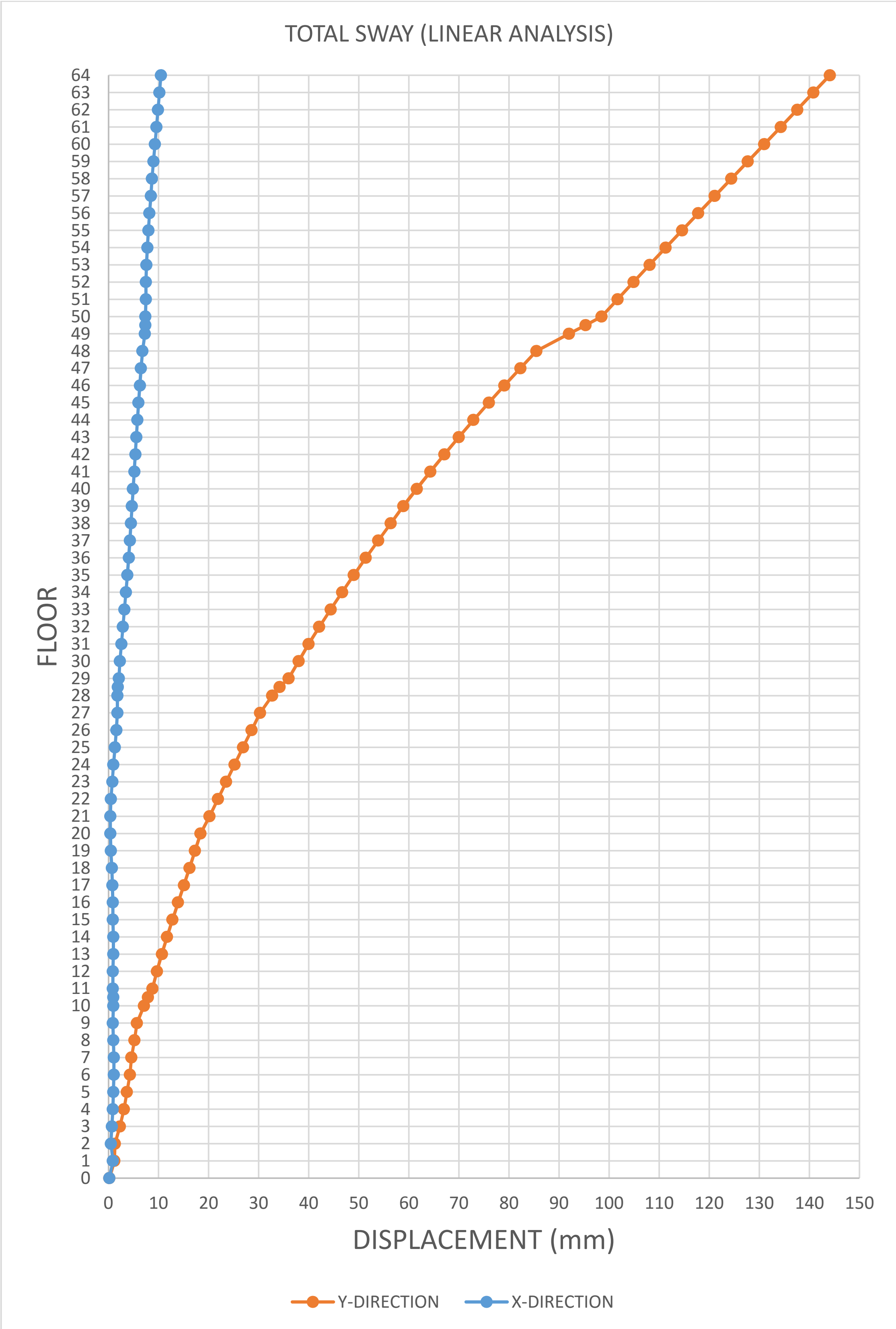


Fig.26 Total lateral sway of all floors (normal analysis)

From the normal linear analysis procedure, the results shown in figure 26 can be summarized as following:

- A minimum displacement of 0.2mm occurred at the lowest floor (ground floor) in the two directions.
- The maximum displacements are10.5mm and 144mm at the highest story in X and Y directions respectively.
- The displacement increased steadily from the lowest floor up to the last floor.
- The percentage of the displacement in X-direction to Y-direction decreased from 100% in the ground floor to 7.3% in the last floor showing that Y-direction displacements increase more rapid than those of the X-direction.
- The percentages of the displacement in the lowest floor to the highest floor are 0.95 % and 0.07 % for X and Y directions respectively.
- The average displacement increments are 0.145m /floor and 2.02mm/floor in X and Y directions respectively.
- A slight jump in the displacement was observed at the 49th floor where the difference between the 49th and the 48th floors displacements is 6.5mm which is attributed to the reduction of all columns and walls sections in the 49th floor.
- The effect of the vertical asymmetry in this type of analysis can't be noticed from the settlement charts i.e. the sway continues to increase from the lowest to the highest floor in the same pattern.

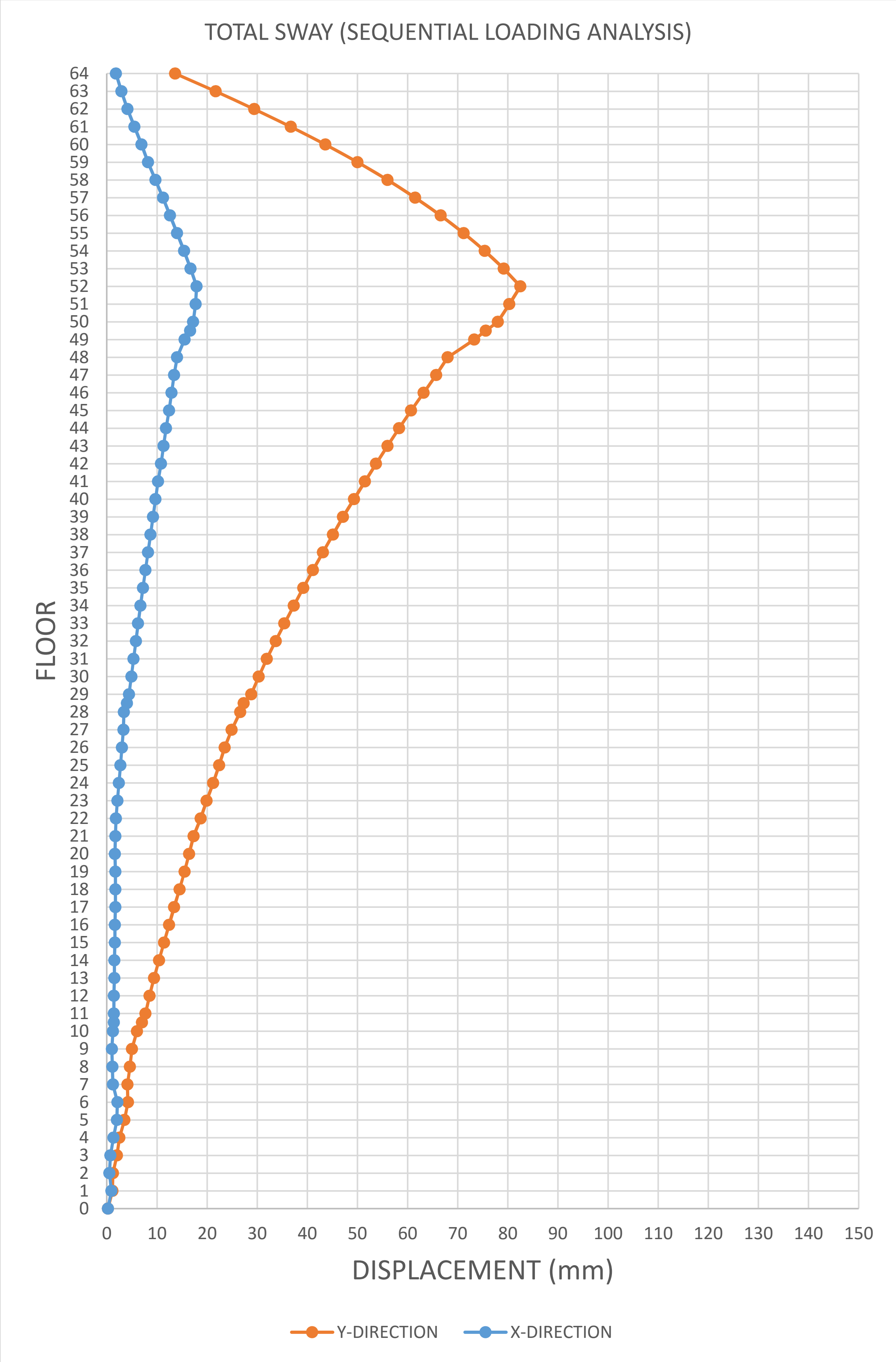


Fig.27 Total lateral sway of all floors (sequential loading analysis)

By looking at the settlement charts of the sequential analysis, it can be directly noticed that the shape of settlement chart is different from that of the normal analysis charts. The following observations can be drawn from figure 27:

- A minimum displacement of 0.2mm occurred at the lowest floor (ground floor) in the two directions.
- The maximum displacements are 17.9mm and 82.5mm in X and Y directions respectively, occurred both at floor 52, however the floors numbering in Etabs represents the below floor, so the maximum displacement occurred at the 53rd floor which is the first reduced floor after the separation floor.
- The increase in lateral displacement in both directions started from ground floor up to 53rd floor where it was reversed to reduction in settlement until the last floor.
- Displacements at the 64th floor are 1.8 mm and 13.6 mm in X and Y directions respectively.
- At highest floor, the sway difference between the two directions is 11.8mm.
- The maximum difference between the two directions displacements is 64.6mm occurred at the 53rd floor.
- The average displacement increments from ground floor to the 52nd floor are 0.32 and 1.47mm/floor in X and Y directions respectively.
- The average displacement decrements from 53rd to the 46th floor are -1.34 and -5.7mm/floor in X and Y directions respectively.
- Again a slight jump in the displacement was observed at the 49th floor where the difference between the 49th and the 48th floors displacements is 5.3mm.
- The effect of the vertical asymmetry can be clearly noticed from the shape of the settlement charts i.e. the sway continues to increase from the lowest to the 53rd floor, then decreases continuously until the last floor.

4.5.2 Comparison of the Two Sway Analysis Procedures

As seen previously the two analysis (normal and sequential) provided totally different deformation shape of the building. For further comparison of the two sets of results, the difference between the two analyses is calculated and plotted as difference charts for both directions X and Y as shown in figure 28. The difference is calculated as the normal analysis sway minus the sequential analysis sway.

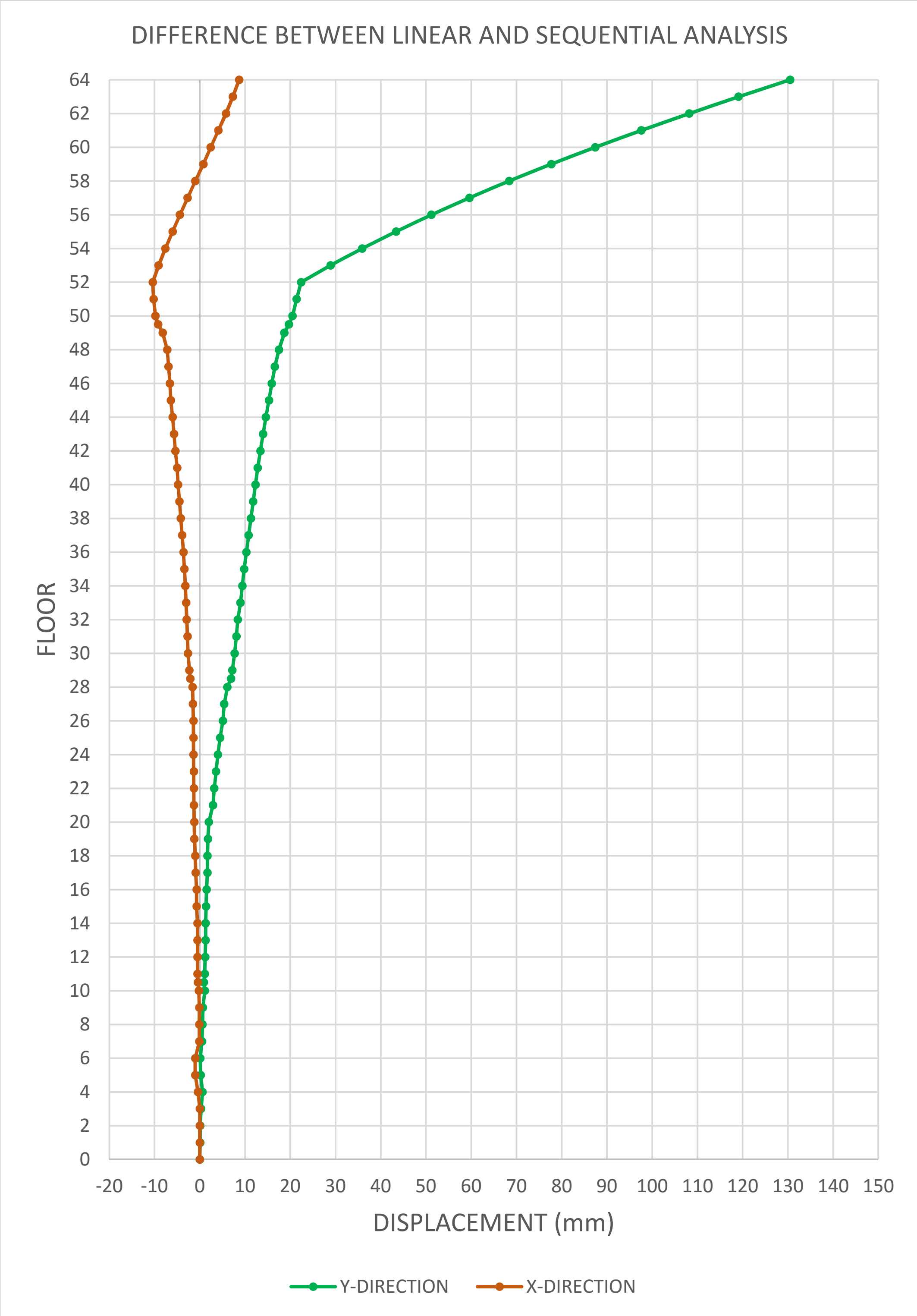


Fig.28 Difference between normal linear and sequential analysis lateral sway

By examining the difference charts shown in figure 28, the following results can be obtained:

- The lateral displacement of the linear analysis is overestimated in the Y-direction for all floors. For the X-direction, the displacement is underestimated from ground floor to 58^{th} floor and then overestimated from the 59^{th} floor to the last floor.
- The maximum difference in Y-direction is 130mm at the last floor.
- The difference in the X-direction has two peaks, -10.2mm at the 52^{nd} floor and +8.7mm at the last floor.
- The average difference in Y-direction displacement is about 7mm/floor in the range from ground floor to the 52^{nd} floor, whereas the average difference for the range 53-64 floors is about 75mm/floor which is represented by the shallower slope of the difference chart after the 52^{nd} floor where the difference gets more obvious and significant.
- In the X-direction, much less average difference of -3mm/floor from ground floor to 58^{th} floor, and then the average difference is +5mm from 59^{th} to 64 th floor.

4.5.3 Sequential Sway of the Separation Floor

A better understanding of the sway behavior in this building can be obtained by monitoring the sway of the separation floor from each additional floor above separately. That can be achieved by the sequential loading analysis only where the displacement of the 52^{nd} floor is plotted against each added floor. The chart in figure 29 illustrates the movement of the 52^{nd} floor after each added floors up to the end of the constructions.

