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Cost Evaluation of Post-tensioned Slabs in Multi-storey Buildings Considering Seismic Effect

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Abstract
Currently, many owners and consultants prefer to use post-tensioned PT slab systems in multi-storey buildings due to their considerable savings in materials, labor, and time. On the other hand, many contractors still use the traditional RC flat slab systems due to their simple construction process. This research focuses on the comparison between the two systems taking into consideration: cost, time, and structural behavior. Detailed cost and time analysis is performed for each system considering all construction resources. The analysis and design of the buildings are conducted using many structural and project management computer programs. These include ETABS, SAFE, RAM, REVIT, and Primavera. The results indicated that, PT systems provide significant savings for spans larger than 6 m. The structural analysis of both systems also showed that PT slabs are more effective in resisting seismic straining actions.
Keywords: Multi-storey; Post Tensioned Slab; Comparative Analysis; Cost; Seismic.

1. Introduction

Post tensioning technique has been used for several decades. With the increasing number of multi-storey buildings, many owners and consultants tend to use post tensioned PT slab systems especially in multi-storey buildings because of their considerable savings in materials, labor, and time. On the other hand, most contractors still prefer to use the traditional flat slab system despite its high reinforcement ratio, punching and deflection problems.
Post tensioning is a technique that can eliminate or reduce the concrete tensile stresses by pre-loading or prestress to produce internal stresses which counteract the stresses due to external load, thus producing a crack- free material and limited deflections. The process of tensioning comes after casting the concrete, the strands are threaded through the duct either before or after the casting. There are two types of tendons end; dead end which is anchored in concrete; live end which is anchored by anchorage block. When the concrete has gained its sufficient strength, the tendons are stressed by a hydraulic jack [1].
Post tension technique is distinguished from traditional flat slab method because of the preloading of the member which counteracts the deflection, and thus can accommodate large spans with thinner cross sections and consequently, leads to considerable material and labor savings. Furthermore, reduction of the slab thickness positively influences the total weight of building which induces a lighter structure that needs a lighter lateral resisting system. Also, the overall height of buildings can be reduced or enables additional floors to be constructed in the building. From the construction time point of view a considerable reduction is obtained as a result of less material used and by the early removal of slab formwork [2-7].
From the foregoing, some advantages of post-tension technique can be summarized by dividing them into advantages which contribute to superior structural performance and advantages which contribute to sustainability. Advantages contribute to superior structural performance can be summarized as: using high strength materials; galvanized system; deflection control; less tensile stresses; good crack behavior; high punching shear strength; reduction in floor-to-floor height; lighter structure; longer spans; good behavior against lateral loads. Advantages contribute to sustainability: less material; reducing carbon footprint; lower cost; reducing noise transmission; less cracking and lower deflection [8].

1.1. Objectives

Most of the previous researches on this topic were studied at the level of the slab element only, regardless the effect of post tension on the vertical elements and foundations. Especially studying the savings in materials and the lack of exposure to labor. In addition, the lack of attention in the analytical study of construction time for each of the two systems. This research deals with the comparison between the post-tensioned PT slab and traditional flat slab systems not only at the level of the slabs, but at the level of all building elements taking most aspects into consideration. These include cost, time, and structural behavior. After obtaining the required quantities of concrete, reinforcing steel, post-tensioning steel, and by considering the labor crews and the production rates for each construction item, cost and time analysis are performed.

2. Materials and Methods

2.1. Case Study

The research case study is a multi-storey residential building designed by the two approaches: traditional flat slabs, and post tensioned slabs considering the seismic effects. The building consists of ground and twelve typical floors located in Cairo, Egypt. The parameter considered in the parametric study is various spans of 6 m, 8 m, and 10 m. Hence, six buildings will be studied: three post tension buildings vs. three traditional buildings. The building height is 36 m, and the plan layout is a square plan of 5x5 bays with a marginal beam around perimeter. The vertical supporting elements consist of 28 columns and 4 shear walls as shown in Figure 1. The buildings are rested on a raft foundation with bearing capacity equal to 200 kN/m².

