Study the procedure of compensation of differential shortening for super-high-rise buildings by the method of moving optimal compensation for construction projects in Vietnam

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Abstract. In this paper, the authors present the procedure of compensation of differential shortening for super-tall buildings by the method of Moving Compensation Optimization (MCO). The MCO method has been studied as well as calculated by computers and clearly shows its superiority. This method has the minimum number of groups of compensation, the minimized compensation value of each group, and the compensated differential shortening values well controlled within the permissible limits of technical requirements, in comparison with methods of Uniform Compensation, Moving Averaging Correction method, and Optimal Compensation method. This differential shortening compensation procedure will be applied for Keangnam Landmark building with 70 floors. The results of the compensation procedure prove the advantages of the method, such as the effective flexibility to adjust the compensation plan in the actual construction phase, handling specific arising situations due to actual column shortening during construction sequences.

Keywords: column shortening; differential shortening; moving optimal compensation; super high-rise building; construction sequences.

1 Introduction

Column shortening is the phenomenon of vertically deformed reinforced concrete members, making columns and walls shorter under the effect of loads, shrinkage and creep. Among them, the deformation due to shrinkage and creep depends on the loading history, material properties, environmental humidity, construction progress, volume to surface area ratio of the member, and reinforcement content. Therefore, column shortening depends on time and is significant when the building has a high height, such as super high-rise buildings. The differential deformation between columns and walls and the core of the building in the same plan is called differential column shortening (DCS), which causes the floor-beams system to tilt, generating internal forces in the horizontal members, damage to partition walls, glass walls, and technical systems such as water pipes, elevators [1]. DCS can be minimized by optimizing the design for uniform compressive stress distribution in vertical members such as: using a cantilever or outrigger; using freely articulated connections for the structural system, and choosing a reasonable architectural shape [2]; increasing the axial stiffness for members that are expected to have large shrinkage by adding reinforcement [3]. However, these solutions generate relatively large construction costs, and it is not easy to ensure adequate control and remedy the DCS during actual construction [4].

A more straightforward but more effective solution is to compensate for the DCS value by providing the column in advance with a short amount of height loss due to shrinkage during construction. The height of the column at the time of construction is greater than the design height by a corresponding DCS value. In the world, super high-rise buildings Burj-Dubai Tower (United Arab Emirates, 828m, 164 floors); Petronas Twin Tower (Malaysia, 432m, 88 floors); Jin Mao Building (Shanghai - China, 421m, 88 floors); Texas Commerce Tower (USA, 305m, 75 floors); Federasia Tower – Moscow City (Russia, 506m, 94 floors) has applied this method. In Vietnam, super high-rise buildings such as Bitexco Financial Tower (269m, 68 floors), Keangnam Landmark 72 Hanoi (350m, 72 floors); Lotte Center Hanoi (272m, 65 floors); Vincom Landmark 81

(461m, 81 floors) must also consider controlling and dealing with column shortening during construction. However, the entire construction process is a secret technology of construction contractors.

Based on the analysis of the advantages/disadvantages of some previous methods of compensating for contractions, such as lumped compensation method (LCM), optimal compensation approach (OC), and moving averaging correction approach (MAC), Xuan et al. [5, 6] proposed a new method of contraction compensation called Moving optimal compensation (MCO). The objective is to select the best shrink compensation plan with the smallest number of pooled groups and the optimal shrink compensation value for each group, and the shrinkage compensation error is controlled within the allowable limits. In addition, the proposed method is also easy to apply flexibly when the actual shrinkage value is much different from the predictive design shrinkage, which can be used by computers to calculate.

In this article, a construction process for DCS compensation of super high-rise buildings in Vietnam is established to solve the following problems: Establish a specific construction process; flexibly handle the situations that arise when the actual observed and forecast compensation values in the construction phases are different from the design offsets; Determine the most effective compensation plan to manage the accumulated DCS error after compensation at each floor level, meeting the technical criteria for the safety of use. That construction process is applied to Keangnam Landmark 72 Hanoi building.