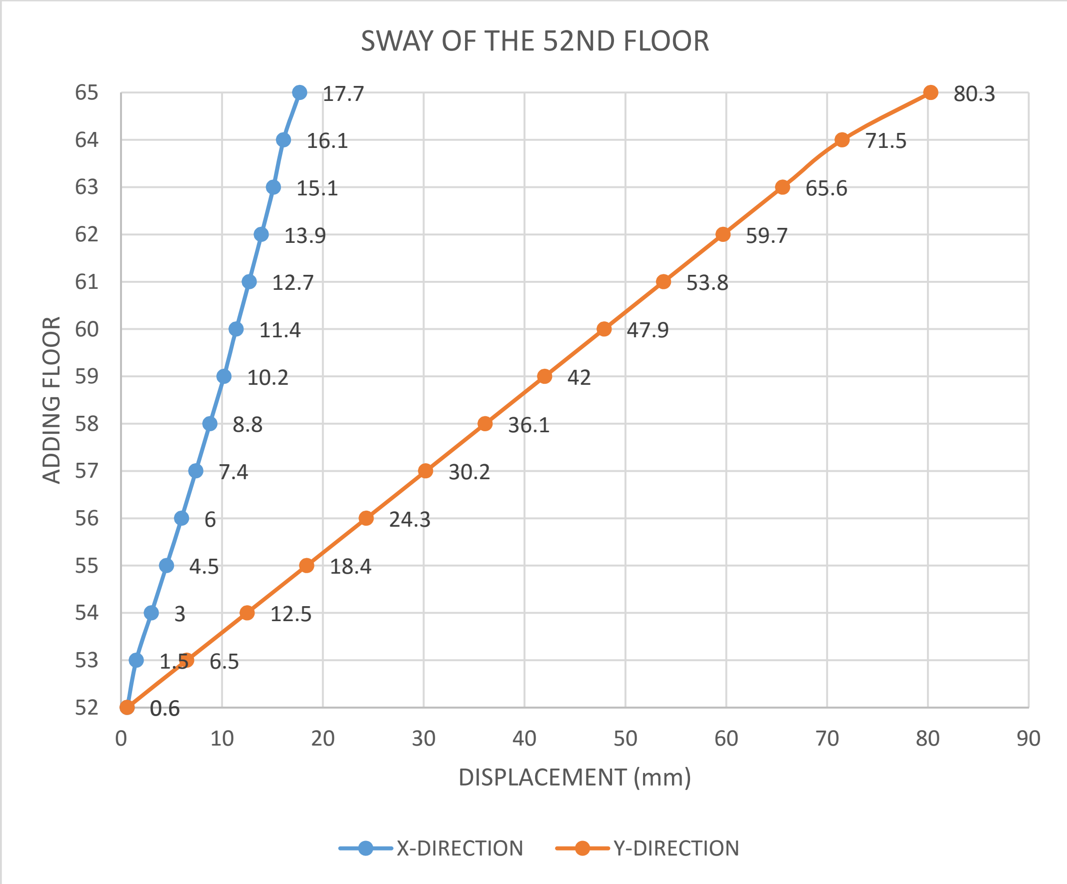


Fig.29 Sequential sway of the separation floor

A linear relationship can be observed from the previous charts between the 52nd floor sway and the additional floors. Each added floor above the separation floor caused almost 1.5mm and 6mm sway in the 52nd floor in X and Y direction respectively. It can be noticed also that when adding the considered floor (52nd floor), the sway was only about 0.6mm for both directions and then increase with the construction progress until it reaches 17.7 and 80.3mm after adding the last floor for X and Y direction respectively.

4.5.4 Sway of Model-2

In the previous comparison, the two analyses were applied on the 64 stories case study building where the sway results were totally different. So, as an additional procedure for understanding the sway behavior, the comparison of the two analyses was repeated on the same building after removing the last 12 floors which caused originally the vertical asymmetry. So, the case study building turned into 52 stories vertically symmetric building called model-2 and the results of the two analyses for the Y-direction only where plotted on sway charts as shown in figure 30.

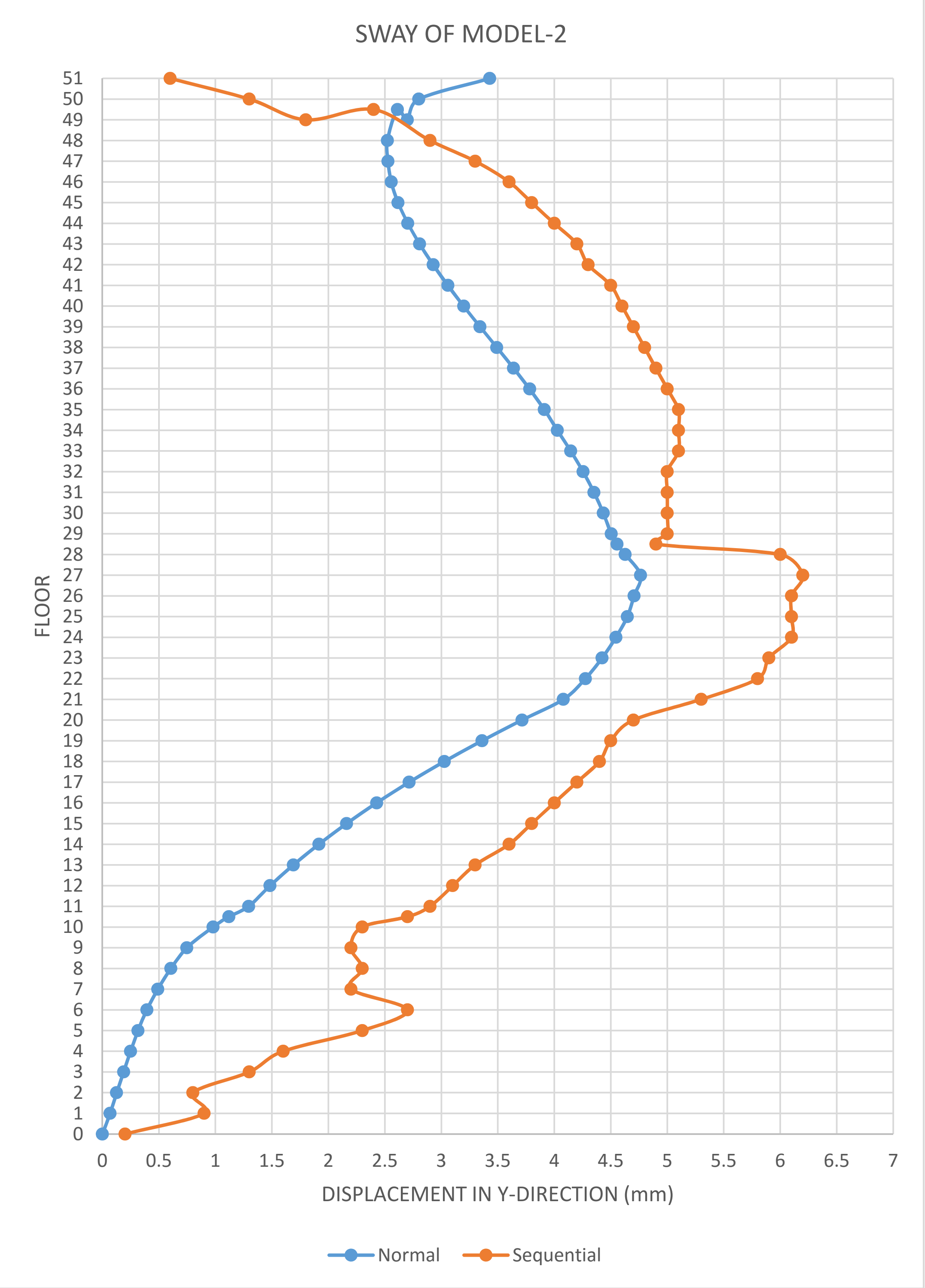


Fig.30 Normal and Sequential sway of model-2

The first observation of figure 30 is the similarity between the deformation shapes of the two analyses. However, although the values are different, they are close with maximum different of around 3mm. In addition to similarity of deformation shape, the sway values in general are not that significant with maximum sway of 4.7 and 6.2 for normal and sequential analysis respectively.

Chapter 5

DISCUSSION OF RESULTS

5.1 Actual Site Readings

As mentioned previously, the survey of the monitored column\wall included the settlement after casting each five stories, hence the absolute shortening can't be predicted from the survey charts. However, the settlement charts presented in figures 6 & 7 provide actual results taken directly from the site which represent a good source for comparison with the theoretical results presented in this research. By examining those charts, a linear relationship can be observed between adding floors and settlement. Approximately, 2mm increment in column settlement is resulted from adding five floors to any of the monitored column level which is a matter of question since the column settlement is the summation of columns shortenings below the considered column as explained in 4.1.2 and shown in figure 3. For example, considering the monitored column in 3rd floor, adding five floors from 38th to 43th increased the total measured settlement from 12mm to 14mm. By considering the shortening summation concept, those 2mm increment are the summation of 9 columns shortenings (from floor B5 to 3rd floor). The same monitored column in the 29th floor experienced, according to the actual readings, the same settlement increment of 2mm (from 2 to 4 mm) which is supposed to be the summation of 35 columns (from floor B5 to 29th floor). Theoretically, the settlement of the monitored column in the 29th floor should be approximately 4 times that in the 3rd floor. Moreover, when adding the considered five floors, the 29th floor column was fresher than the 3rd floor column, which consequently increases the time dependent effects at that period of time leading to more settlement of the 29th column. The previous discussion reveals a conflict in the measured values with all the literatures reviewed in chapter 2 who agree on the shortening summation concept. In spite of all the influencing factors that lead to results disparity, such as human error, lateral restrain and construction sequence and conditions, the reliability of the provided measures is suspected to a large extent. Although the data collection tools provided in 3.3 confirms the method of the survey presented in 4.3, the settlement charts shown in both figures 6 & 7 are more likely to be shortening charts where at each monitored floor the shortening is calculated as the settlement difference between the two ends of the monitored column. The previous possibility could be related to a confliction between the survey method which is clearly mentioned in (Hajjar 2007) and the technician who was responsible for site readings and recording. As a result of the previous discussion, the research at this point is turned into a more careful comparison between the actual and the theoretical values depending on the two theoretical methods presented using the developed spreadsheet and the Etabs software model to assess the actual site readings rather than taking them as granted.

5.2 Shortening of Monitored Column and Wall below 4th Floor

The absolute shortening graphs of the monitored column and wall below 4th floor due to adding floors 4th to 8th are shown in figures 8 & 9 respectively. There is a quite difficulty in understanding the shortening behavior in different floors by examining those graphs. It's because the absolute shortening is basically dependent on the column length which is different between floors (3.2m for floors B5 to B1, 5.5m for ground floor, 4.5m for floors 1st to 2nd and 3.95m for the 3rd floor). However, a relationship between the different shortening components (elastic, creep and shrinkage) can be obtained for each floor. By examining the three shortening components for each floor individually, it can be seen that in all floors the creep shortening has the least value where shrinkage caused more shortening followed by the elastic shortening. A better understanding of the differences between the three shortening components can be achieved by comparing creep and shrinkage shortenings to elastic shortening. So, the percentage of each creep and shrinkage shortening is calculate with respect to elastic shortening and it was found that creep shortening increased with floor from 26% in floor B5 to 32% in the 3rd floor, where shrinkage percentage increased from 39% in floor B5 to 64% in the 1st floor and then decreased to 36% in the 3rd floor. The approach of the creep shortening to the elastic one when going up in floors is an evidence that creep has higher effects on the fresher columns (in higher floors) where they were loaded on earlier age than those in the below floors for the same considered period of loading. On the other hand, shrinkage effects take place with no regard to loading. The fact that shrinkage consumes most of its effect in the first days of column age is evidenced when the shrinkage to elastic percentage is increased for fresher columns in the considered period (between casting 4th and 8th floors). However, after the first floor the percentage is decreased allowing another two factors to take place. The first factor is the rapid increase of the elastic shortening for fresher column as a consequence of lower modulus of elasticity for fresh columns in the 2nd and 3rd floors. The second factor is that the considered shrinkage time frame is less for 2nd and 3rd floor columns since a curing period of 7 days is deducted from the whole period where the lower floors columns (older columns) had already finished the curing period when the considered shrinkage period had started and thus their shrinkage is calculated for the whole considered period. The previous results and discussion evidenced the following facts:

- Creep effect due to loads applied at later ages have much less effects than those applied at early age.
- Shrinkage effects have higher proportion in the initial time of the column age than later ages.
- Elastic shortening of newly loaded column is higher than older loaded column having the same section and length.

5.3 Strain of Monitored Column and Wall below 4th Floor

In the previous discussion, the shortening of monitored walls and columns involved the length of each column floor which allowed to study the behavior of individual floors only. In the strain charts shown in figures 10 & 11, a comparison is allowed between different floors since the strain is given for unit length of the column. The previously concluded three facts about shortening components are clearly observed in the strain charts by comparing the strain in different floors. A continuous increase in the three components is an evidence that shortenings of fresher columns is more than those of older columns. The drop in shrinkage strain after 1st floor is explained by the curing period described in the previous discussion. An example of the comparison is that the creep strain of column in 3rd floor has almost double the strain of column in B5, that is because the five floor loads are applied to column in 3rd floor sequentially at early ages, 3, 6, 9, 12 and 15 days old, where to column in B5 at late ages, 27, 30, 33, 36 and 39 days old. Additional contributing factor to creep strain increase between column in 3rd and B5 floor is the difference between columns section size, 1.4 m and 1.2 m diameter, which has an effect on the applied stress and thus the elastic and creep strain. In addition to applied stress, on the other hand, elastic strain is increased in each floor column due to age of concrete at loading for each column which has effect on the modulus of elasticity, for example, when adding the 8th floor, the age of column in B5 was 39 days and Ec=33974 N/mm², where for the column in 3rd floor the age was 15 days and Ec=32075 N/mm². Shrinkage strain shows a peak value at 1st floor decreasing on both side. On the left side, the shrinkage strain is decreasing with column aging for the same considered period. The decrease in shrinkage strain for columns in 1st and 2nd floor is because for the same considered period (12 days), the shrinkage is delayed 7 days for the curing period which is deducted from the newly casted columns. The comparison of all columns settlement to the column in floor B5 shown in table 2 illustrates the increase in all settlements where the 3rd floor column and wall strain reaches 228 and 184 % of the B5 column respectively which is a considerable increase reflecting the fact that most of the settlement in tall buildings occurs during the building construction.

5.4 Settlement of Monitored Column and Wall in 3rd Floor

5.4.1 Elastic Settlement

The prediction of elastic strain was based on average loading for all floors from 8th to 63rd floor. Thus, the elastic settlement has almost a linear relation between applied load and settlement, that is, each additional five floors cause around 2 mm settlement in the 3rd floor column. As shown in table 2, concrete strength and elasticity modulus used to predict the elastic strain were based on time dependent formulas, Eq. 3 & 4. However, the influence of time on elastic settlement has minimal effect and that is evidenced by the linear relation between settlement and casting floor.

By comparing the elastic settlement chart to actual total settlement chart, it’s noticeable that prediction of elastic settlement was overestimated to at least after casting the 28th floor because the elastic settlement should always be less than the total actual settlement leaving some creep and shrinkage settlement to be added to elastic strain to get the total settlement. The theoretical elastic settlement is about 56-60% of the total theoretical settlement.