2.2. Design Code

The design of slabs is performed according to the requirements of the ACI code for structural concrete, ACI-19, while the rest of the elements including the seismic design follows the Egyptian code requirements, ECP 2018.

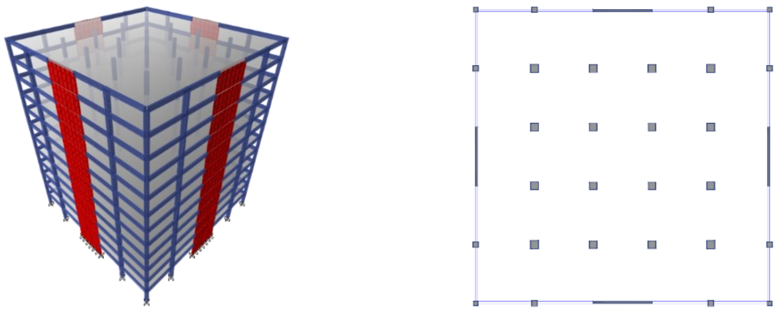

Figure 1. Case Study Building.

2.3. Design Materials

Material properties used for concrete, non-prestressed steel, prestressing strands are shown in Table 1.

Table 1. Design material properties.

Concrete compressive strength (fcu)*, (fc`)	35, 28	MPa
Non-prestressed steel yield stress (fy)	420	MPa
Post tension bonded system properties:		
Strands 12.7mm area	100	mm²
Ultimate strength of strands (fpu)	1860	MPa
Strands yield stress (fpy)	1674	MPa
Jacking stress (fpj)	1395	MPa
Anchor friction	0.025	
Wobble friction	0.003	1/m
Angular friction	0.3	1/radians
Seating distance	6	mm

*Cube strength fcu for foundations= 30 MPa.

2.4. Design Loads

2.4.1. Gravity Loads

Gravity loads include self-weight, 2 kPa flooring, 4 kPa partitions and 2 kPa residential live loads.

2.4.2. Seismic Loads

The building is designed using response spectrum method as per ECP-201-2012. The building is assumed to be in Cairo, Egypt, in seismic zone III and spectrum type 1, soil class C is assumed as a building is resting on medium dense sandy soil with an importance factor of 1 and a response reduction factor of 5.

2.5. Design Methodology

The analysis and design of the buildings are conducted using structural engineering and project management software. These include ETABS, SAFE, RAM, REVIT, and Primavera. ETABS to design columns and walls, SAFE to design raft foundation, RAM Concept program to design the traditional and post-tensioned slabs, Revit is used to make a 3D model for a building to facilitate some bill of quantities works and Primavera is used to assign the construction items and their durations to obtain the total project duration. The design is performed to comply with the code requirements and to satisfy strength and serviceability limit states.

3. Results and Discussions

Some comparisons between the two systems should be highlighted along the different spans under study.

3.1. Slab Thickness

Assuming the slab thickness depends on the approximate L/D for post tensioned slab without drops is 40 and L/D for traditional flat slab without drops is 32. The required thickness of reinforced concrete slabs for spans 6m, 8m, and 10m is 200mm, 260mm, and 330mm, respectively. While the required thickness of post tensioned slabs for spans 6m, 8m, and 10m is 180mm, 220mm, and 280mm, respectively.

3.2. Storey Stiffness and Storey Drift

Despite PT slabs are thinner than traditional RC flat slabs, but PT slabs act as a frame with vertical supports since they are much stiffer than the RC slab. This leads to better behavior against seismic loads in case of PT slabs as shown in Fig. 2 for the results of storey stiffness and storey drift.

