


The Reliability of the ACI 209R-92 Method in Predicting Column Shortening in High-Rise Concrete Buildings

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Abstract. The early prediction of column shortening during the design of high-rise concrete buildings is of high importance to allow for shortening compensation measures to be proposed and taken in the construction. However, a column shortening that consists of elastic, creep and shrinkage shortening can be very complex to predict influenced by many uncertainties, such as inelasticity and non-homogeneity of the concrete structures and highly affected by the chosen method for time-dependent effects. In this paper, the ACI 209R-92 method (ACI Committee 209 in Prediction of creep, shrinkage, and temperature effects in concrete structures (ACI 209R-92). American Concrete Institute, Farmington Hills [1]) for predicting creep and shrinkage effects is evaluated by comparing its results to actual site readings taken during the construction of a high-rise building presented as a case study in this research. For that purpose, an Excel (Microsoft Corporation in Excel (computer program), <https://www.office.com/>, [2]) spreadsheet including all the factors of this method is developed to provide a simple interface to predict the elastic and time-dependent column shortening and settlement. Furthermore, the presented case study building was analyzed using a finite element software, Etabs (Computers and Structures in Etabs 2015 ultimate, version 15.0.0 (computer program), <http://www.csiamerica.com/>, [3]) where column shortening and settlement were predicted based on the CEB-FIB 90 method (Comite Euro-International Du Beton in CEB-FIB model code, Thomas Telford, London, [4]) for time-dependent effects. By comparing the two methods' results to the actual readings, it was found that both methods overestimated column settlement in all floors. 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%.

Keywords: Column shortening · Creep · Shrinkage · Modulus of elasticity

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.

1.1 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 non-structural 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 differential 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.

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.

1.2 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.

1.3 Research Objectives

This research intends to obtain the following targets:

1. To assess the reliability of the ACI 209R-92 method in predicting column shortening in high-rise concrete buildings.
2. To predict both elastic and time-dependent column shortening in high-rise buildings and provide a spreadsheet for that purpose.
3. To provide a simple procedure for engineers to predict the columns shortening at an early stage of the design.

1.4 Case Study

In order to evaluate the theoretical results of the considered ACI 209R-92 method, a case study of 360 m 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 Dubai, UAE. The typical plan shapes into two intersecting ellipses which, after floor 52, only one ellipse continues to floor 64. 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 Fig. 1.

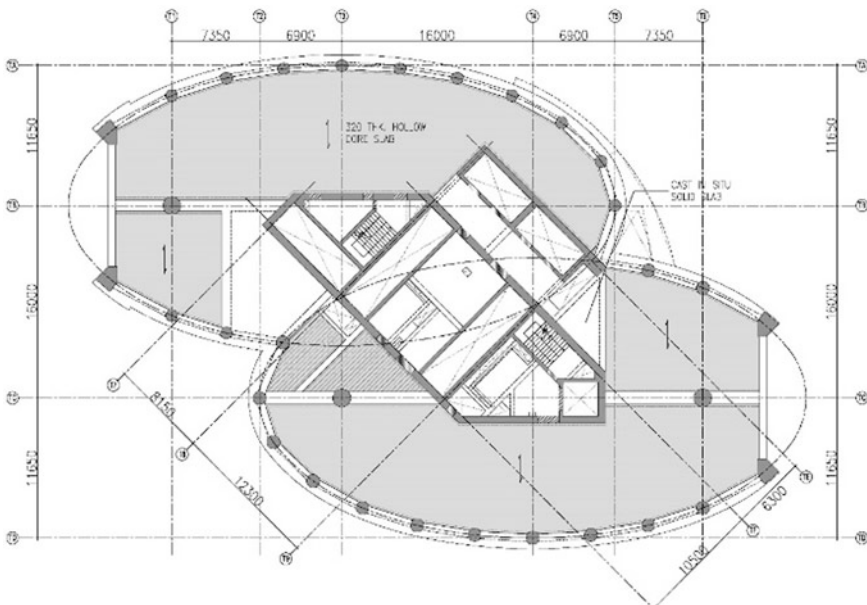


Fig. 1. Typical structural plan of the tower

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.