2 Moving compensation optimization (MCO)

2.1 Formulation

The floors are divided into groups with an equal correction amount for every floor in a group as described in fig.1. x_j^i is the calculated shortening of a vertical element of the jth floor in ith group. To simplify the compensation or the construction process in practice, the number of lumped groups should be minimized. This can be achieved by maximizing the number of floors, Ni, in each group. On the other hand, there will be errors between the compensation amounts and the prediction amounts. The correction amount δ_i, used for the ith group, therefore, should be chosen such that the cumulative error between the predicted differential shortening and the correction amounts is minimum. Thus, the objective function for the optimal compensation of the ith group is formulated in the following form:

$$\text{Min.} f(N_i, \delta_i) = -N_i + w \times \left| \sum_{k=1}^{i-1} \varepsilon_k + \sum_{j=1}^{N_i} \left(x_j^i - \delta_i \right) \right| \tag{1}$$

$$\varepsilon_k = \sum_{j=1}^{N_k} \left(x_j^k - \delta_k \right), k = 1, \ldots, i-1 \tag{2}$$

where, $w \geq 1$ is a weighted factor; ε_k is the cumulative error between the compensation amount and the predicted differential shortening in the kth group. The value of the weight factor w is chosen to ensure a numerical correlation between the two terms in the objective function. For example, if the unit of differential shortening is mm, w can be chosen to be 1; otherwise, if the unit is m, then the cumulative error will have a minimal value compared to N_i so we need to choose a large enough value of w.

To control the slab tilt caused by the axial shortenings, an allowable error value, θ_i is introduced [6]. Moreover, the cumulative error is limited to a tolerance, d_j^i, which is limited by ξ_i. These constraints are written in the following forms [9]:

$$\left| x_j^i - \delta_i \right| \leq \theta_i \tag{3}$$

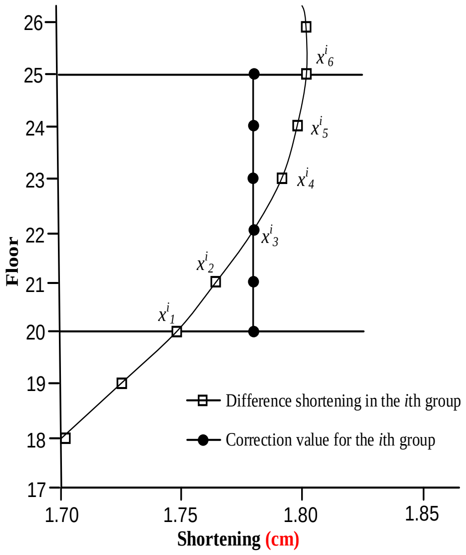


Fig. 1. Illustration of the lumped compensation approach.

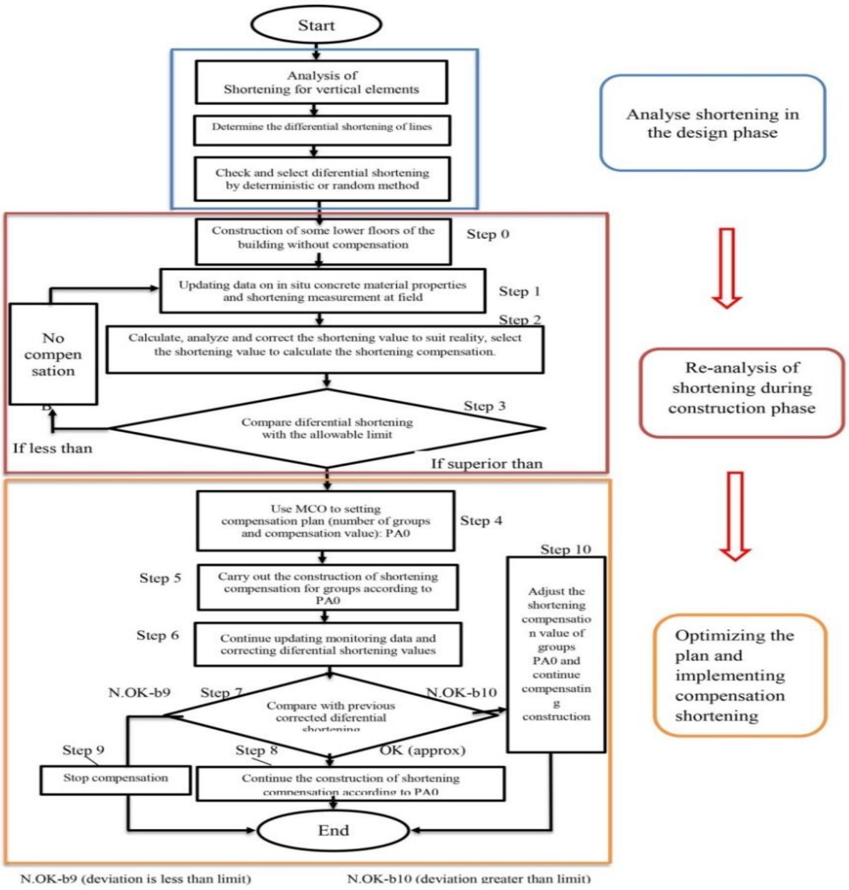


Fig. 2. Process of performing shortening compensation.