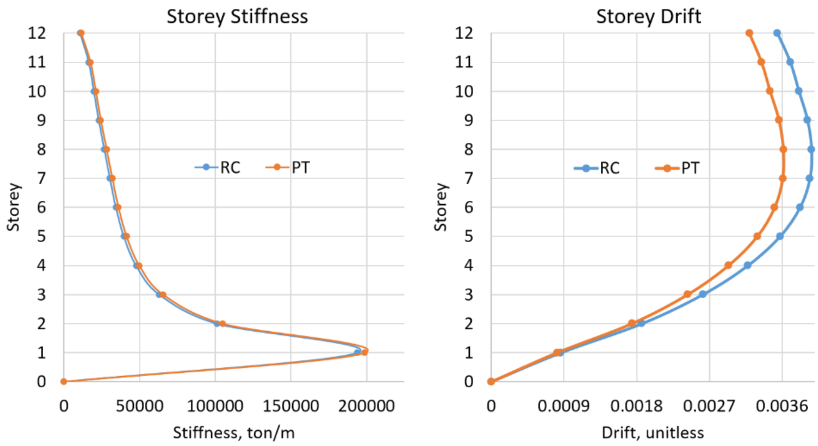

Figure 2. Storey Stiffness & Storey Drift PT Vs. RC.

3.3. Slab Deflection

Although post-tension slabs have thinner thicknesses than RC slabs, they are highly resistant to deflection due to the presence of tendons as shown in Figure 3.

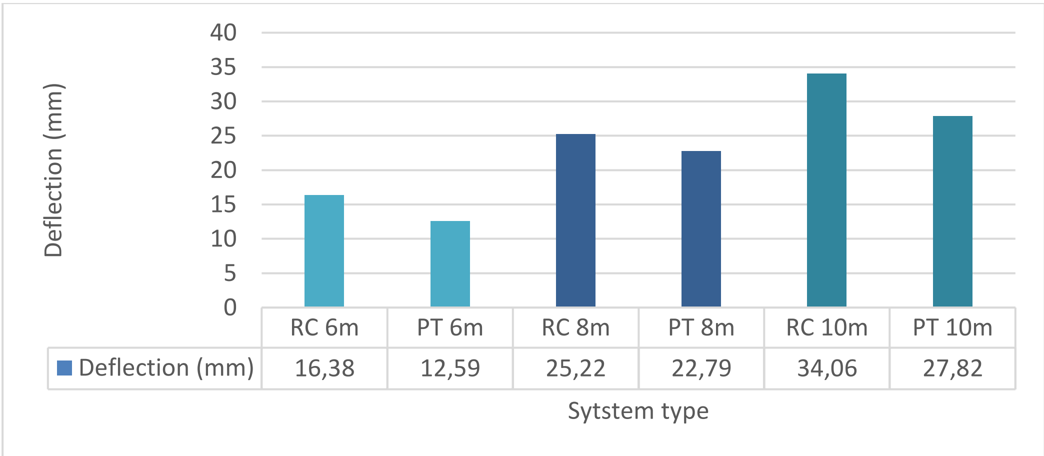

Figure 3. Slab Deflection PT Vs. RC.

3.4. Slab Punching

Post-tension tendons improve punching shear resistance due to the vertical component of the tendons (Vp) and the prestressing force (Fpc). Hence, using appropriate layout of tendons, the designer can consider additional resistance of punching in PT slabs. Table 2 shows a comparison between punching shear strength for the two systems according to the spans under study. The results show that considering tendon forces in punching calculations can lead to neglecting punching shear links. Conservatively, most designers do not consider the effect of tendon forces in punching resistance.

Table 2. Punching Capacity shear strength and Ultimate Shear Strength.