2 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 [5–7] 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 [8] firstly originated a model to quantify the axial shortening of a concrete column. The model was proposed in [6] 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 [9] is a refinement of Fintel and Khan method [8] which gives according to Jayasinghe and Jayasena [10] almost the same results. Swamy and Arumugasaamy [7] 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. 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 good agreement between measured and predicted values reflected the accurate and precise procedure of the latter study utilizing controlled experiments. In addition to column shortening, a very recent

study [11] investigated the effects of creep on the whole behavior of RC columns including geometric nonlinearity, cracking and aging.

3 Procedure of Excel Sheet Calculation

The procedure for creep and shrinkage strain prediction presented in this paper is a direct application of the ACI 209R-92 model. The ACI 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} . Where S_{ih} : shortening of a column in floor (i) caused by the instantaneous and time-dependent effects of adding one single floor (h).
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} , the total shortening of a column in floor (k) below floor (n) caused by adding number of floors ($j - n + 1$).

$$TS_{kj} = \sum_{h=n}^j S_{ih} \quad (1)$$

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} , the total displacement of a column in floor (n) after casting floor (j).

$$\Delta_{nj} = \sum_{k=1}^n TS_{kj} \quad (2)$$

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.

An example of the developed Excel sheet is shown in Fig. 2.

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 Δs_{sh} (mm)		0.058
Elastic Data	f'_c (mpa)	70	Total Shortening TS_{kj} (mm)		0.192
	Column Cross Section (m ²)	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) supports slab (#1)					
Column in basement (i) input as -i					
Column in ground floor input as 0					

Fig. 2. Developed excel sheet for column shortening prediction

4 Case Study Results

The developed spreadsheet in Sect. 3 is used to estimate the columns and walls shortening in each floor and then accumulate them to predict the settlement of the considered column in the same survey results style for comparison between actual and theoretical values.

4.1 Shortening of Monitored Column Below 4th Floor

The previous procedure in Sect. 3 is used to calculate the settlement of the monitored column and wall in 3rd, 10th, 21st, 29th, 4th, 50th and 60th floor. Those columns are the ones which were monitored during the tower construction. Below are the steps for the monitored column 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 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 below 4th floor for each of the twelve groups of floors, 3rd to 8th, 3rd to 13th, 3rd to 18th, ..., 3rd to 63rd.

The total shortening of columns below 4th floor for the first floors group (3rd to 8th) are plotted as a chart in Fig. 3 for each shortening component.

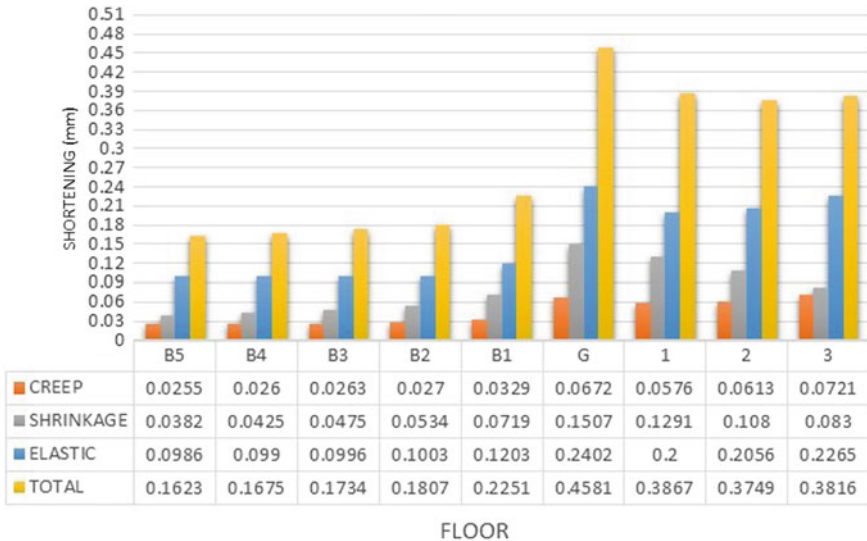


Fig. 3. Shortening of monitored columns below 4th floor due to adding floors 4th–8th

To eliminate the influence of column 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 by the column length (Fig. 4).