$$d_j^i = \left|\sum_{k=1}^{i-1}\varepsilon_k + \sum_{l=1}^{j}\left(x_l^i - \delta_i\right)\right| \le \xi_i \qquad (4)$$

The optimal number of floors N_i together with the correction amount δ_i for the ith group is determined by solving the above-constraint optimization problem (3) and (4).

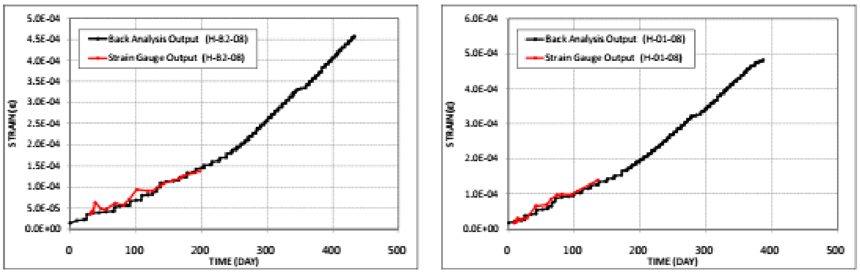
3 Applications

a) Process of performing shortening compensation (Fig. 2)

Keangnam Hanoi Landmark Tower is a high-end complex project consisting of 3 high-rise buildings, including a 72-story hotel-office building and two 48-story apartment buildings, located on Pham Hung Street, Nam Tu Liem District, Hanoi. The buildings use a reinforced concrete floor-beam and column frame structure, a combination of a rigid core subjected to wind and earthquake loads, a hard outrigger floor, and a belt boundary wall, constructed by the method of pouring concrete in situ (full block) (Figure 3).

b) Realistic construction compensation application

Fig. 3. Landscape plan of Keangnam Hanoi Project.



(c) Hotel (B2F)

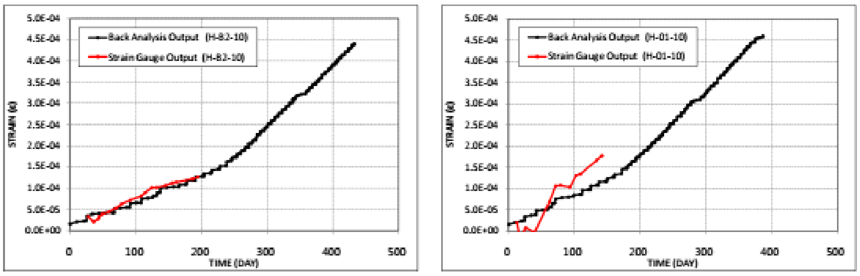
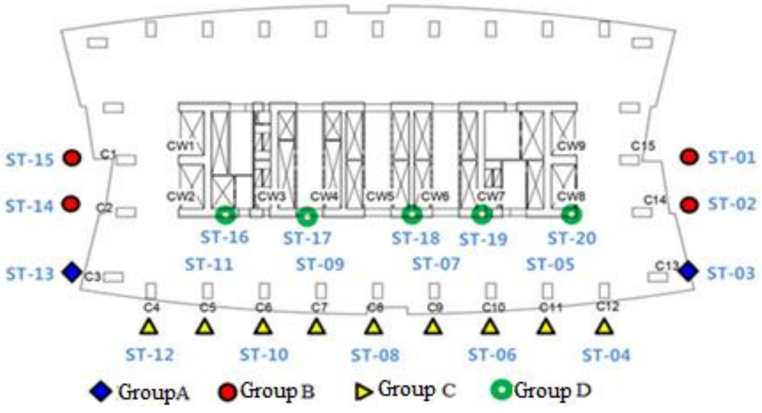


Fig. 4. Forecasted and monitoring shortening of columns C8 and C10 of basement B2 and fist floor.

- **Analysising of forecast design data and monitoring data of shortening**

The field monitoring of shortening by strain gauge sensors was carried out for one year, from August 2008 to September 2009. The sensors are attached to the vertical members of basement B2, 1st floor, 3rd floor, and 7th floor, of which basement B2 and 1st floor are measured over three months. The results of the shortening comparison of the forecast design and the field measurement results are shown in Fig. 4.