	Fpc (MPa)	Vp (kN)	Vc (MPa) considering tendons	Vc (MPa)	Vu (MPa)
RC 6m				1.31	1.929
PT 6m	1.38	16.6	1.999	1.31	1.954
RC 8m				1.31	1.387
PT 8m	1.57	38	2.065	1.31	1.968
RC 10m				1.31	1.485
PT 10m	1.59	54.5	2.059	1.31	1.880

4. Cost Evaluation

4.1. Quantity Takeoffs

Revit program is used in quantity surveying of columns, walls, and beams, while MS Excel is used in quantity surveying of slabs, raft foundation, and some other works. 3D model is made for all buildings using Revit program. In addition, Naviate Rebar Extension is used to assign reinforcement of columns, walls, and beams in an easy way, Fig. 4. Quantity takeoffs is summarized in Tables 3.

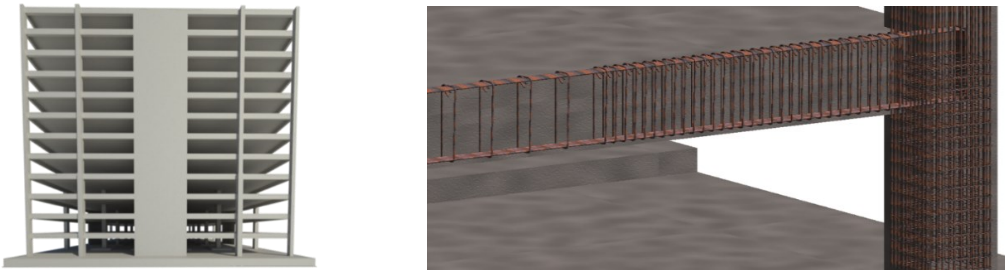

Figure 4. Modelling Concrete and Reinforcement Using Revit.

4.2. Cost Analysis

The pricing is performed according to the Egyptian labor market, and the average prices were taken from several Egyptian companies, whether quantities or contracting prices as shown in Tables 4 and 5. Bill of quantities are made for all buildings starting from excavation works to the concrete slab works.
(Note: 1 US Dollar= 15.61 Egyptian Pound).

4.2.1. Cost of Elements

From the present study, it has been observed that the cost of the slabs represents approximate 64% of the total cost of the building, while the vertical elements represent 13%, raft foundation represents 21% and other elements such as excavation, backfilling, insulation, and slab on grade represent 2%. The following sections show the cost details of each of the structural elements:

- Cost of slabs

The cost of traditional flat slabs for spans 6m, 8m, and 10m is 398,886 $, 960,718 $, and 1,966,811 $, respectively. While the cost of post tensioned flat slabs for spans 6m, 8m, and 10m is 361,499 $, 786,458 $, and 1,584,345 $, respectively. Using PT system results in savings of 37,387 $ (9%), 174,260 $ (18%), and 382,466 $ (19%) for spans 6m, 8m, and 10m, respectively.

Table 3. Quantity Takeoffs Summary.

Items	Unit	RC 6m	PT 6m	RC 8m	PT 8m	RC 10m	PT 10m
Excavation	m³	1390	1390	3276	3276	6376	6353
Backfilling	m³	228	228	906	927	1978	2141
PC raft	m³	107	107	193	193	304	303
RC raft	m³	1056	1056	2177	2158	4094	3912
	ton	79	75	201	191	371	359
	kg/m³	75	71	92	88	91	92
Insulation work	m²	1209	1208	2240	2222	3809	3667
Slab on grade	m²	900	900	1600	1600	2500	2500
Columns and shear walls	m³	408	397	780	698	1212	1179
	ton	87	83	167	142	244	225
	kg/m³	213	209	213	203	201	191

Slabs	m³	2246	2035	5186	4434	10201	8726
	ton	273	106	690	189	1472	435
	kg/m³	122	52	133	43	144	50
Prestressing System							
Strand 12.7 mm	ton	-	37	-	91	-	176
Anchorage S2-12.7 mm	No.	-	864	-	0	-	0
Anchorage S3-12.7 mm	No.	-	96	-	1248	-	1632
Anchorage S4-12.7 mm	No.	-	192	-	192	-	0
Anchorage S5-12.7 mm	No.	-	96	-	288	-	864
Steel ducts 20x50 mm	m.L	-	13248	-	24960	-	1632
Steel ducts 20x70 mm	m.L	-	4320	-	8592	-	864

Table 4. Material Prices.