5.4.2 Creep settlement

The creep charts show a linear relation between settlement and construction progress. That is every added floor will cause creep settlement in a column till the end of construction added to the settlement caused by the previous added floors. However, the slope of creep chart is less than the elastic chart evidencing the fact that creep effects are reduced with time.

5.4.3 Shrinkage settlement

Different from elastic and creep charts, the shrinkage settlement chart which is independent from the applied load starts increasing until casting of 33rd floor and then continues with shallow slope until the settlement is almost set at the end of construction. The shrinkage chart evidences the fact that most of the shrinkage effects take place during the first period of member age.

5.4.4 Total settlement

Both column and wall charts total theoretical settlement show an overestimation in predicting the settlement of the column and wall in all the construction stages compared to the actual settlements. With construction progress the theoretical values get closer to the actual values where the overestimation after casting the 8th floor is 250% and 240% for column and wall respectively, it gets then down to 107% and 110% after end of construction for column and wall respectively as shown in table 3. The close values of theoretical and actual results reveal the ability of the developed program based on the ACI 209R-92 model to predict the total settlement of a column with good approximation. Moreover, a good consistent correlation between theoretical and actual results is maintained during the whole building construction period which is obvious by the parallelism between the theoretical line and the approximated linear trend line of the actual chart. The theoretical settlement chart tends to have a more direct relation that is every additional 5 floors increase the settlement by almost 2 mm. The actual results have more scattered values due to some inconsistent construction conditions or due to site reading errors.

5.5 Settlement of Monitored Column in all Monitored Floors

Similar to 3rd floor column settlement, figures 14 to 19 shows the settlement of the monitored columns in all monitored floors. However, creep, shrinkage and elastic settlement charts were removed for the purpose of focusing on the total settlement only. Additionally, Two Etabs models charts were added for further comparison. In the first Etabs model, columns reinforcement is not considered whereas columns are modeled with the real reinforcement in the second model. An overview of all the settlement charts shows that the theoretical (ACI 209R-92) settlement is significantly overestimated in all the monitored floors after the 3rd floor column. Where the theoretical settlement after the end of construction for the 3rd floor column was only 110%, it reached 280%, 544%, 777%, 900% and 1174% for columns in the 10th, 21st, 29th, 41st and 50th floors respectively. Another observation is that theoretical settlements have close values to actual ones in the first added floors before they get far with construction progress unlike the 3rd floor column settlement where the gap between theoretical and actual settlement is maintained from the first added floors till the end of construction. By looking at Etabs charts, it can be noticed that including reinforcement in the columns had no significant effect on the total settlement where the values for both Etabs charts are so close. On the other hand, both Etabs charts (CEB-FIP model) had much closer values to actual settlements than the theoretical (ACI 209R-92) settlements. In other words, Etabs charts lines slope is shallower than the theoretical chart line slope allowing the Etabs charts to get closer to the actual one. It's obvious from all the charts that the difference between theoretical and actual results starts to increase rapidly from the 10th floor column up to the last monitored floor. So, does that mean the proposed method of predicting column settlement is appropriate for only low rise building and not for high-rise buildings? To answer this question, both actual and theoretical results are examined more broadly. The actual charts showed unusual trend which is different from the normal settlement trend for any building stated by many literatures (Chowdhary and Sharma, 2009; Jayasinghe and Jayasena, 2004; Kamath, Rao and Shruthi, 2015; Kim and shin, 2014; Kim, Jeong and Shin, 2012). In the normal case, adding loads to columns in different floors will cause different settlement. That is because the settlement of one column is dependent on the shortenings of the columns below. For example, settlement of a column in the 50th floor from adding 5 floors above will include the shortening of 50 columns below loaded with those floors, where the settlement of a column in the 5th floor from adding the same floors above will include shortening of 5 columns only. Consequently, the settlement of the 50th floor column will be in the range of 10 times of the 5th floor settlement disregarding the time-dependent effect. However, actual settlements showed very unusual results compared to the previous discussed procedure of settlement. For instance, adding 5 floors (54 to 58) caused a 2mm settlement in the 50th floor column and the same settlement of the 3rd floor column. As a consequence, the actual site readings could be affected by many factors such as, human errors and inconsistency between the method of site reading and the method by which the site readings charts were set. The theoretical results on the other hand, showed a consistence relation in line with the previously discussed procedure. For instance, adding 5 floors (54 to 58) caused a 22.6mm settlement in the 50th floor column but only 2mm in the 3rd floor column. Despite of this good relation between settlements in different floors, the theoretical results still show overestimation if compared to the Etabs results where the settlements of the same column in Etabs are 1 mm and 11 mm for the 3rd floor and 50th floor column respectively. The reasons for that overestimation can be related to three major factors:

- The ACI 209R-92 model doesn't account for column reinforcement which have a direct effect on the elastic shortening and the time dependent effect where reinforcement relaxation reduces the stresses transmitted to concrete with time, especially for such a composite section with high steel percentage.
- The developed excel sheet accumulates the individually predicted columns shortenings to get the total settlement with no regards to horizontal members' stiffness which affect the total settlement significantly.
- There are a lot of approximations considered in the proposed excel sheet related to concrete properties, method and rate of construction and environmental conditions due to poor information about this 10 years old building.

In this occasion, the Etabs results are considered more realistic where a full 3D model of the tower is built into the program considering all the connections between columns and horizontal members as well as considering the as built reinforcement

and concrete-steel composite column section. The sequential loading analysis was also a real representation of the construction sequence where members' loads are added floor by floor and new floors are added up to the pre-determined level. In-spite of the enhanced results of the second Etabs model which considered reinforcement, the time dependent relaxation (stress transfer between steel and concrete) is still not considered in Etabs model and that is why the settlements between the two Etabs model (with and without reinforcement) are very close.
So as an answer to the previously asked question, the simple developed program of this research using the ACI 209R-92 model can't be assumed inappropriate but rather is suitable for prediction of only individual column shortening or low rise buildings (up to ten floors) settlements where horizontal members' stiffness and reinforcement relaxation have minor effect on the total predicted settlement. For higher buildings, a more complicated 3D analysis is needed to consider the vertical members as part of a whole building where all vertical and horizontal members interact together like in a real building. The results taken from a software analysis should not be considered as granted until they are modified to account for relaxation action between steel and concrete. More research and developed software are needed to account for stress transfer in highly reinforced columns.

5.6 Final Settlement of Monitored Column

By examining the final settlement charts in figure 20, a better understanding about the actual and predicted settlement can be build. In the theoretical chart, the shortening accumulation concept is clearly stated where the settlement increases with floors up until the mid-height of the building where it reaches a maximum value, then decreases until a minimum value at the top floor. Since the settlement is related to the applied loads and the shortening of columns below it, so the mid-height maximum value is explained by the loading of half of the building above that mid-level and shortening of half of the building below that column. In the lower half of the building, columns have less summation of columns shortenings below where settlements of columns in the upper half are caused by less floors loads. The advantage of the Etabs results over the theoretical results are presented by the reduced and smoothed Etabs settlement chart in the mid-height reflecting the effects of all the previously discussed factors of the 3D analysis. On the other hand, the actual chart shows a very different trend where settlement is decrease continuously from 3rd floor to the end of floors. Again, the actual settlement showed different trend from what expected as stated by many literatures. Consequently, Etabs results in this case are considered to be the most realistic values and can be used in the design of tall buildings with good estimation of the initial and final settlement. Those predicted settlements are to be used in the compensation of columns lengths during the construction or to account for some allowance for installation of services equipment and other non-structural elements.

5.7 Deferential Settlement of Monitored Column and Wall

Again, the actual site readings show a strange behavior by which the differential settlement is almost 1mm in all floors. Since the differential settlement is related to different level of stresses, volume to surface ratio and reinforcement ratio which are all different between the monitored column and wall, the actual differential settlement is unlikely to be as low as only 1mm and therefore, it should be much more. This is again a matter of question to the reliability of the presented site readings. On the other hand, theoretical and Etabs charts show a more realistic relation where the maximum differential settlement occurs at the maximum absolute column settlement. Nevertheless, with a maximum differential settlement of 20.3 and 9.3 mm for theoretical and Etabs respectively, the resulted differential settlements seem to be low for such a high-rise building. To investigate this, the three major factors affecting the differential settlement are looked into. First, the reinforcement ratio was not considered in the theoretical method and partially considered in Etabs model, hence not affecting the differential settlement results. The average volume-to-surface ratio for column and wall are very close with value of 248 and 244 for column and wall respectively. The difference in the applied stress which is a primary factor of elastic and creep shortening is also low with average value of 0.4 and 0.33 N/mm^2 for column and wall respectively. The approach between column and wall stresses is attributed to the closely spaced columns which reduced the applied load and the shape of the plan which transfer a significant amount of load to the wall. After all, with respect to the three discussed factors, a low differential settlement is expected and previously evidenced from the theoretical and Etabs differential settlement charts.

Despite the low differential settlement, a good decision can be built upon those results by setting out a compensation method for the column length during construction to ensure the horizontal final position of the slab.

5.8 Lateral Sway

The sway charts of the two analysis procedures provide important tools to investigate and understand the sway behavior of such a vertically asymmetric high-rise building. The focus in this discussion will be on the more concerning direction, the Y-direction as the mass reduction which caused the vertical asymmetry occurred mostly in this direction. The first important observation by comparing figures 26 and 27 is the different deformation shape resulted from the two analysis. In the normal analysis, the building swayed laterally in a uniform shape toward the higher part from the ground to the last floor. On the other hand, in the sequential analysis, the building tends to deform in a unique shape increasing from ground floor reaching a peak value in the separation floor, and then decreasing till the last floor. The inherent discrepancy between the two deformation shapes is that the two analysis are substantially different in the way the building is modeled and loaded in the program. Because the building is first modeled as elements without loads even the self-weight and then loaded at once, the uniform deformation shape is expected and the effect of vertical asymmetry is revealed unrealistically overestimating the total sway. In the sequential loading analysis, the building is modeled and loaded stage by stage where each stage includes adding one floor and then loading it at a pre-determined loading age (3 days in this case). In addition, every new column is added to its exact positions before the above floors are added and the column then starts to deform. This method of modeling is a real representation of the compensation work done in the site. Consequently, the real behavior of the vertical asymmetric building was captured by the sequential analysis in which the building deformed in two oppose phases rather than the one uniform phase provided by the normal analysis. So, it’s essential for this type of building to have a 3d model analyzed using a nonlinear staged construction analysis to have realistic and reliable results which to be used in design and construction. The other important observation from comparing the two analysis is the significant difference in the sway value itself. The two analysis resulted in different maximum displacements at different floors in the Y-direction, 144 mm in the 64th floor for normal analysis and 82.5mm in the 52nd for sequential analysis. So, in order to compare those results, the overestimation of the normal analysis is calculated at the 52nd and the 64th floor and found to be 127% and 1060% respectively. Further comparison is identified by the difference chart in figure 28 which shows a 130mm difference in lateral sway of the last floor between the two analyses in the Y-direction. The significant difference is again related to the nature of the analysis method as well as creep and shrinkage effects which were inherently contained in the staged construction analysis. The sway chart of the 52nd floor in figure 29 provided another insight on how the building acted under the construction stages after the separation floor. It showed that when adding the 52nd floor (the separation floor), the lateral sway was only 0.6mm only and then increased with almost 6mm with each additional floor above. This increment in the sway is the real behavior of the vertically asymmetric high-rise building. Hence, from all evidences showed by comparing the two analysis results, it's obvious that the normal analysis is unable to realistically predict the real behavior of special buildings where a significant mass shifting exists. However, using the nonlinear sequential loading analysis is a time and effort consuming and for such a complex building it needs a very powerful hardware. So, in order to set a practical assessment of the two analysis, the comparison between the two analyses is repeated for a second model where the last twelve floors are removed and the modified building is vertically symmetric. In a totally different behavior of the case study building, the sway of model-2 in figure 30 showed a reasonable similarity between the two analyses procedures where the building is typically leveled and vertically symmetric. With a maximum displacement of 4.7 and 6.2 mm for the normal and sequential analyses respectively, the gravity load induced sway of such a typical building is ignored and considered not to affect the overall stability and serviceability of the building. In this case, the normal analysis is adequate and no lengthy complicated nonlinear staged analysis is needed for such a uniform building.

Chapter 6

SUMMARY AND CONCLUSION

In this research, a case study of high-rise vertically asymmetric concrete building was presented to describe the complexity of column shortening behavior and the prediction of elastic and time-dependent effects associated with this phenomenon. The case study had further emphasis on a particular event caused by column shortening which is gravity load induced lateral sway.

This case study research was initiated by establishing a firm research focus on how accurate and reliable the prediction of column shortening using the developed codes models and the related available information can be. The research question was further extended to accommodate the importance of considering lateral sway of a high-rise vertically asymmetric building in both design and construction. Targeting those questions was assisted by conducting a comprehensive literature review which explored the previous researches conducted about the different elements included in this research such as, creep and shrinkage effects, modulus of elasticity, prediction models and absolute and deferential column shortening.

In the selection of the case study, the approach of a single unique real-life building was chosen to address those events and their relationships with other behaviors and conditions related to high-rise buildings. Thus, the selected case study was both high-rise to specifically account for column shortening and vertically asymmetric to develop a lateral sway induced by the eccentricity of the gravity loads.

The approach of this research included first developing an excel program for calculating the axial shortening of a concrete column caused by sustained load. The program included the prediction of the three shortening components, elastic, shrinkage and creep and adding them together to get the total shortening caused by sustained loads after a certain period of time. Based on ACI 209R-92 method for creep and shrinkage prediction of concrete buildings, the proposed sheet contained all the affecting factors used in this model for prediction of creep and shrinkage shortening and adding them to elastic shortening. Then, a full 3D model of the case study building was built using a finite element software, Etabs based on all the geometric and loading information collected from the building construction drawings and the information received from the building consultant engineers. The Etabs analysis was based on two approaches, the normal and the sequential loading approaches. Predicting creep and shrinkage effects was based on the CEB-FIP method that was built-in the software. All the information used in the excel sheet were similarly adopted in Etabs analysis. The Etabs results were used for further comparison with the ACI 209R-92 model and the actual results.

6.1 Column Shortening

The developed excel sheet was first used to predict the shortening of the monitored column and wall in the first 9 floors by adding the next 5 floors loads floor by floor and print the results on shortening and strain charts to investigate the difference between all the shortening components. For that purpose, every sheet was replicated for each column floor where the considered floor and column section and length where changed in each sheet. The other variables related to time effects were automatically considered by the program. The program procedure included the following main steps:

- Elastic shortening is calculated using adjusted modulus of elasticity based on age of concrete at time of applying load. Shortenings accumulation for each incremental load is taken as the total elastic shortening.
- Creep shortening was predicted for each incremental load considering the time at loading and the loading age and modified for relative humidity, volume surface ratio, slump and aggregate percentage.
- Shrinkage shortening was predicted for each considered member age using the adjusted ultimate shrinkage strain to account for volume-surface ratio, relative humidity, slump and aggregate percentage.
- The summation of the three components was taken as the total column shortening under the considered incremental load during the considered period of time.

Studying and discussing the results of the shortening charts led to the following summary and conclusion:

- Prediction of column shortening is a complex task associated with many uncertain factors related to information that may not be available during the design stage.
- The shortening behavior can be better represented and understood in the shortening strain rather than absolute shortening since the results are not affected by the column length.