In this analysis, the shortening of vertical elements divided into groups with similar structural characteristics on the basement structure plan B2 and first floor were updated within six months (from February 2009 to September 2009) to compare with shortened forecast design (Figure 4, Table 1). By comparing measured actual shortening with predicted design shortening, the design consultant evaluates, analyzes, and updates the characteristic parameters of concrete materials in situ and environmental conditions to apply for a shortening calculation more accurately the next time.



Group: A 104% (corner col); B 102% (short span); C 107% (typical col); D 98% (core wall)

Fig. 5. Location plan of measuring sensor for shortening by column /core-wall group.

- **Forecasted shortening and differential shortening in the long-term**

The forecasted long-term shortening and measured shortening of 15 columns and 9 core walls five years after the construction completion and use of the building are shown in Table 1.

Table 1. Forecasted maximum shortening and measured shortening five years after completion of construction [60]

Element	**Maximum shortening /Floor**				**Difference**
	Forecast at the design stage		**Measure at construction stage**		
	Max value	**Floor**	**Max value**	**Floor**	
C1	101.40	58F	85.9	44F	85%
C2	97.02	58F	83.2	44F	86%
C3	84.49	56F	76.1	46F	90%
C4	84.66	52F	78.8	44F	93%
C5	86.65	38F	80.8	43F	93%

Element	**Maximum shortening /Floor**				**Difference**
	Forecast at the design stage		**Measure at construction stage**		
	Max value	**Floor**	**Max value**	**Floor**	
C6	91.80	41F	87.0	43F	95%
C7	95.92	42F	91.9	44F	96%
C8	97.45	42F	94.1	44F	97%
C9	96.84	42F	93.3	44F	96%
C10	94.24	42F	90.2	43F	96%
C11	91.55	41F	86.1	43F	94%
C12	93.65	53F	87.0	43F	93%
C13	99.51	57F	83.5	46F	84%
C14	106.68	57F	87.6	43F	82%
C15	105.00	57F	86.1	44F	82%
CW1	50.29	52F	47.5	44F	94%
CW2	50.01	53F	47.2	46F	94%
CW3	36.28	55F	36.3	41F	100%
CW4	44.00	57F	43.3	43F	98%
CW5	47.38	57F	47.6	62F	100%
CW6	47.00	56F	42.1	43F	90%
CW7	44.95	54F	40.1	42F	89%
CW8	50.07	53F	49.07	46F	90%
CW9	49.01	53F	48.4	44F	99%

Differential shortening between adjacent vertical elements is established through lines (L), as shown in Figure 6.

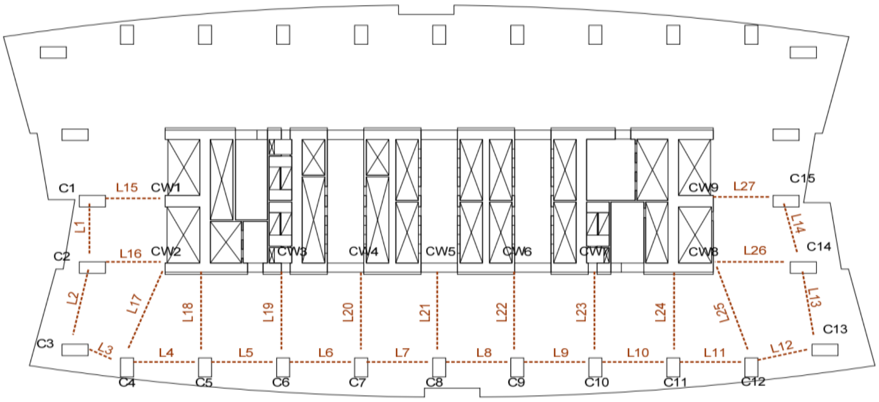


Fig. 6. Setting plan of differential shortening lines (L) to calculate the compensation.