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

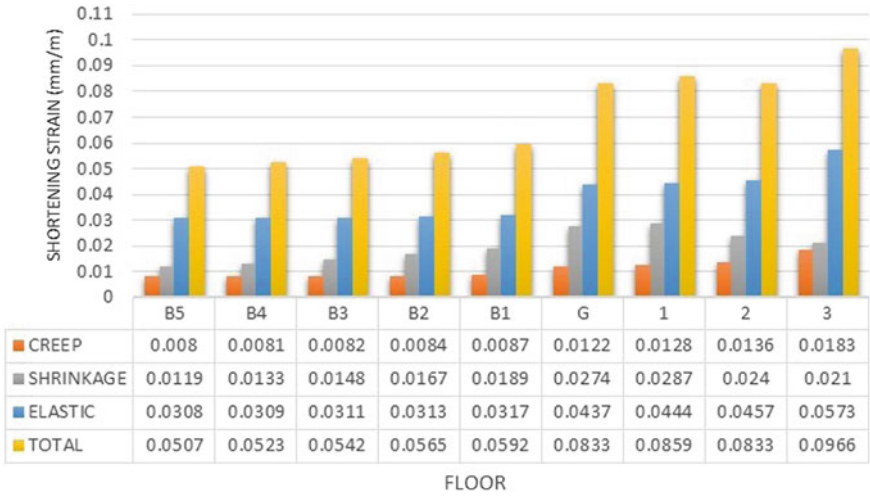


Fig. 4. Strain of monitored columns below 4th floor due to adding floors 4th–8th

noticed that the increase in elastic strain is much less than of creep and shrinkage. For further examination of the results, the differences in strain between floors are expressed as a percentage of column strain in floor B5 as shown in Table 1.

Table 1. 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 examining the results in Table 1, it's possible to see the leap in all column strains in ground floor (108–152% for creep, 158–230% for shrinkage and 103–141% for elastic). However, the elastic strain revealed a very slight increase until the jump in ground floor.

4.2 Settlement of Monitored Column in 3rd Floor

For each group of floors, the shortenings of all the columns below 4th floor were accumulated to get the final settlement of the monitored column 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 the actual results style plotted on the same chart for comparison (Fig. 5).