- The highest total strain was found at the most fresh columns where loads were applied at earlier age.
- The highest portion of concrete column shortening is caused by instantaneous (elastic) shortening.
- The relationship between the three shortening components, elastic, creep and shrinkage is column age-dependent where the elastic strain is dominant and the shrinkage strain has middle effect followed by the least effect of the creep strain.
- Where in fresh columns, shrinkage has the most of its effect, on the contrast, creep effects tend to increase with column age.
- When load is applied to fresh column, both elastic and creep shortening are higher than those caused by applying load at older age.
- Despite that creep and shrinkage effects are time dependent, most of their effects take place during the construction time or the first few years of the structure age. Thus, in design of high-rise buildings, the most critical period to account for those effects is the construction time under self-weight load of the structure and some of the construction loads.

6.2 Column Settlement

The resultant shortenings were then accumulated to get the total settlement of the 3rd floor column caused by adding floors 4 to 8. The procedure was repeated again to calculate the settlement of the 3rd floor column for each additional five floors and to get the settlement results in line with the actual site readings for comparison between them. The obtained results of the 3rd floor column settlement and the related conclusion can be summarized as follows:

- Theoretical elastic settlement of the monitored column in the 3rd floor was in the range of 65-60 % of the total theoretical settlement.
- Theoretical total creep settlement keeps increasing with construction progress but with less effect for loads applied at late stages than those applied at earlier stages.
- The effect of shrinkage on the total theoretical settlement of the 3rd floor column is almost disappeared after the 33rd floor (about 90 days column age),

only 0.4mm additional settlement is caused by shrinkage for the remaining 90 days of the construction time.

- Total settlement is overestimated by the theoretical approach in all the construction stages.
- The overestimation is reduced to accepted settlement values when it's only 107% of the actual site readings after casting the last floor.
- The proposed approach of this research based on developed Excel sheet program of the ACI 209R-92 method was able to predict the 3rd floor column settlement with reasonable accuracy compared to site measurements.

The same approach of the 3rd floor settlement was then followed for the other monitored floors where for each monitored floor, the settlement of that floor was calculated for each additional five floors. Results were plotted on settlement charts and compared to the actual settlement charts. Etabs results are also plotted on column settlement charts for two models with and without reinforcement. The conclusion of all monitored columns settlements are organized as follows:

- The overestimation of settlement by the proposed theoretical approach increased steadily after the 3rd floor reaching 1174% of the actual settlement in the 50th floor.
- For a certain floor, each added load (constructed floor) increased the difference between the theoretical and the actual settlement.
- In any monitored floor, the proposed theoretical approach was able to predict the settlement in good accuracy only for the first added floors. The more added floors, the more deviation from the actual results takes place.
- In general, the proposed approach of this research was unable to provide reliable prediction of the column settlement after the 3rd floor.
- The average overestimation of the developed Excel sheet based on the ACI 209R-92 model was 630%.
- The provided actual site readings are considered unreliable since they showed unusual trend of settlement compared to the normal settlement charts of high-rise buildings. However, for the purpose of this study, they still provided criteria for the comparison of the proposed method of this research.
- The shortage of the ACI 209R-92 model in accounting for steel reinforcement and relaxation had a substantial effect on the predicted time-dependent effects.

- Ignoring the restraining effect of slabs, beams and outrigger walls caused the theoretical predicted settlement to be significantly overestimated.
- In addition to steel reinforcement and restraining effect, another uncertain factors such as concrete properties, ambient humidity and rate of construction contributed to the unreliability of the theoretically predicted column settlement of the proposed method.
- No considerable difference between results from the two Etabs models (with and without reinforcement) was found.
- Etabs had no recognition of the time-dependent stress transfer between concrete and steel reinforcement (relaxation). Hence, the Etabs settlement results are still far from the actual site readings.
- Etabs analysis using CEB-FIP method was able to predict the settlement better than the theoretical approach of the ACI 209R-92 model with average overestimation of 258%.
- Due to the many variables and uncertainties of the two proposed methods (theoretical and Etabs), it was difficult to compare the ACI 209R-92 and CEB-FIP models on which is better in predicting the time-dependent effects.
- The compensation technique for columns length which was used in the construction of the building was very useful in reducing the total settlement of the building keeping it within the allowable limits.
- By representing the compensation technique, staged construction analysis (sequential loading) done by Etabs provided a realistic scenario on how the building was constructed, and thus the obtained results had more reliability than those of normal analysis.
- The developed simple excel sheet program associated with the proposed method of this research is found suitable for predicting shortening of individual columns and the total settlement of low-rise buildings up to 10 stories.
- A reasonable accuracy of predicting settlement of high-rise building can be achieved with a three-dimensional computer analysis where the restraining effects of all the structural members and the steel-concrete interaction are considered.
- The accuracy of column shortening and settlement prediction can be greatly enhanced by firm knowledge and information about the materials,

environmental conditions and construction method that are involved in the building construction.

- The final actual settlement chart showed unusual trend, whereas both theoretical and Etabs charts had a consistent relationship with the expected column deformation in multi-story building. Etabs results are considered hence, adequate for design purpose, where early recommendations for construction have to be provided.
- Differential settlement is of practical interest more than absolute settlement because its consequences are structural as well as non-structural.
- The differential settlement of the presented case study building between boarder column and core wall is as low as 20mm.
- Based on the differential settlement charts, a compensation method for column length during construction can be set as follow: 10mm for the first 21 stories, 20mm for the following 21 stories and 10 mm for the last 21 stories.
- Differential settlement can be controlled at early stage in the design by maintaining level of stresses of columns near to those of core wall, for instance, decreasing the distance between neighboring columns and increasing the column cross section.

6.3 Lateral Sway

The self-weight induced sway behavior of such a unique vertical asymmetric high-rise building was investigated in this research. Unlike the study provided for column shortening, there was no site readings provided for the sway. Thus the sway study was provided using only the developed Etabs model. Two analysis models were provided, the original case study building and the modified model where the last twelve stories were removed and the building became vertically typical. The two analysis methods used in the study are the normal linear and the nonlinear sequential loading analysis. The results of the two analyses evidenced the reliability of the nonlinear analysis in capturing the real sway behavior thought it is time and effort consuming considering the huge amount of joints and members in this building which needed a very strong hardware computer to successfully complete the analysis. The normal analysis, on the other hand predicted the sway behavior unrealistically and overestimated the displacement in all levels with maximum difference of 130mm at the last floor. The building model-2 was analyzed using the same two analyses. The results of the two analyses showed similarity in deformation shape as well as in sway values. The sway of such a uniform building (model-2) was too small to affect the stability and serviceability of the building. The conclusion of the sway investigation can be summarized as follows:

- A significant reduction in floor area in high-rise buildings will result in a vertically asymmetric building which will, due to eccentric load, rotate and deflect laterally toward the higher side.
- A compensation method during the construction by adjusting the columns forms horizontally is an effective way to reduce and control the lateral sway.
- The maximum lateral deflection of the presented case study building was 82.5mm at the 53rd floor which is equivalent to H/2800, much less than an assumed accepted limit of H/1000 (where H: height of the building)
- The nonlinear staged construction analysis based on step by step modelling and loading is the realistic way to capture the real behavior of this type of buildings.
- The disadvantage of nonlinear analysis is the significant time, effort and hardware computer capability needed to complete this analysis.
- The normal linear analysis is inadequate in predicting the sway of this type of buildings due to unrealistic shape and values of deformations provided by this analysis. However, it’s adequate for typical buildings where no significant eccentricity or mass shifting exist.

6.4 Recommendations for Design and Further Research

This research revealed the importance of studying creep and shrinkage effects in concrete tall buildings. Column shortening, differential settlement and lateral sway of vertically asymmetric high-rise building are all behaviors that should be investigated and checked during the design of such buildings. It’s very important to predict the absolute and deferential column shortening as it will affect the serviceability of the building as well as the installation of non-structural systems.

Prediction of column shortening is a complex task associated with many uncertain factors that may not be available during the design stage. Also, prediction of time-dependent effects is an important part of column shortening estimation and it's highly affected by the chosen method of prediction.
Recommendations are shown below for design and further research on the overall behavior of this type of buildings.

6.4.1 Design Recommendations

The design stage should extend during the construction of the building to ensure that design results are well met. The following steps are general outlines on how to overcome the uncertainties in this type of buildings:

- After the strength design and member sizing are finalized, the shortening and lateral deflection verification should initiate.
- A prediction method of creep and shrinkage should be chosen to account for time-dependent effects.
- A three dimensional software model to be developed and all the parameters and concrete properties required by the chosen method to be inputted into the model.
- A nonlinear staged construction analysis should be relied on to predict both settlement and sway of the building.
- Based on shortening and sway results, a compensation method to be specified to be adopted in the construction.
- During the construction, many laboratory tests to take place on concrete specimens taken from the same concrete patch used in the construction of the building to determine all the concerning concrete properties, such as elasticity modulus, concrete specified strength and creep and shrinkage strain.
- The design model inputs are then to be modified to account for the results of those tests. A modification to the compensation method to be done if needed.
- A monitoring survey system for both settlement and sway is a very effective and helpful way to assess the design results as it represents the real building behavior.

6.4.2 Research Recommendations

The site readings provided by the case study building was a substantial part of this research as it was the only real site readings which reflected the real performance of the building. However, the research, in most of it, was based on assumed concrete properties and site conditions where all the column shortenings were predicted based on those estimations. Moreover, many of the affecting factors were not included for simplifying the process of this research, such as the effect of horizontal members and columns reinforcement. The general lines below highlight the factors that need to be considered in future researches about columns shortening and time-dependent effects in concrete buildings.

- A study about the behavior of high-rise buildings is effectively held in association with a systematic site reading for both settlement and sway where floors deflection under construction loads are monitored.
- Choosing a good case study is accompanied with laboratory tests that done during the construction to determine the real properties of the concrete used in the construction.
- Including the effects of horizontal members, such as beams and outrigger walls will enhance the results and provide a realistic behavior of the building.
- Where possible, experimental tests to be done on reinforced concrete specimens in addition to plain concrete to account for the reinforcement relaxation effects and the load sharing between concrete and steel.
- Any method for predicting time-dependent effects should be modified as per the laboratory tests and the provided site readings.
- Predicting the time-dependent effects with more than one method is an effective way to compare their results with the site readings and determine the better method to be used in design.
- A combination between gravity and lateral forces (seismic and wind) effects on vertically asymmetric high-rise building will be a very useful and interesting subject to research. A building which had previously swayed due to eccentric gravity loads will experience more induced sway by lateral forces.

- Selection and arrangement of different structural systems to minimize the effects of sway induced by gravity and lateral loads is another interesting research area especially when coupled with tests and monitoring methods.