Table 2. Maximum actual shortening after five years since completion of construction

Line	**El-em. (i)**	**Elem. (j)**	**Distance between two elem. (L, mm)**	**Allowable limit of differential shortening ([Δs] =L/240, mm)**	**Maximal differen-tial short-ening Δs (mm)**	**Location of floor**	**Δs/ [Δs]**	**Assess-ment**	**Check**
L14	C14	C15	8986	37.4	3.6	61F	0.10	O.K	O.K
L15	C1	CW1	9050	37.7	41.2	58F	1.09	N.G	N.G
L16	C2	CW2	9050	37.7	39.7	61F	1.05	N.G	N.G
L17	C4	CW2	14038	58.5	37.7	57F	0.65	O.K	Check
L18	C5	CW2	13000	54.2	37.7	57F	0.70	O.K	Check
L19	C6	CW3	13000	54.2	50.8	44F	0.94	O.K	Check
L20	C7	CW4/C 101	13000	54.2	63.5	46F	1.17	N.G	N.G
L21	C8	CW5/C 102	13000	54.2	65.7	Out1	1.21	N.G	N.G
L22	C9	CW6/C 103	13000	54.2	65.2	Out1	1.20	N.G	N.G
L23	C10	CW7	13000	54.2	50.2	44F	0.93	O.K	Check
L24	C11	CW8	13000	54.2	36.6	41F	0.67	O.K	Check
L25	C12	CW8	14038	58.5	37.4	43F	0.64	O.K	Check
L26	C14	CW8	11300	47.1	42.8	61F	0.91	O.K	Check
L27	C15	CW9	9050	37.7	40.7	58F	1.08	N.G	N.G

N.G: Exceeding the allowable limit of safe use; Check: Exceeding the control limit (taken 1/2 of the usage limit)

- **Establishing construction plans for adequate shortening compensation**

Run MCO to come up with a shortening compensation plan, in which the calculated shortening compensation value will be rounded to mm. The calculation results of the shortening compensation plan are presented in Table 3.

Table 3. MCO compensation plan for Kengnam Building

Group	**Number of floors in group**	**Floor**	**Shortening compen-sation value (mm)**
1	17	5 - 22	31
2	42	23 - 65	42
3	9	66–PH2	26

The comparison of the proposed MOC compensation plan with that of the contractor MiDad applied to the Keangnam project is shown in Table 4. Midad's plan has four groups of shortening compensation with values of 10mm, 20 mm, 30 mm, and 40 mm, respectively. The proposed MCO plan has three groups with shortening compensation values of 17 mm, 42 mm, and 9 mm, respectively. Thus, the MCO compensation plan has a smaller number of compensation groups than the MiDad's plan.

Table 4. Comparison between MOC shortening compensation plan and MiDad’s plan

PA Keangnam			**PA-MCO**		
i (group)	**N_i (number of floors)**	**δ_i (mm) (compensation value)**	**i (group)**	**N_i (number of floors)**	**δ_i (mm) (compensation value)**
0	5	No compensation	0	6	No compensation
1	4	10	1	17	31
2	7	20	2	42	42
3	10	30	3	9	26
4	48	40			

- **Checking the differential shortening after compensation**

Figure 7 shows the compensation curve (left image) and the post-compensation curve (right image) for the column-wall lines (Line 15-27). It can be seen that the shortening compensation plan according to the MCO's method controls the differential shortening of all lines, which is within the required limit of 0.5*L/240 (dotted line marked "check"). Meanwhile, according to MiDad's plan (PA-0), Line 21 still has differential shortening at the top 2 floors exceeding the test value (Figure 6).

In addition, the shortening compensation plan according to MCO has the value of differential shortening error after compensation asymptotically or equal to the allowable value (at Lines 27, 16, and 15), which is the preeminent feature of the proposed method. In contrast, the plan implemented by MIDAS is not optimal.

- **Compensating realization**

It is starting to perform shortening compensation from the 7th floor (the floor number is calculated starting from the basement) of the building with a shortening compensation value of 31mm by making column formwork with a length greater than the design length by 31mm. Alternatively, it is possible to make the formwork exactly according to the design length and adjust the compensation amount by applying the column head and column top compensation technique. From the 7th floor to the 22nd floor, maintain the value of shortening compensation of column of the 7th floor by constructing columns of 8th floors to 22nd floor according to the design length. Similarly, the construction of group 2 shall start from the 23rd floor with an offset value of 42mm by adjusting the length of the column formwork so that the actual height of the column head of the 23rd floor is 42mm higher than the design height of the column head, then maintain the amount of shortening compensation for floors 24th to 65th by constructing the correct column length. Similarly, compensate for group 3 from the 66th floor to the PH2 floor with the compensation value of 26mm.