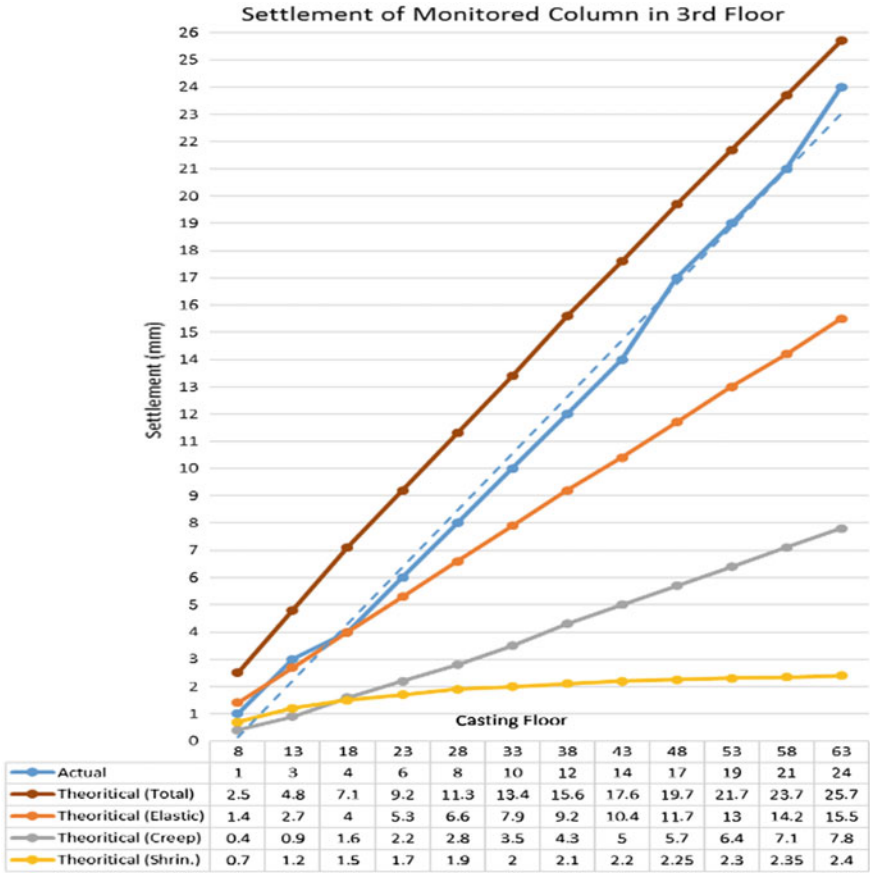


Fig. 5. Actual and theoretical settlement of monitored column in 3rd floor

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.

4.3 Settlement of Monitored Columns in All Monitored Floors

The procedure presented in Sects. 4.1 and 4.2 to predict the total settlement of monitored column in 3rd floor is repeated for the same monitored column 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. The monitored column settlement charts are plotted for both ACI and CEB-FIP model with the actual settlement chart (Figs. 6, 7, 8, 9, 10 and 11).

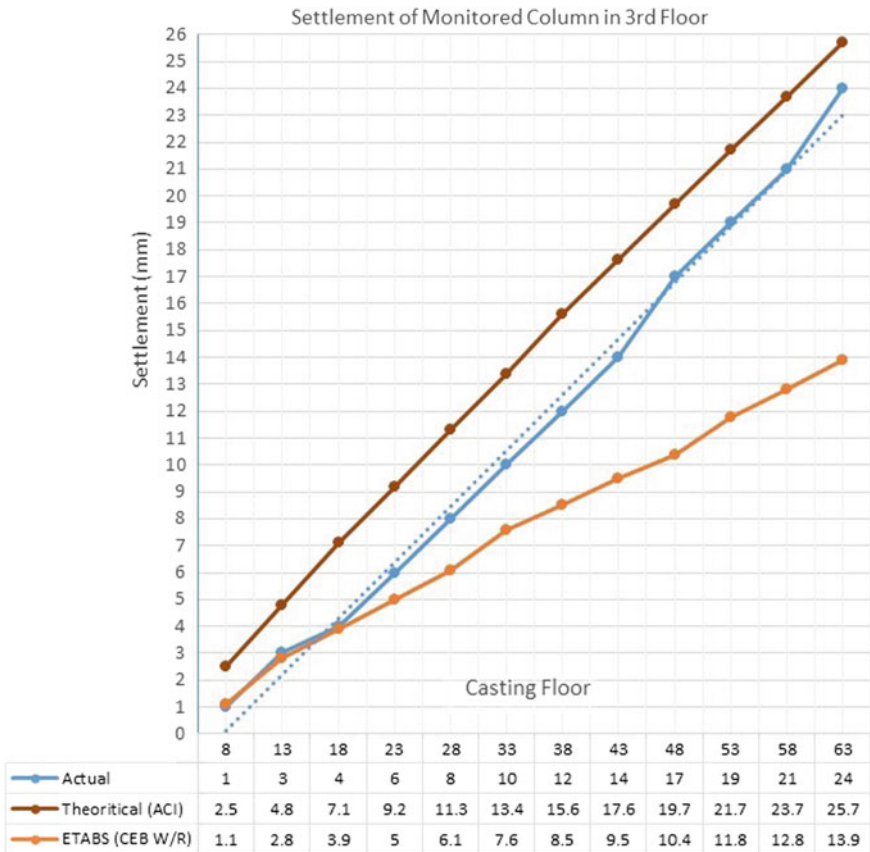


Fig. 6. Actual, theoretical and ETABS settlement of monitored column in 3rd floor

In the 3rd floor column settlement, the CEB-FIP model results extrapolated from the Etabs model analysis 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. Unlike the ACI model chart, the CEB-FIP chart shows 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.