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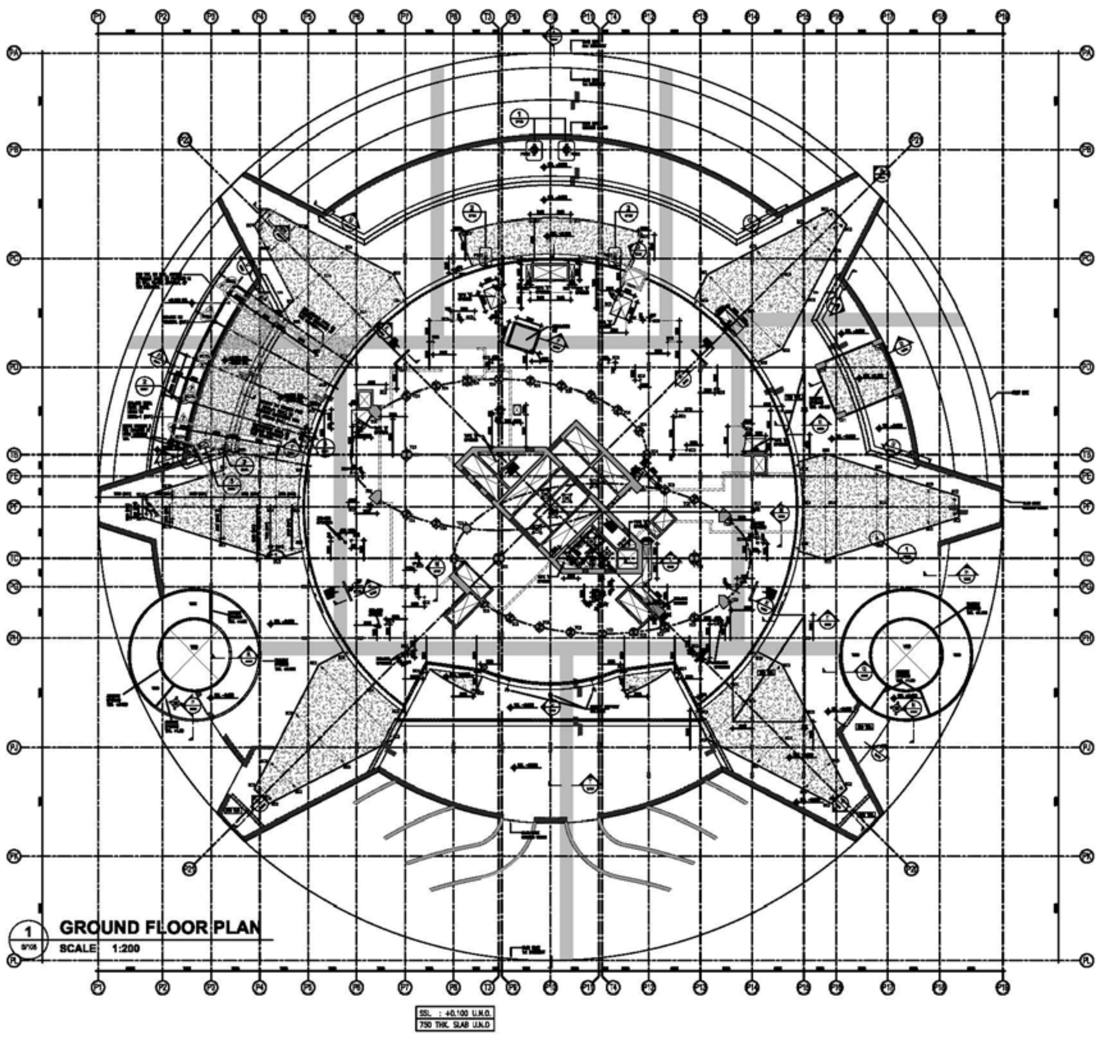
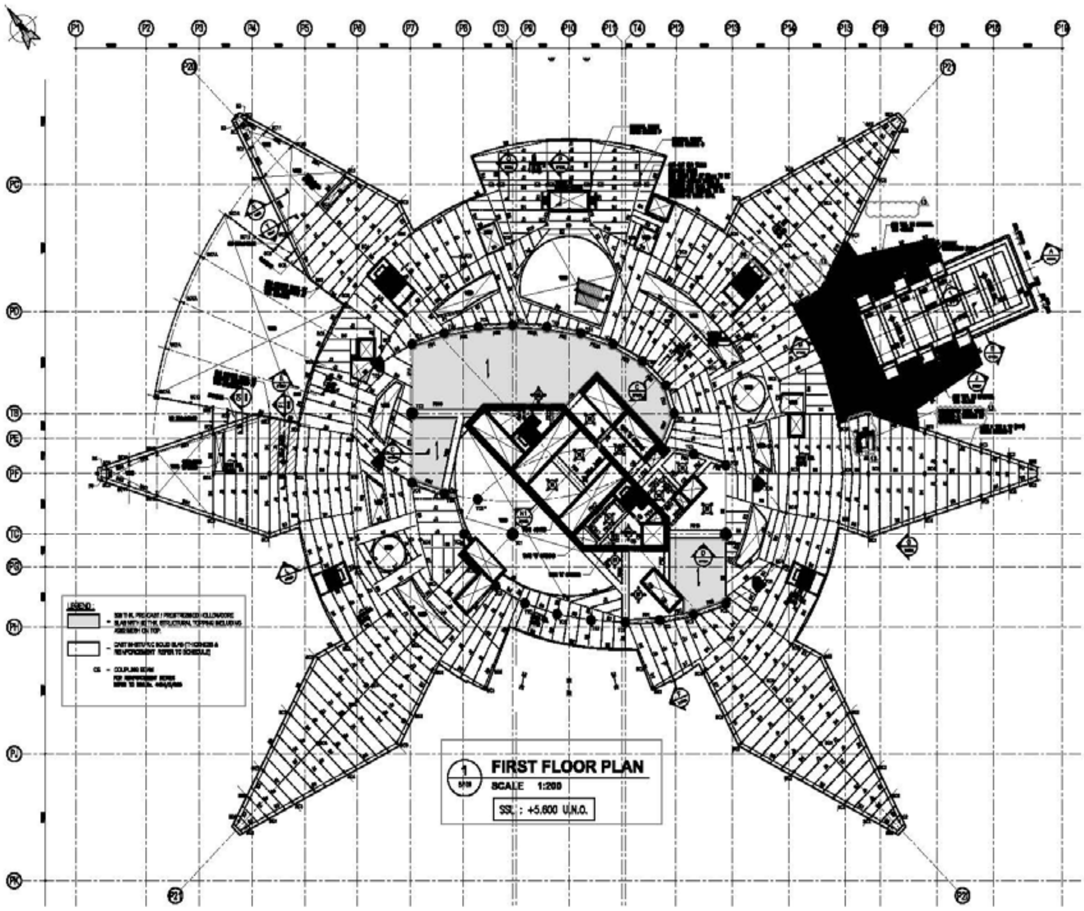
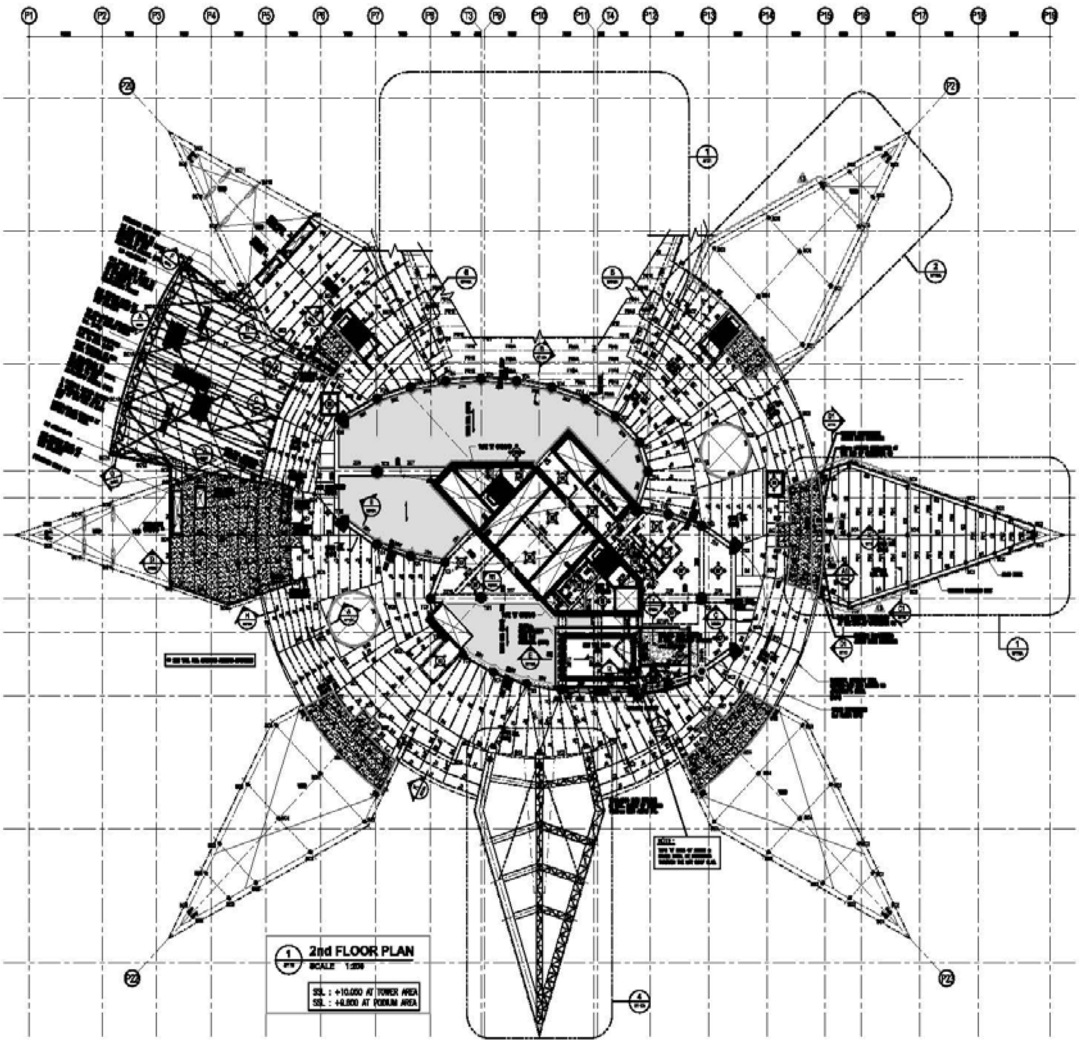
APPENDICES

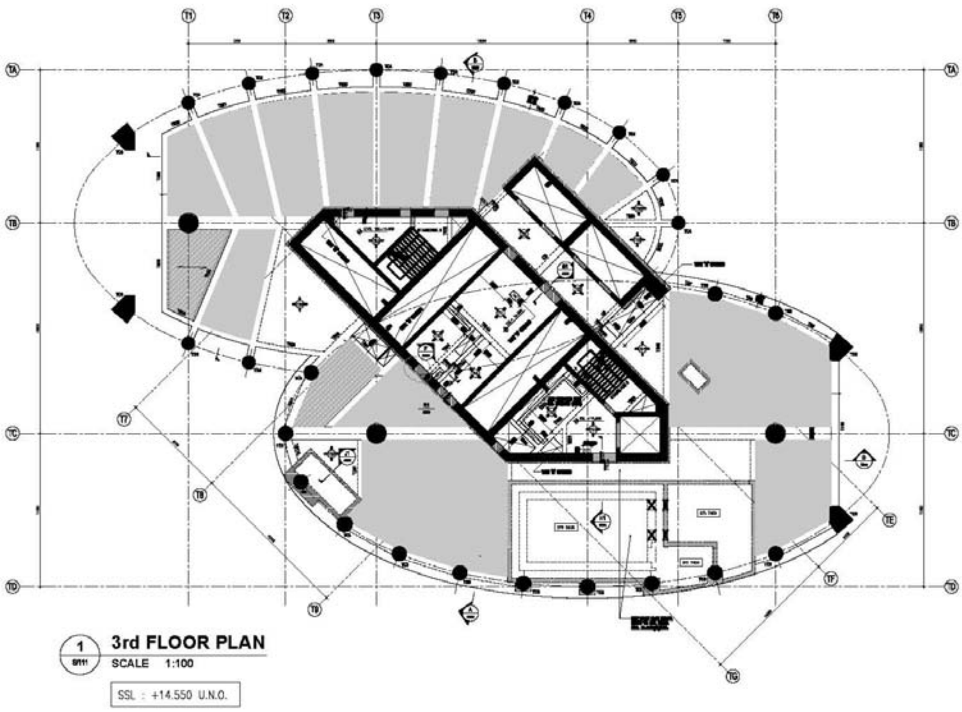
Appendix A

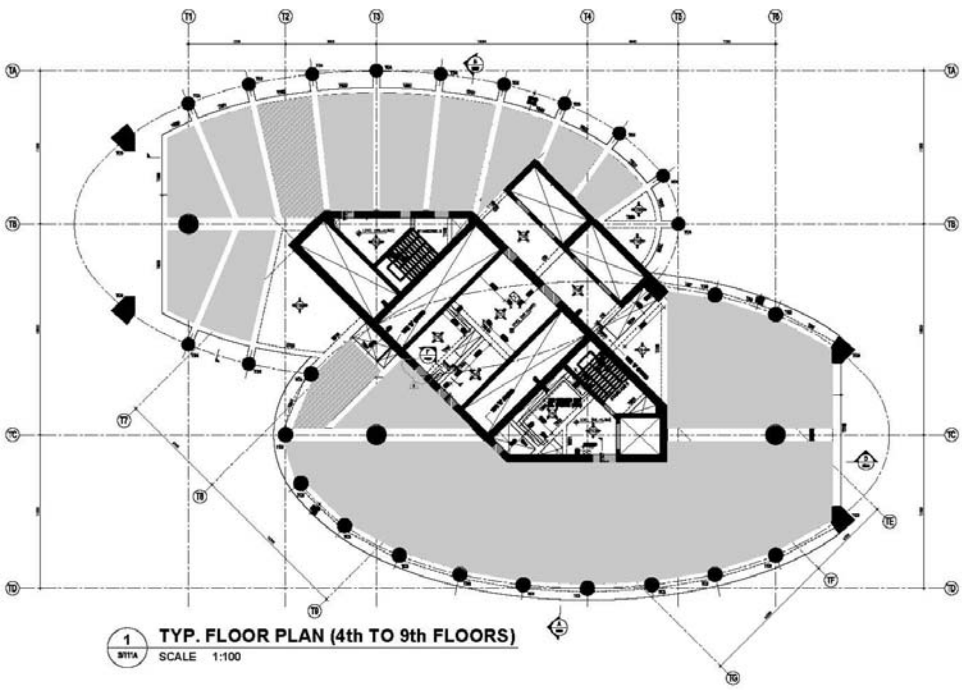
Structural Drawings for Case Study Building

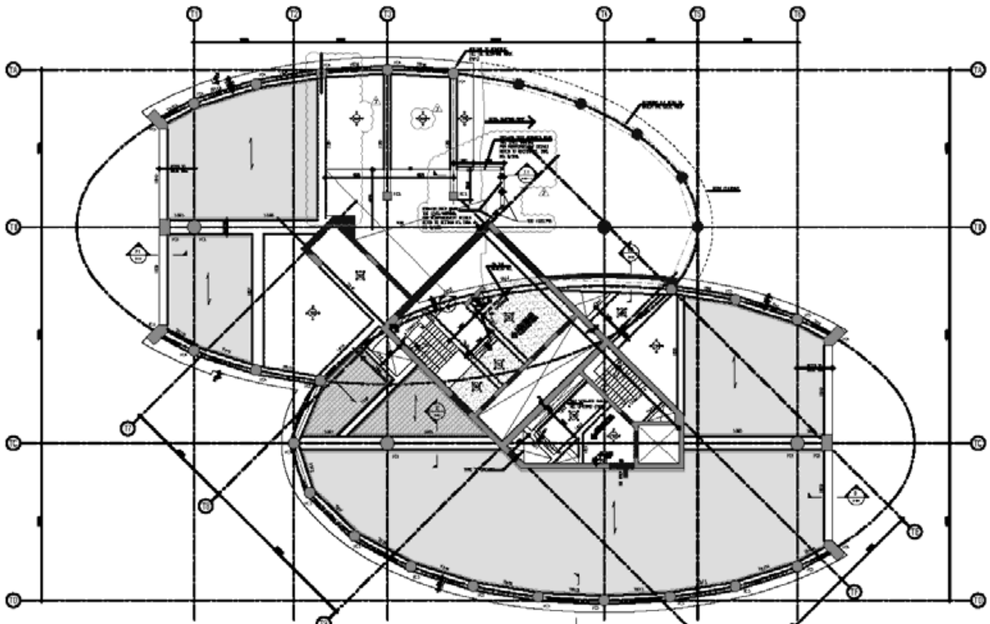



FIRST FLOOR PLAN
SCALE 1:200
SSL : +5.600 U.N.O.

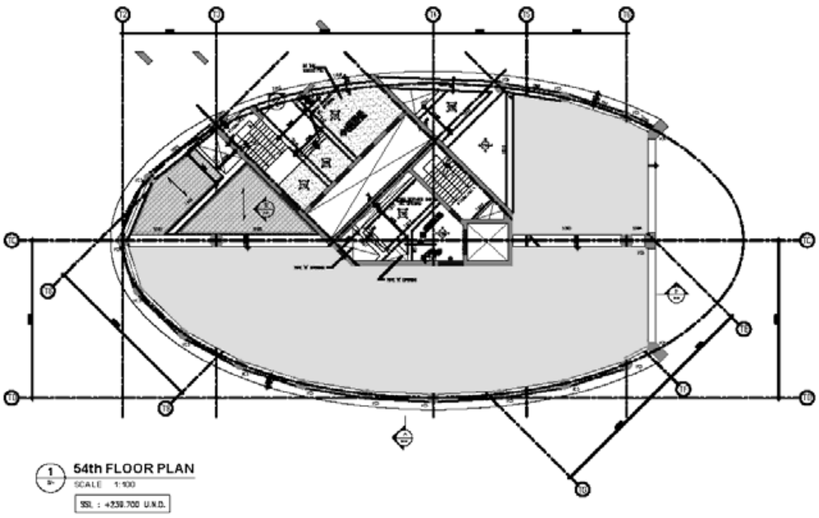

1
2nd FLOOR PLAN
SSL : +10.000 AT TOWER AREA


1
S/11
3rd FLOOR PLAN
SCALE 1:100
SSL : +14.550 U.N.O.

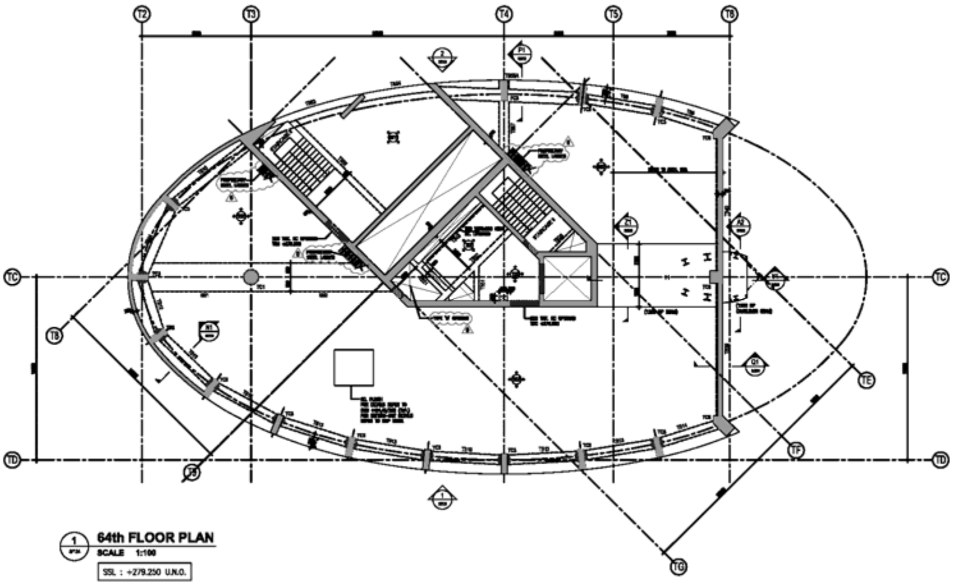

1
TYP. FLOOR PLAN (4th TO 9th FLOORS)
SCALE 1:100



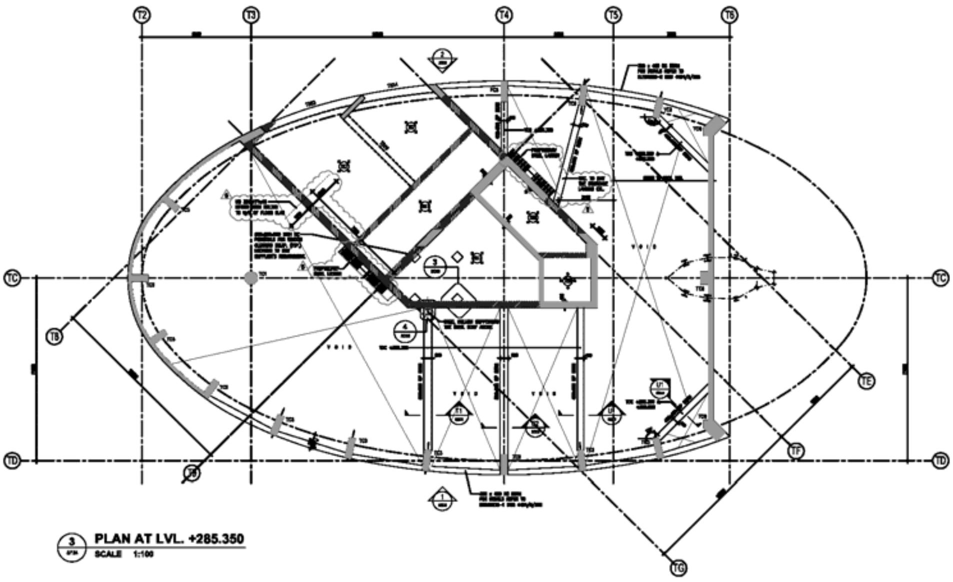
2 52nd FLOOR PLAN
SCALE 1:100
SSL : +231.800 U.N.O.