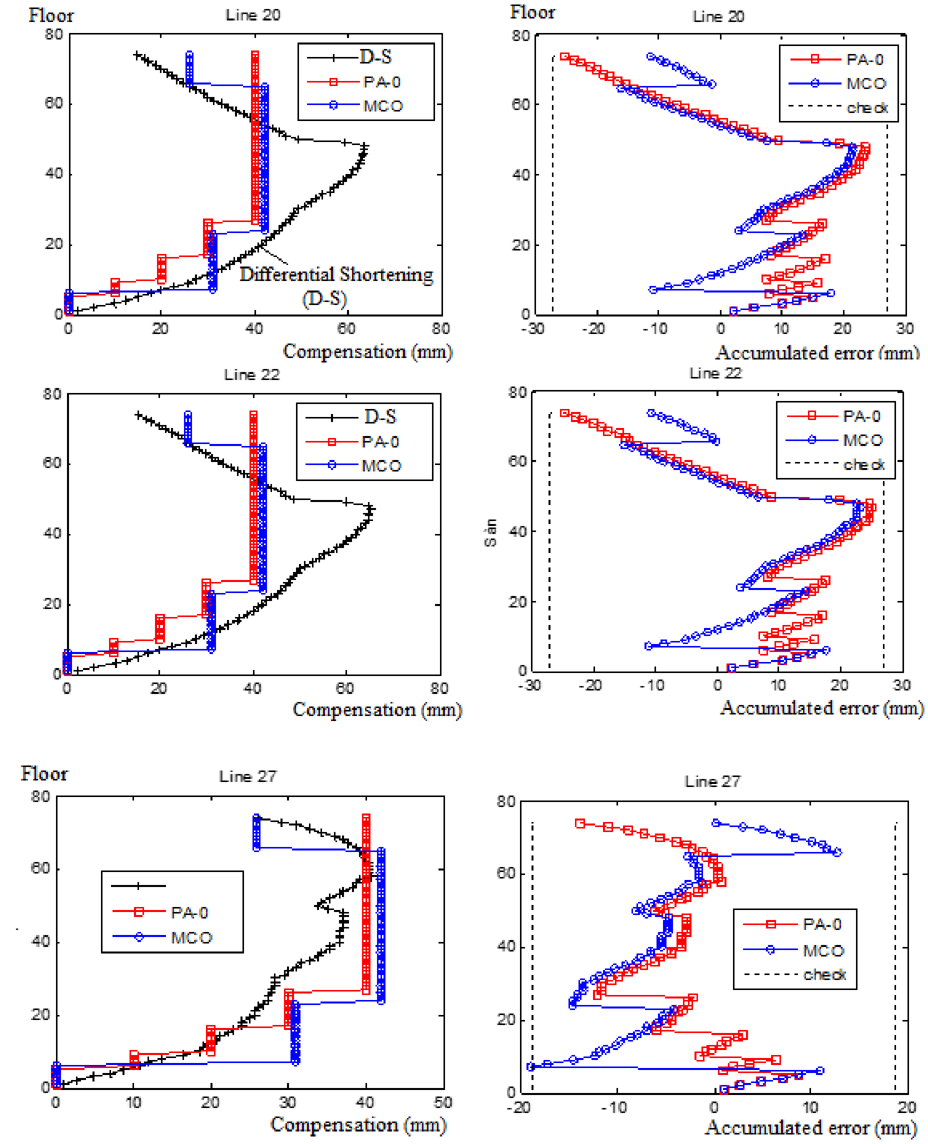


Fig. 7. Compensation curve (left) and differential shortening after compensation (right) of PA-0 (MiDad) and MCO.

- **Adjust the contract compensation plan when there is a big deviation**

If there is an actual fluctuation, the adjusted differential shortening value is much deviated compared to the forecast value. Accordingly, assuming this event occurs at the 49th floor, then perform group shortening compensation from the 50th floor to the PH2 floor with an adjusted compensation value according to the fluctuating differential value and check the condition of the shortening compensation error for the group.

4 Conclusions

This article has presented a construction process for shortening compensation of columns, walls in the construction of super high-rise buildings according to an effective method and its application in a practical project in Vietnam. This compensation method has been compared with other methods to test its effectiveness. Through the obtained results, the proposed process is effective and flexible when there is a change in the actual shortening value and the one of design forecast. In addition, the calculation program can be easily applied to ordinary computers. Specifically, the MCO method of shortening compensation has been applied to determine the column shortening compensation plan for a 72-story building in Vietnam. The research has investigated and applied to three cases occurring in reality: The actual shortening is much smaller than the design forecast; Actual shortening is roughly equal to design forecast; The actual Shortening is much larger than the design forecast.

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