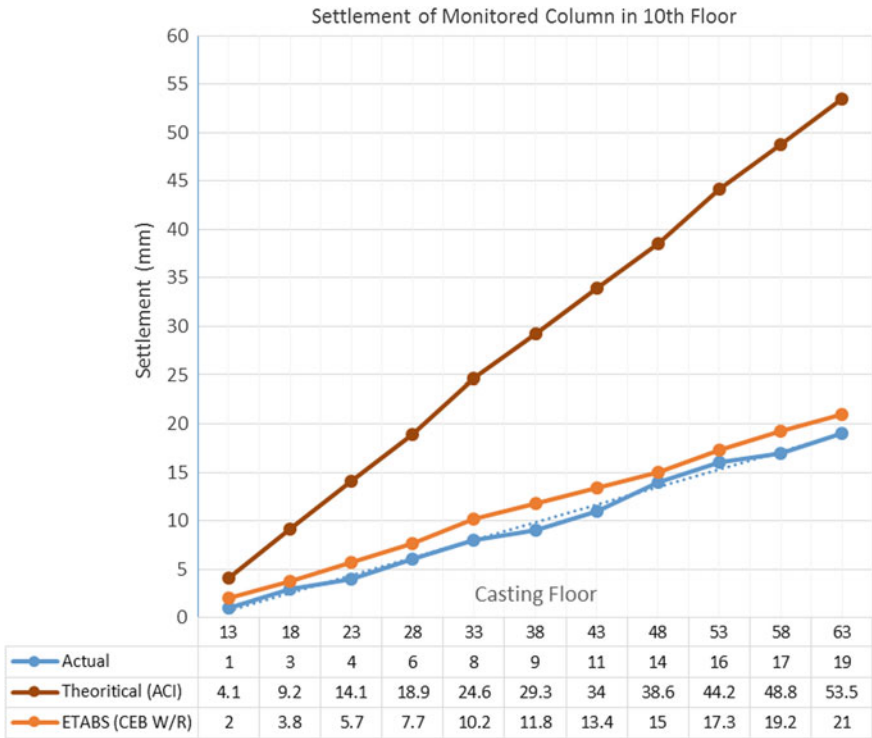


Fig. 7. Actual, theoretical and ETABS settlement of monitored column in 10th floor

By studying the 10th floor column settlement, it can be noticed that both models (CEB and ACI) overestimate the settlement in all construction stages. 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 chart now is, unlike the 3rd floor, parallel to the actual chart with average overestimation of 120%. The continuous linear chart of the Etabs model (CEB-FIP method) represents the consistency with the actual results despite the overestimation of the total settlement.