1 54th FLOOR PLAN
SCALE 1:100
SSL : +239.700 U.N.O.



64th FLOOR PLAN
SCALE 1:100
SSL : +279.250 U.N.O.



PLAN AT LVL. +285.350
SCALE 1:100

Appendix B

Case Study Site Readings and Settlement Charts

stress for one floor and self weight only,N/mm2

ENTER stress in member

0.278

T.SET= total settlement

set.R= settlement reading

S.R=site reading

COLUMN

20-6-2007

FINAL

Col /Floor	8	13	18	23	28	33	38	43	48	53	58	63	Actual set
3.THEORETICAL.SR	1.3	2.7	4.2	5.9	7.8	9.7	11.8	14.1	16.4	18.9	21.6	24.4	38
3.SR.ACTUAL	1	3	4	6	8	10	12	14	17	19	21	24	
10.THEORETICAL.SR		1.2	2.6	4.0	5.7	7.4	9.3	11.3	13.5	15.8	18.3	20.8	65
10.SR.ACTUAL		1	3	4	6	8	9	11	14	16	17	19	
21.THEORETICAL.SR				1.2	2.6	4.0	5.7	7.4	9.3	11.3	13.5	15.8	112
21.SR.ACTUAL				1	3	4	6	7	9	11	13	15	
29.THEORETICAL.SR						1.2	2.6	4.0	5.7	7.4	9.3	11.3	157
29.SR.ACTUAL						1	2	4	6	7	9	12	
41.THEORETICAL.SR								1.2	2.6	4.0	5.7	7.4	200
41.SR.ACTUAL								1	2	3	6	9	
50.THEORETICAL.SR										1.2	2.6	4.0	236
50.SR.ACTUAL										1	3	5	
60.THEORETICAL.SR												1.2	266
corrective factor between computer (ETAB) and actual													v=2.15

stress for one floor and self weight only,N/mm2

ENTER stress in member

0.163

T.SET= total settlement

set.R= settlement reading

S.R=site reading

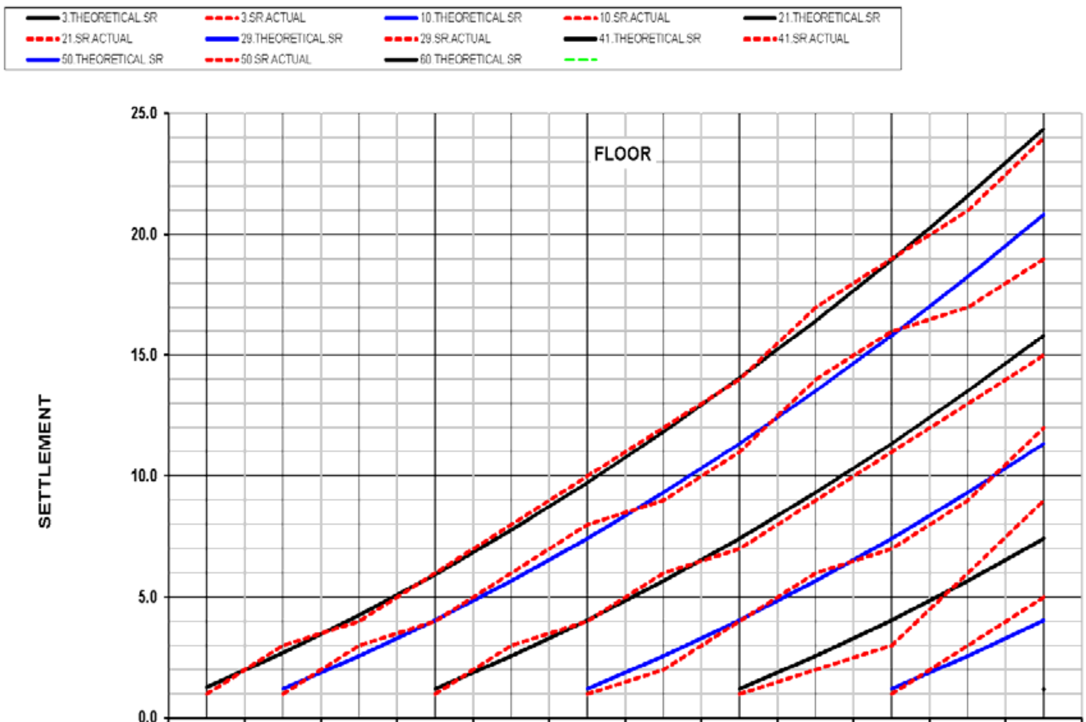
WALL

20-6-2007

FINAL

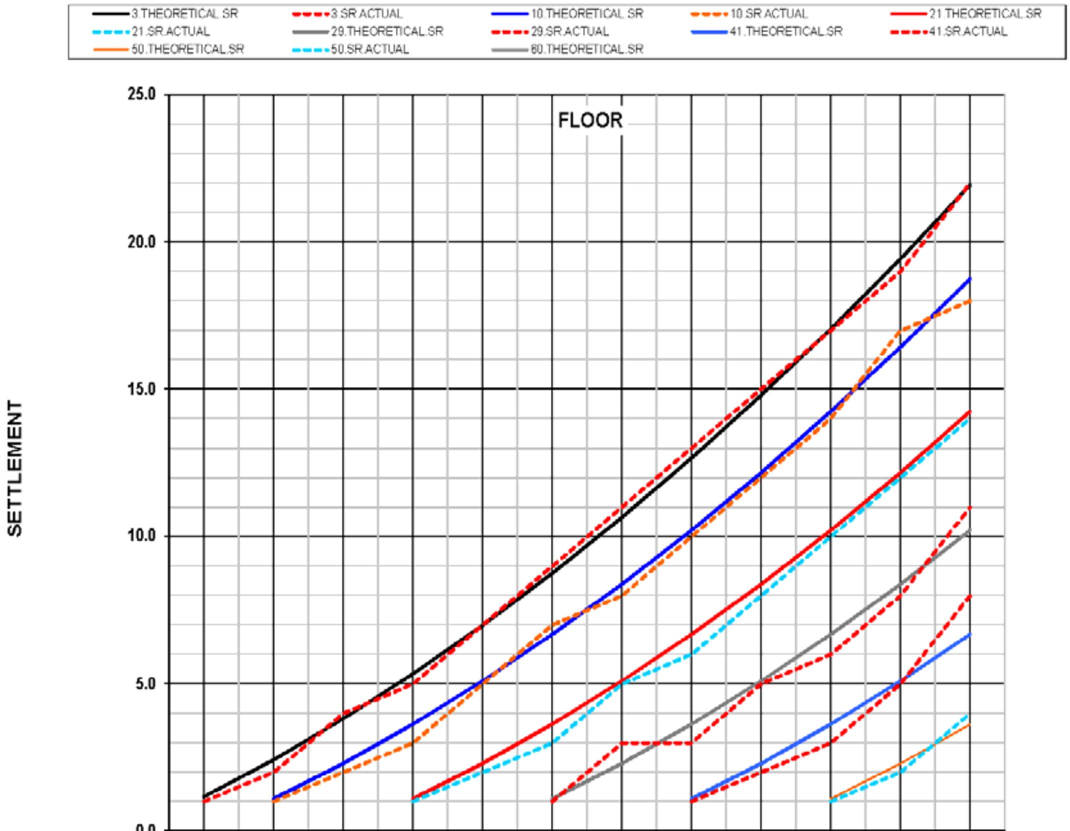
Col /Floor	8	13	18	23	28	33	38	43	48	53	58	63	Actual set
3.THEORETICAL.SR	1.2	2.4	3.8	5.3	7.0	8.7	10.6	12.7	14.8	17.0	19.4	21.9	34
3.SR.ACTUAL	1	2	4	5	7	9	11	13	15	17	19	22	
10.THEORETICAL.SR		1.1	2.3	3.6	5.1	6.7	8.4	10.2	12.2	14.2	16.4	18.8	61
10.SR.ACTUAL		1	2	3	5	7	8	10	12	14	17	18	
21.THEORETICAL.SR				1.1	2.3	3.6	5.1	6.7	8.4	10.2	12.2	14.2	106
21.SR.ACTUAL				1	2	3	5	6	8	10	12	14	
29.THEORETICAL.SR						1.1	2.3	3.6	5.1	6.7	8.4	10.2	149
29.SR.ACTUAL						1	3	3	5	6	8	11	
41.THEORETICAL.SR								1.1	2.3	3.6	5.1	6.7	191
41.SR.ACTUAL								1	2	3	5	8	
50.THEORETICAL.SR										1.1	2.3	3.6	225
50.SR.ACTUAL										1	2	4	
60.THEORETICAL.SR												1.1	254
corrective factor between computer (ETAB) and actual													v=2.55

CHART 2 PROJECT BORDER COLUMNS SITE READING (THEO & ACTUAL)



	8	13	18	23	28	33	38	43	48	53	58	63
3.THEORETICAL.SR	1.3	2.7	4.2	5.9	7.8	9.7	11.8	14.1	16.4	18.9	21.6	24.4
3.SR.ACTUAL	1	3	4	6	8	10	12	14	17	19	21	24
10.THEORETICAL.SR		1.2	2.6	4.0	5.7	7.4	9.3	11.3	13.5	15.8	18.3	20.8
10.SR.ACTUAL		1	3	4	6	8	9	11	14	16	17	19
21.THEORETICAL.SR				1.2	2.6	4.0	5.7	7.4	9.3	11.3	13.5	15.8
21.SR.ACTUAL				1	3	4	6	7	9	11	13	15
29.THEORETICAL.SR						1.2	2.6	4.0	5.7	7.4	9.3	11.3
29.SR.ACTUAL						1	2	4	6	7	9	12
41.THEORETICAL.SR								1.2	2.6	4.0	5.7	7.4
41.SR.ACTUAL								1	2	3	6	9
50.THEORETICAL.SR										1.2	2.6	4.0
50.SR.ACTUAL										1	3	5
60.THEORETICAL.SR												1.2
---			0									

CHART 3 TOWER CORE WALL SITE READING (THEO & ACTUAL)



	8	13	18	23	28	33	38	43	48	53	58	63
3.THEORETICAL.SR	1.2	2.4	3.8	5.3	7.0	8.7	10.6	12.7	14.8	17.0	19.4	21.9
3.SR.ACTUAL	1	2	4	5	7	9	11	13	15	17	19	22
10.THEORETICAL.SR		1.1	2.3	3.6	5.1	6.7	8.4	10.2	12.2	14.2	16.4	18.8
10.SR.ACTUAL		1	2	3	5	7	8	10	12	14	17	18
21.THEORETICAL.SR				1.1	2.3	3.6	5.1	6.7	8.4	10.2	12.2	14.2
21.SR.ACTUAL				1	2	3	5	6	8	10	12	14
29.THEORETICAL.SR						1.1	2.3	3.6	5.1	6.7	8.4	10.2
29.SR.ACTUAL						1	3	3	5	6	8	11
41.THEORETICAL.SR								1.1	2.3	3.6	5.1	6.7
41.SR.ACTUAL								1	2	3	5	8
50.THEORETICAL.SR										1.1	2.3	3.6
50.SR.ACTUAL										1	2	4
60.THEORETICAL.SR												1.1

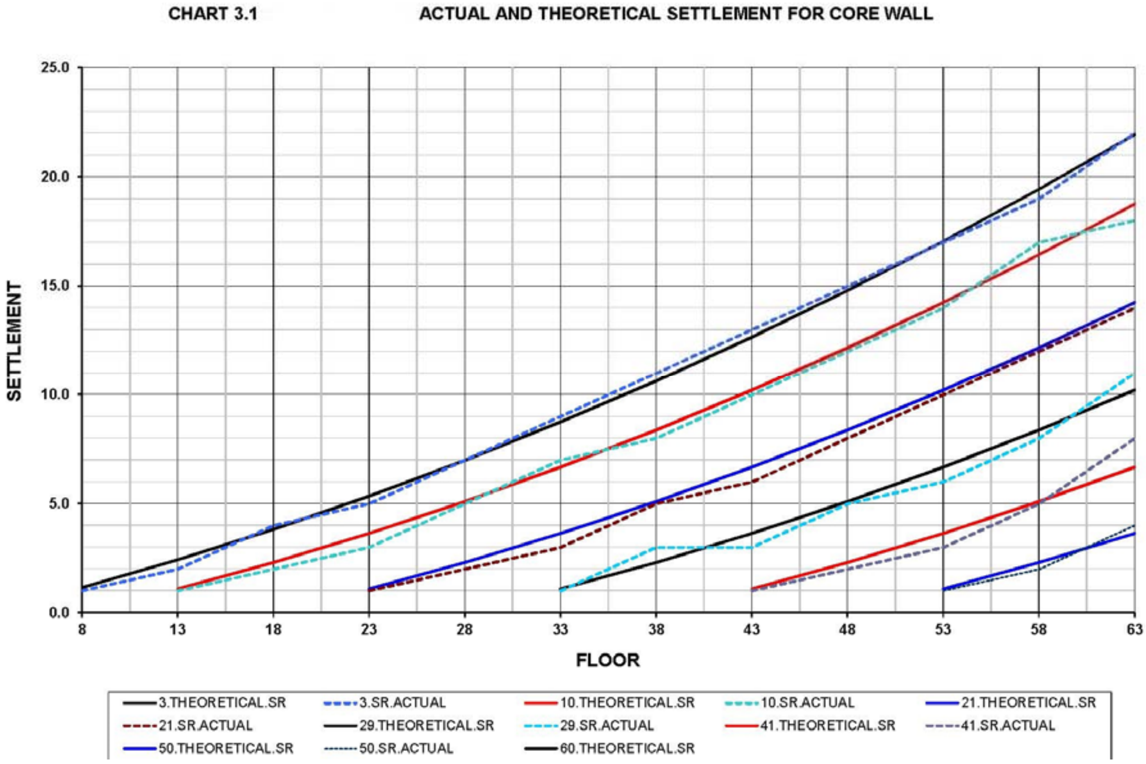


CHART 3.1
ACTUAL AND THEORETICAL SETTLEMENT FOR CORE WALL
SETTLEMENT
FLOOR
0.0
5.0
10.0
15.0
20.0
25.0
8
13
18
23
28
33
38
43
48
53
58
63
3.THEORETICAL.SR
3.SR.ACTUAL
10.THEORETICAL.SR
10.SR.ACTUAL
21.THEORETICAL.SR
21.SR.ACTUAL
29.THEORETICAL.SR
29.SR.ACTUAL
41.THEORETICAL.SR
41.SR.ACTUAL
50.THEORETICAL.SR
50.SR.ACTUAL
60.THEORETICAL.SR

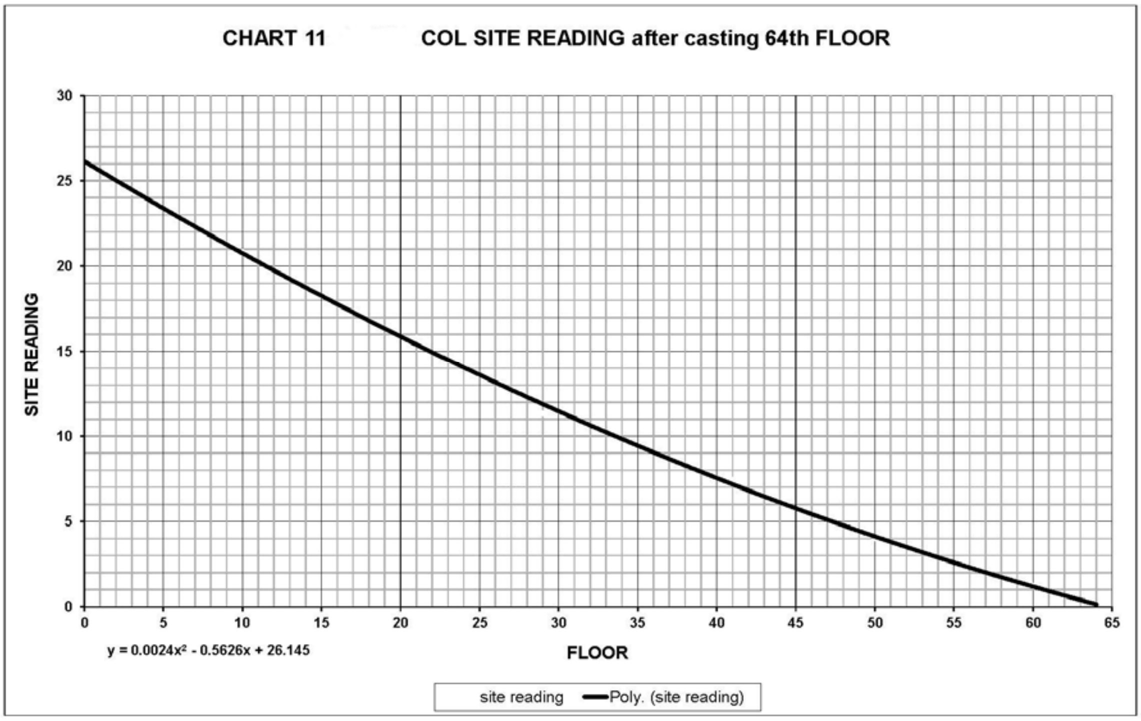


CHART 11
COL SITE READING after casting 64th FLOOR
SITE READING
FLOOR
0
5
10
15
20
25
30
0
5
10
15
20
25
30
35
40
45
50
55
60
65
y = 0.0024x² - 0.5626x + 26.145
site reading
Poly. (site reading)

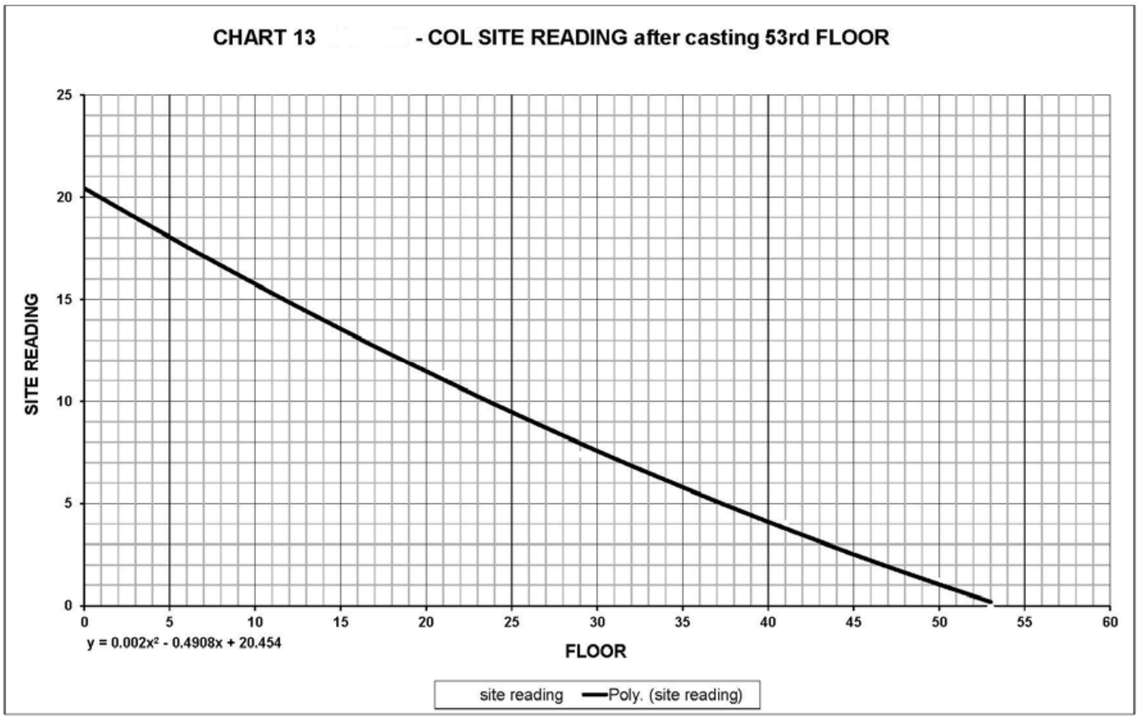


CHART 13 - COL SITE READING after casting 53rd FLOOR
SITE READING
FLOOR
y = 0.002x² - 0.4908x + 20.454
site reading
Poly. (site reading)


CHART 12 COL SITE READING after casting 58th FLOOR
SITE READING
FLOOR
y = 0.0021x² - 0.5194x + 23.181
site reading
Poly. (site reading)

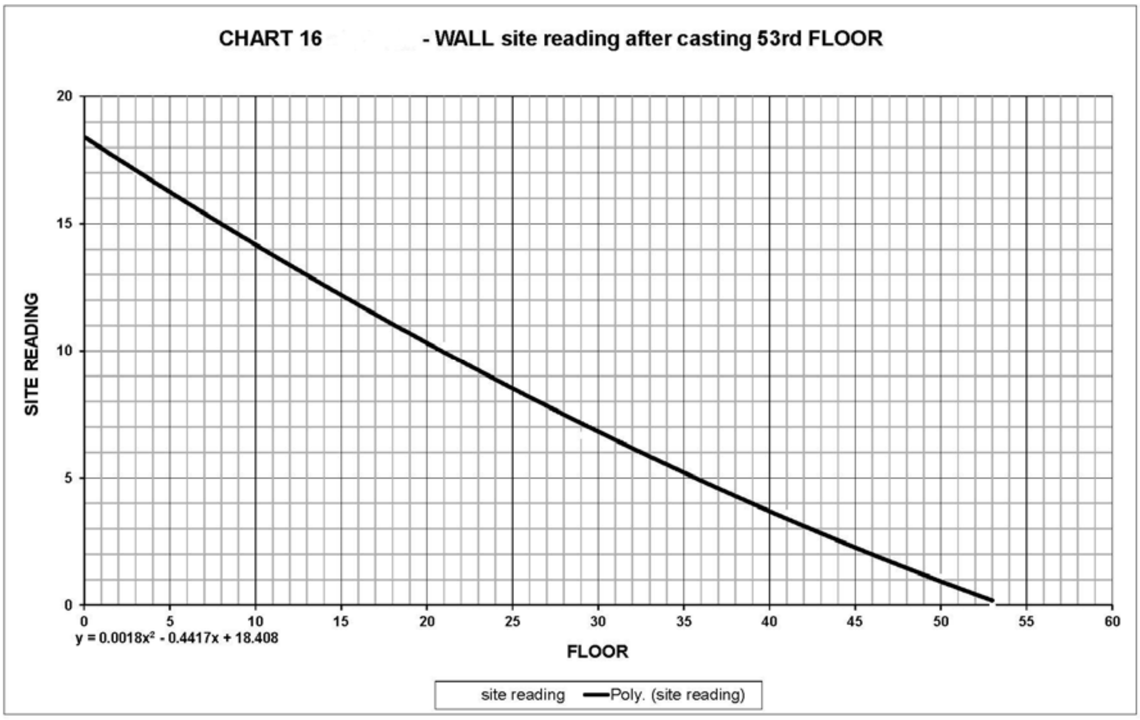


CHART 16 - WALL site reading after casting 53rd FLOOR
SITE READING
0
5
10
15
20
0
5
10
15
20
25
30
35
40
45
50
55
60
y = 0.0018x² - 0.4417x + 18.408
FLOOR
site reading
Poly. (site reading)

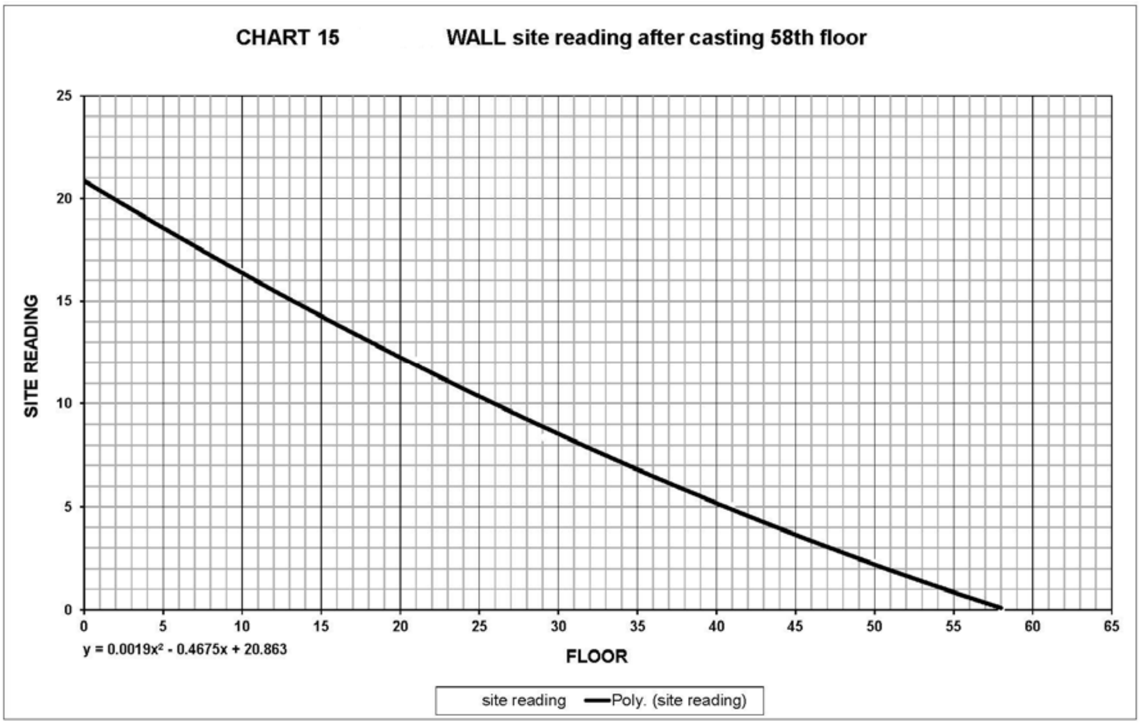


CHART 15 WALL site reading after casting 58th floor
SITE READING
0
5
10
15
20
25
0
5
10
15
20
25
30
35
40
45
50
55
60
65
y = 0.0019x² - 0.4675x + 20.863
FLOOR
site reading
Poly. (site reading)

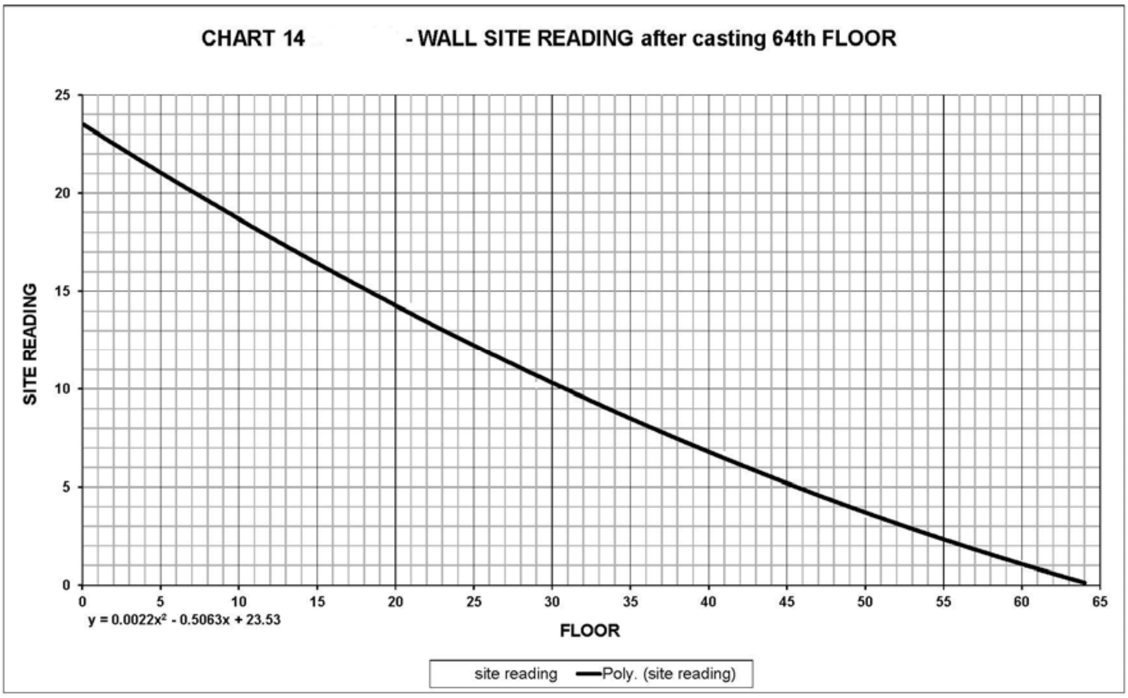


CHART 14 - WALL SITE READING after casting 64th FLOOR
SITE READING
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65
$y = 0.0022x^2 - 0.5063x + 23.53$
FLOOR
site reading
Poly. (site reading)

Appendix C

Examples of Excel Sheet Calculations of Column Shortening

Shortening Prediction of Column in Floor (B5) by Adding Floors (4 to 48)