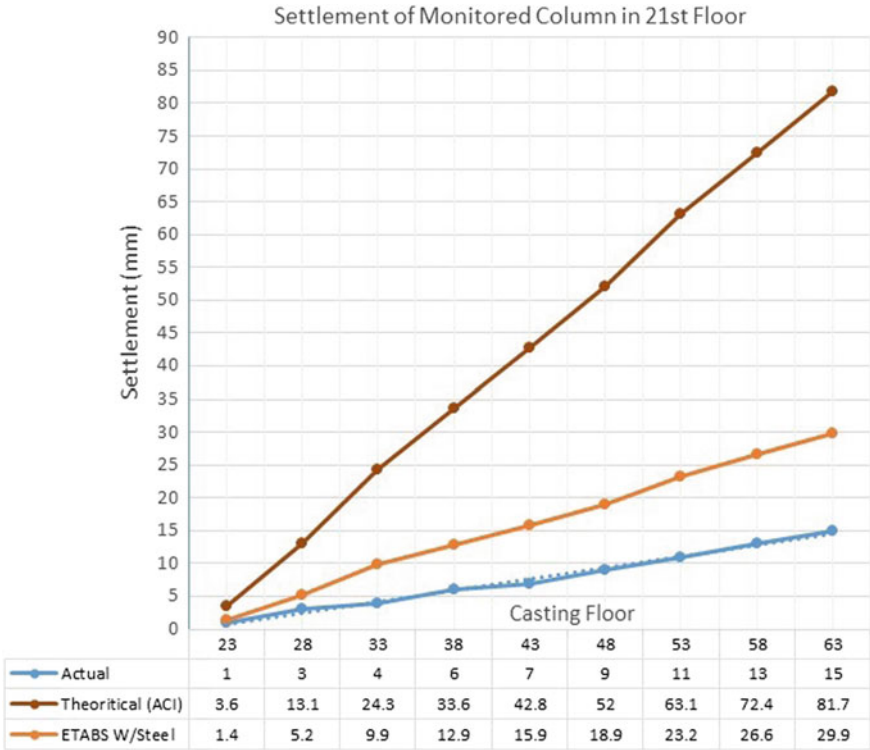


Fig. 8. Actual, theoretical and ETABS settlement of monitored column in 21st floor

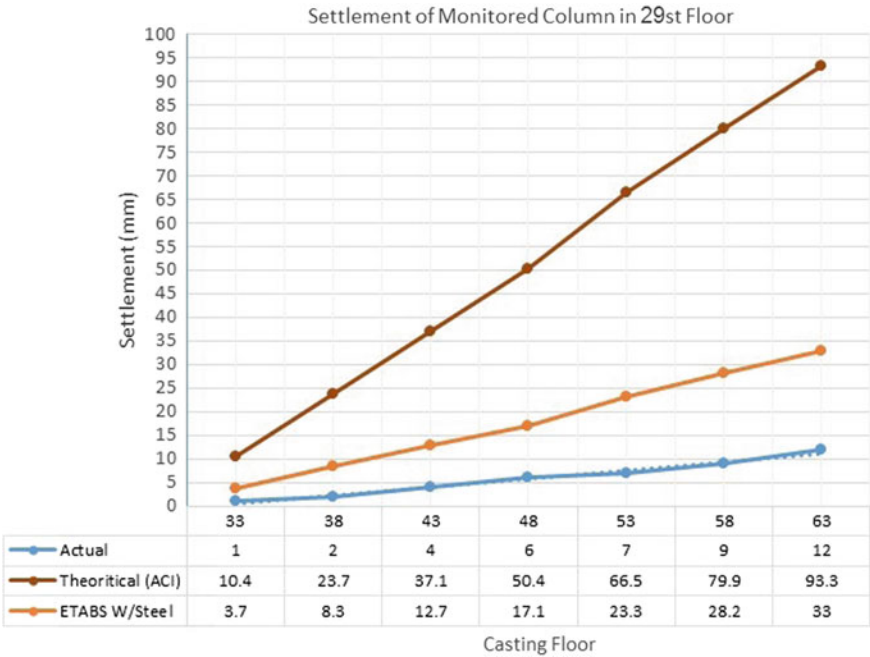


Fig. 9. Actual, Theoretical and ETABS settlement of monitored column in 29th floor