Input Data

Floors Data	Considered Column Floor	-5
	Floor Height (m)	3.2
	Casting Floors from	4
	to	48
	Rate of Construction (days/floor)	3
Elastic Data	*f'c* (mpa)	70
	Column Cross Section (m²)	1.54
	Load Increment (kN/floor)	320
Creep & Shrinkage Data	Column volume/surface (mm)	350
	Percentage of fine agg. (%)	30
	Slump (mm)	100
	Relative Humidity (%)	80

Output Data

Elastic Shortening Δe (mm)	0.8643
Creep Shortening Δc (mm)	0.4031
Shrinkage Shortening Δsh (mm)	0.1233
Total Shortening TS_{kj} (mm)	**1.391**

Calculating Shortening of Column in B5 due to loads from 4th floor to 48th floor

	Creep							Elastic		
Casting Floor	loading age	γla	γc	Vu	t	Vt	Δcr	f'ct	Ect	Δe
4	27	0.847	0.428	1.006	135	0.659	0.0131	63.7	33398	0.0199
5	30	0.837	0.423	0.994	132	0.648	0.0128	64.6	33584	0.0198
6	33	0.827	0.418	0.983	129	0.637	0.0126	65.3	33728	0.0197
7	36	0.819	0.414	0.972	126	0.628	0.0123	66	33872	0.0196
8	39	0.811	0.41	0.963	123	0.619	0.0121	66.5	33974	0.0196
9	42	0.804	0.406	0.955	120	0.61	0.0119	67	34075	0.0195
10	45	0.798	0.403	0.947	117	0.602	0.0117	67.4	34156	0.0195
11	48	0.792	0.4	0.94	114	0.594	0.0115	67.7	34217	0.0194
12	51	0.786	0.397	0.933	111	0.586	0.0114	68.1	34298	0.0194
13	54	0.781	0.394	0.927	108	0.579	0.0112	68.4	34358	0.0194
14	57	0.776	0.392	0.921	105	0.571	0.011	68.6	34398	0.0193
15	60	0.771	0.39	0.916	102	0.564	0.0109	68.9	34458	0.0193
16	63	0.767	0.387	0.91	99	0.557	0.0107	69.1	34498	0.0193
17	66	0.762	0.385	0.905	96	0.55	0.0106	69.3	34538	0.0193
18	69	0.758	0.383	0.901	93	0.543	0.0104	69.4	34558	0.0192
19	72	0.755	0.381	0.896	90	0.536	0.0103	69.6	34598	0.0192
20	75	0.751	0.379	0.892	87	0.529	0.0102	69.8	34637	0.0192
21	78	0.748	0.378	0.888	84	0.522	0.01	69.9	34657	0.0192
22	81	0.744	0.376	0.884	81	0.515	0.0099	70	34677	0.0192
23	84	0.741	0.374	0.88	78	0.508	0.0098	70.2	34717	0.0192
24	87	0.738	0.373	0.876	75	0.501	0.0096	70.3	34737	0.0191
25	90	0.735	0.371	0.873	72	0.494	0.0094	70.4	34756	0.0191
26	93	0.732	0.37	0.869	69	0.486	0.0093	70.5	34776	0.0191
27	96	0.729	0.369	0.866	66	0.479	0.0091	70.6	34796	0.0191
28	99	0.727	0.367	0.863	63	0.471	0.009	70.7	34816	0.0191
29	102	0.724	0.366	0.86	60	0.463	0.0088	70.8	34835	0.0191
30	105	0.722	0.365	0.857	57	0.455	0.0087	70.8	34835	0.0191
31	108	0.719	0.364	0.854	54	0.447	0.0085	70.9	34855	0.0191
32	111	0.717	0.362	0.851	51	0.438	0.0084	71	34875	0.0191
33	114	0.715	0.361	0.849	48	0.429	0.0082	71.1	34895	0.0191
34	117	0.713	0.36	0.846	45	0.419	0.008	71.1	34895	0.0191
35	120	0.711	0.359	0.844	42	0.409	0.0078	71.2	34914	0.019
36	123	0.708	0.358	0.841	39	0.399	0.0076	71.2	34914	0.019
37	126	0.706	0.357	0.839	36	0.388	0.0074	71.3	34934	0.019
38	129	0.704	0.356	0.837	33	0.376	0.0071	71.4	34954	0.019
39	132	0.703	0.355	0.834	30	0.363	0.0069	71.4	34954	0.019
40	135	0.701	0.354	0.832	27	0.349	0.0066	71.5	34973	0.019
41	138	0.699	0.353	0.83	24	0.334	0.0063	71.5	34973	0.019
42	141	0.697	0.352	0.828	21	0.317	0.006	71.5	34973	0.019
43	144	0.695	0.351	0.826	18	0.299	0.0057	71.6	34993	0.019
44	147	0.694	0.351	0.824	15	0.277	0.0053	71.6	34993	0.019
45	150	0.692	0.35	0.822	12	0.253	0.0048	71.7	35012	0.019
46	153	0.69	0.349	0.82	9	0.223	0.0042	71.7	35012	0.019
47	156	0.689	0.348	0.818	6	0.185	0.0035	71.7	35012	0.019
48	159	0.687	0.347	0.816	3	0.132	0.0025	71.8	35032	0.019
	0	0	0	0	0	0	0.4031	0	0	0.8643

Shortening Prediction of Column in Floor (3) by Adding Floors (4 to 48)				
Input Data			**Output Data**	
Floors Data	Considered Column Floor	3	Elastic Shortening Δe (mm)	1.7733
Floors Data	Floor Height (m)	3.95		
Floors Data	Casting Floors from	4	Creep Shortening Δc (mm)	0.8954
Floors Data	to	48		
Floors Data	Rate of Construction (days/floor)	3	Shrinkage Shortening Δsh (mm)	0.3504
Elastic Data	*f'c* (mpa)	70	**Total Shortening TS_{kj} (mm)**	**3.019**
Elastic Data	Column Cross Section (m^2)	0.95		
Elastic Data	Load Increment (kN/floor)	320		
Creep & Shrinkage Data	Column volume/surface (mm)	275		
Creep & Shrinkage Data	Percentage of fine agg. (%)	30		
Creep & Shrinkage Data	Slump (mm)	100		
Creep & Shrinkage Data	Relative Humidity (%)	80		

Calculating Shortening of Column in B5 due to loads from 4th floor to 48th floor

	Creep								Elastic		
Casting Floor	loading age	γla	γc	Vu	t	Vt	Δcr	f'ct	Ect	Δe
4	3	1.098	0.556	1.307	135	0.856	0.045	30.7	25295	0.0526
5	6	1.012	0.513	1.205	132	0.785	0.0364	43.3	28747	0.0463
6	9	0.965	0.489	1.148	129	0.745	0.0326	50.2	30423	0.0437
7	12	0.932	0.472	1.11	126	0.716	0.0304	54.5	31410	0.0424
8	15	0.908	0.46	1.081	123	0.694	0.0288	57.5	32075	0.0415
9	18	0.889	0.45	1.058	120	0.676	0.0276	59.7	32552	0.0409
10	21	0.873	0.442	1.039	117	0.66	0.0267	61.4	32915	0.0404
11	24	0.859	0.435	1.023	114	0.646	0.0259	62.7	33189	0.0401
12	27	0.847	0.429	1.009	111	0.633	0.0252	63.7	33398	0.0398
13	30	0.837	0.424	0.996	108	0.622	0.0246	64.6	33584	0.0396
14	33	0.827	0.419	0.985	105	0.611	0.0241	65.3	33728	0.0394
15	36	0.819	0.415	0.975	102	0.601	0.0236	66	33872	0.0393
16	39	0.811	0.411	0.966	99	0.591	0.0232	66.5	33974	0.0392
17	42	0.804	0.407	0.957	96	0.581	0.0227	67	34075	0.039
18	45	0.798	0.404	0.95	93	0.572	0.0223	67.4	34156	0.039
19	48	0.792	0.401	0.942	90	0.564	0.0219	67.7	34217	0.0389
20	51	0.786	0.398	0.936	87	0.555	0.0215	68.1	34298	0.0388
21	54	0.781	0.396	0.929	84	0.547	0.0212	68.4	34358	0.0387
22	57	0.776	0.393	0.924	81	0.538	0.0208	68.6	34398	0.0387
23	60	0.771	0.391	0.918	78	0.53	0.0205	68.9	34458	0.0386
24	63	0.767	0.388	0.913	75	0.522	0.0201	69.1	34498	0.0386
25	66	0.762	0.386	0.908	72	0.513	0.0198	69.3	34538	0.0385
26	69	0.758	0.384	0.903	69	0.505	0.0194	69.4	34558	0.0385
27	72	0.755	0.382	0.898	66	0.496	0.0191	69.6	34598	0.0385
28	75	0.751	0.38	0.894	63	0.488	0.0187	69.8	34637	0.0384
29	78	0.748	0.379	0.89	60	0.479	0.0184	69.9	34657	0.0384
30	81	0.744	0.377	0.886	57	0.47	0.0181	70	34677	0.0384
31	84	0.741	0.375	0.882	54	0.461	0.0177	70.2	34717	0.0383
32	87	0.738	0.374	0.879	51	0.452	0.0173	70.3	34737	0.0383
33	90	0.735	0.372	0.875	48	0.442	0.0169	70.4	34756	0.0383
34	93	0.732	0.371	0.872	45	0.432	0.0165	70.5	34776	0.0383
35	96	0.729	0.37	0.868	42	0.421	0.0161	70.6	34796	0.0382
36	99	0.727	0.368	0.865	39	0.41	0.0157	70.7	34816	0.0382
37	102	0.724	0.367	0.862	36	0.398	0.0152	70.8	34835	0.0382
38	105	0.722	0.366	0.859	33	0.386	0.0147	70.8	34835	0.0382
39	108	0.719	0.364	0.856	30	0.372	0.0142	70.9	34855	0.0382
40	111	0.717	0.363	0.854	27	0.358	0.0137	71	34875	0.0382
41	114	0.715	0.362	0.851	24	0.342	0.013	71.1	34895	0.0381
42	117	0.713	0.361	0.848	21	0.325	0.0124	71.1	34895	0.0381
43	120	0.711	0.36	0.846	18	0.306	0.0117	71.2	34914	0.0381
44	123	0.708	0.359	0.843	15	0.284	0.0108	71.2	34914	0.0381
45	126	0.706	0.358	0.841	12	0.259	0.0099	71.3	34934	0.0381
46	129	0.704	0.357	0.839	9	0.228	0.0087	71.4	34954	0.0381
47	132	0.703	0.356	0.836	6	0.19	0.0072	71.4	34954	0.0381
48	135	0.701	0.355	0.834	3	0.135	0.0051	71.5	34973	0.038
0	0	0	0	0	0	0	0.8954	0	0	1.7733

Shortening Prediction of Column in Floor (1) by Adding Floors (4 to 43)				
Input Data			**Output Data**	
Floors Data	Considered Column Floor	1	Elastic Shortening Δe (mm)	1.2156
	Floor Height (m)	4.5		
	Casting Floors from	4	Creep Shortening Δc (mm)	0.5828
	to	43		
	Rate of Construction (days/floor)	3	Shrinkage Shortening Δsh (mm)	0.3237
Elastic Data	*f'c* (mpa)	70	**Total Shortening TS_{kj} (mm)**	**2.122**
	Column Cross Section (m²)	3.038		
	Load Increment (kN/floor)	700		
Creep & Shrinkage Data	Column volume/surface (mm)	316		
	Percentage of fine agg. (%)	30		
	Slump (mm)	100		
	Relative Humidity (%)	80		

Calculating Shortening of Wall in 1st floor due to loads from 4th floor to 43th floor

	Creep							Elastic		
Casting Floor	loading age	γla	γc	Vu	t	Vt	Δcr	f'ct	Ect	Δe
4	9	0.965	0.488	1.146	120	0.732	0.025	50.2	30422.85	0.0341
5	12	0.932	0.471	1.108	117	0.704	0.0232	54.5	31409.61	0.033
6	15	0.908	0.459	1.079	114	0.682	0.022	57.5	32075.15	0.0323
7	18	0.889	0.449	1.056	111	0.663	0.0212	59.7	32552.24	0.0319
8	21	0.873	0.441	1.037	108	0.647	0.0204	61.4	32914.91	0.0315
9	24	0.859	0.434	1.021	105	0.633	0.0197	62.7	33188.87	0.0312
10	27	0.847	0.428	1.007	102	0.62	0.0192	63.7	33397.68	0.031
11	30	0.837	0.423	0.994	99	0.608	0.0188	64.6	33584.21	0.0309
12	33	0.827	0.418	0.983	96	0.597	0.0183	65.3	33728.39	0.0307
13	36	0.819	0.414	0.973	93	0.587	0.0179	66	33871.81	0.0306
14	39	0.811	0.41	0.964	90	0.577	0.0176	66.5	33973.78	0.0305
15	42	0.804	0.407	0.956	87	0.567	0.0172	67	34075.37	0.0304
16	45	0.798	0.403	0.948	84	0.557	0.0169	67.4	34156.37	0.0304
17	48	0.792	0.4	0.941	81	0.548	0.0166	67.7	34216.96	0.0303
18	51	0.786	0.397	0.934	78	0.539	0.0163	68.1	34297.54	0.0302
19	54	0.781	0.395	0.928	75	0.53	0.016	68.4	34357.83	0.0302
20	57	0.776	0.392	0.922	72	0.521	0.0157	68.6	34397.94	0.0301
21	60	0.771	0.39	0.916	69	0.512	0.0154	68.9	34458	0.0301
22	63	0.767	0.388	0.911	66	0.503	0.0152	69.1	34497.97	0.0301
23	66	0.762	0.386	0.906	63	0.494	0.0148	69.3	34537.88	0.03
24	69	0.758	0.384	0.901	60	0.485	0.0146	69.4	34557.81	0.03
25	72	0.755	0.382	0.897	57	0.476	0.0143	69.6	34597.64	0.03
26	75	0.751	0.38	0.892	54	0.466	0.0139	69.8	34637.4	0.0299
27	78	0.748	0.378	0.888	51	0.457	0.0137	69.9	34657.26	0.0299
28	81	0.744	0.376	0.884	48	0.447	0.0134	70	34677.11	0.0299
29	84	0.741	0.375	0.881	45	0.436	0.013	70.2	34716.77	0.0299
30	87	0.738	0.373	0.877	42	0.425	0.0127	70.3	34736.57	0.0298
31	90	0.735	0.372	0.873	39	0.414	0.0123	70.4	34756.36	0.0298
32	93	0.732	0.37	0.87	36	0.402	0.012	70.5	34776.14	0.0298
33	96	0.729	0.369	0.867	33	0.389	0.0116	70.6	34795.9	0.0298
34	99	0.727	0.368	0.864	30	0.376	0.0112	70.7	34815.65	0.0298
35	102	0.724	0.366	0.861	27	0.361	0.0108	70.8	34835.39	0.0298
36	105	0.722	0.365	0.858	24	0.345	0.0103	70.8	34835.39	0.0298
37	108	0.719	0.364	0.855	21	0.328	0.0097	70.9	34855.11	0.0297
38	111	0.717	0.363	0.852	18	0.308	0.0092	71	34874.82	0.0297
39	114	0.715	0.361	0.849	15	0.286	0.0085	71.1	34894.51	0.0297
40	117	0.713	0.36	0.847	12	0.26	0.0077	71.1	34894.51	0.0297
41	120	0.711	0.359	0.844	9	0.23	0.0068	71.2	34914.19	0.0297
42	123	0.708	0.358	0.842	6	0.191	0.0057	71.2	34914.19	0.0297
43	126	0.706	0.357	0.839	3	0.136	0.004	71.3	34933.86	0.0297
							0.5828			1.2156