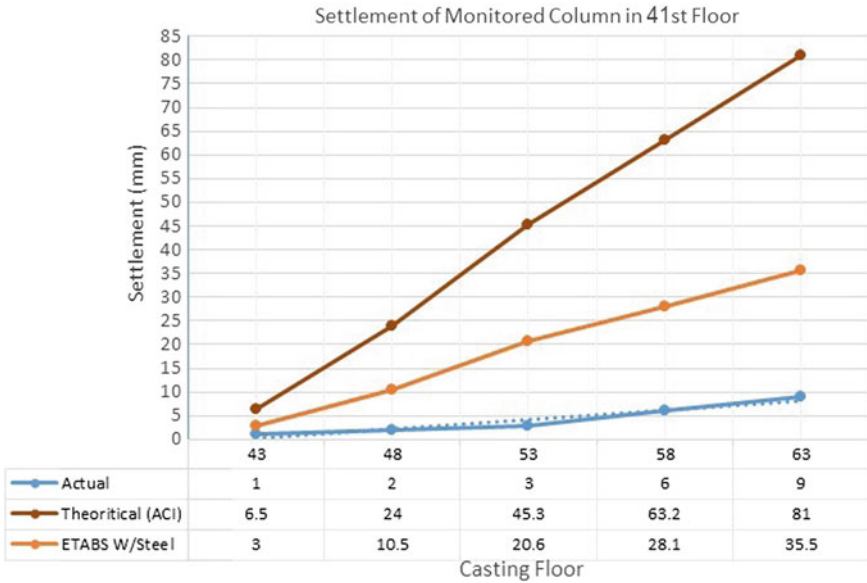


Fig. 10. Actual, theoretical and ETABS settlement of monitored column in 41st floor

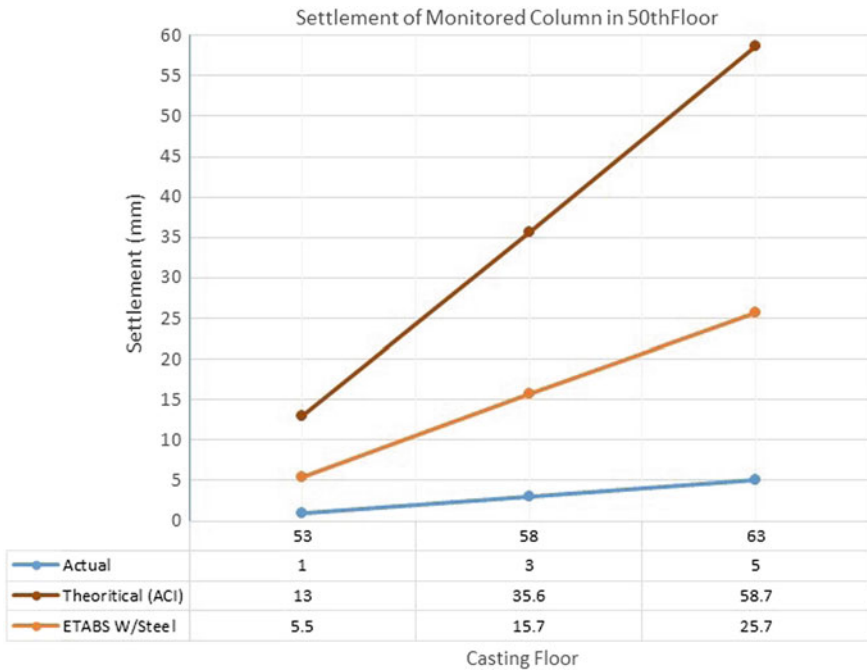


Fig. 11. Actual, theoretical and ETABS settlement of monitored column in 50th floor

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 Final Settlement of Monitored Column

The final settlement of the monitored column 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 (Fig. 12).

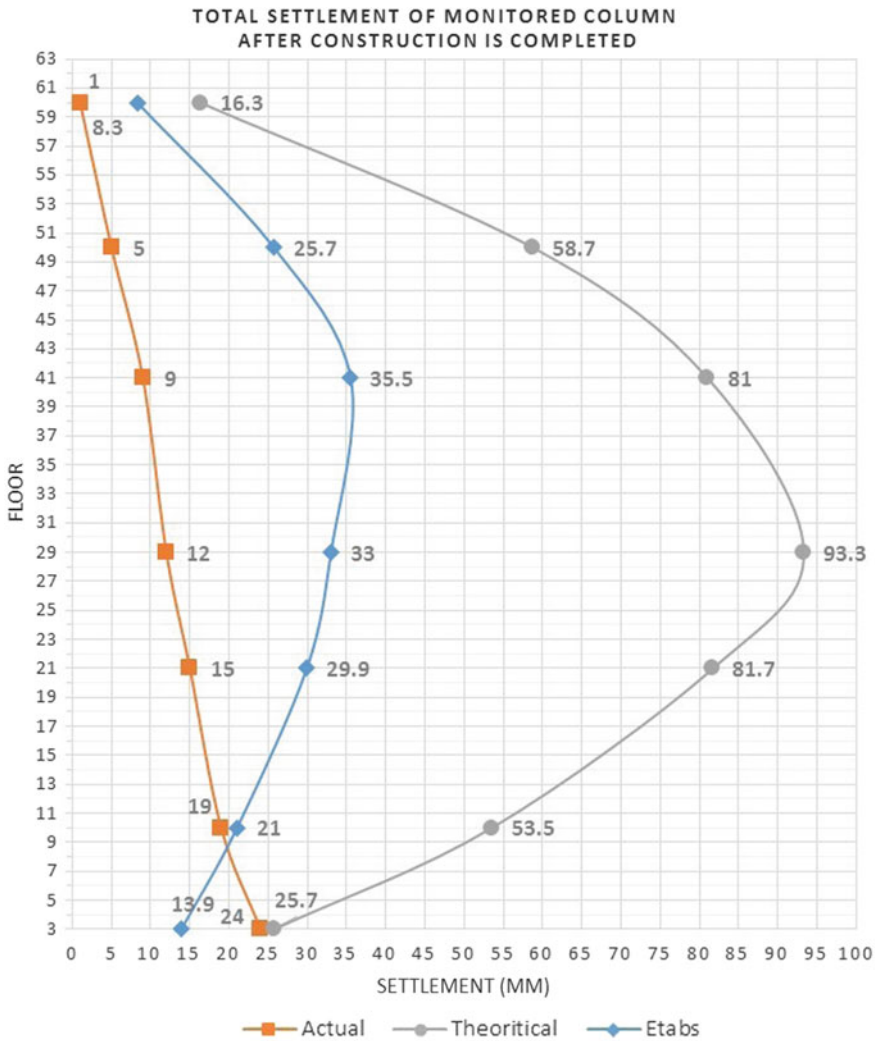


Fig. 12. Total settlement of monitored column after completion of construction

In the total settlement actual chart, the settlement has almost a linear relation with floors decreasing continuously from 24 mm in the 3rd floor to only 1 mm 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 and 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 20 mm). In general, the theoretical settlements are the highest, the actual settlements are the least where Etabs settlements are between those values.

5 Conclusions

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 is highly affected by the chosen method of prediction. The ACI 209R-92 method for predicting creep and shrinkage effects was evaluated by comparing its results to actual site readings of the case study presented in this research. That comparison led to the following conclusions:

- Theoretical elastic settlement of the monitored column in the 3rd floor was in the range of 60–65% of the total theoretical settlement.
- Theoretical total creep settlement keeps increasing with construction progress but with less effect for loads applied at later stages than those applied earlier.
- The effect of shrinkage on the total theoretical settlement of the 3rd floor column almost disappeared after the 33rd floor (about 90 days column age), only 0.4 mm additional settlement is caused by shrinkage for the remaining 90 days of the construction time.
- 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 overestimation of settlement by the proposed theoretical approach increased steadily after the 3rd floor reaching 1174% of the actual settlement in the 50th floor.
- The average overestimation of the developed Excel sheet based on the ACI 209R-92 model was 630%.
- 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 was unable to provide reliable prediction of the column settlement after the 3rd floor.
- Etabs analysis using CEB-FIP method was able to predict the settlement better than the theoretical approach of the ACI model.
- The average overestimation of Etabs analysis based on the CEB-FIB 90 model was 258%.

- Due to the many variables and uncertainties of the two proposed methods (theoretical and Etabs), it was difficult to compare the ACI and CEB-FIP models on which is better in predicting the time-dependent effects.
- 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 ten stories.
- 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.
- 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.

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 column shortening 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.
- Based on shortening results, a compensation method to be specified to be adopted in the construction.
- During the construction, tests are necessary on concrete specimens taken from the concrete patch used in the construction to determine all relevant 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 settlement is a very effective and helpful way to assess the design results.

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