Items			Unit	Price
Ready mix concrete Fcu= 35 MPa			$/m³	$56.37
Steel bars			$/ton	$672.65
PT system	Anchor	S2&S3	$/PC	$12.81
		S4&S5	$/PC	$24.34
	Duct	20x50 mm	$/m	$0.90
		20x70 mm	$/m	$1.28
	Strand	12.7 mm	$/ton	$1,153
	Air vent, grout, tapes		$/m²	$0.36
	Supply and apply price		$/ton	$2,690
Supply and apply	Excavation		$/m³	$1.41
	Backfilling		$/m³	$4.48
	Slab on grade		$/m²	$9.61
	Insulation		$/m²	$2.24

Table 5. Labor Prices.

Labor		Unit	RC	PT
Carpentry	PC raft	$/m³	$12.81	$12.81
	RC raft	$/m³	$15.37	$15.37
	Columns, walls and slabs	$/m³	$28.83	$28.83
Steel fixer	RC raft	$/m³	$9.61	$8.33
	Columns, walls	$/m³	$9.61	$8.33
	Slabs	$/m³	$9.61	$7.69
Concrete workers		$/m³	$0.96	$0.96
PT labor		$/ton		$320.31

- <u>Cost of Columns and walls</u>

The cost of columns and walls in traditional flat slabs building for spans 6m, 8m, and 10m is 97,590 $, 186,798 $, and 279,945 $, respectively. While the cost of columns and walls in PT flat slab building for spans 6m, 8m, and 10m is 93,217 $, 161,236 $, and 263,022 $, respectively. Hence, savings in vertical elements are 4,373 $ (4%), 25,563 $ (14%), and 16,924 $ (6%) for spans 6m, 8m, and 10m, respectively.

- <u>Cost of Raft Foundation</u>

The cost of raft foundation in traditional flat slabs building for spans 6m, 8m, and 10m is 142,121 $, 317,355 $, and 588,917 $, respectively. While the cost of raft foundation in PT flat slab building for spans 6m, 8m, and 10m is 138,560 $, 306,282 $, and 561,424 $, respectively. Hence the savings are 3,561 $ (3%), 11,073 $ (3%), and 27,493 $ (5%) for spans 6m, 8m, and 10m, respectively.

- <u>Cost of Total Building</u>

The cost of total building using the traditional flat slabs for spans 6m, 8m, and 10m is 652,938 $, 1,493,949 $, and 2,886,092 $, respectively. While the cost of total building using PT flat slab for spans 6m, 8m, and 10m is 607,616 $, 1,283,108 $, and 2,459,588 $, respectively. Hence total savings are 45,321 $ (7%), 210,842 $ (14%), and 426,504 $ (15%) for spans 6m, 8m, and 10m, respectively.

4.2.2. Cost of Material and Labors

Materials and labors or contracting are among the most important resources in the field of construction engineering, comparison is made here at this level to find out the cost of each resource in the different buildings. The comparison is carried out on raft foundation, columns, walls, and slabs, Fig. 5.

Materials cost represents about 78% of the total cost of the building, while labors cost represents 22%. The following sections show cost details for materials and labors in each building and the cost of concrete, non prestressing steel, and prestressing steel.

- Cost of materials

The cost of material in traditional flat slab buildings for spans 6m, 8m, and 10m is 505,152 $, 1,170,663 $, and 2,275,590 $, respectively. The cost of material in PT flat slab buildings for spans 6m, 8m, and 10m is 458,162 $, 934,067 $, and 1,721,296 $, respectively. Hence the savings in materials cost are 46,991 $ (9%), 236,596 $ (20%), and 554,294 $ (24%) for spans 6m, 8m, and 10m, respectively.

- Cost of labors

The cost of labors in traditional flat slab buildings for spans 6m, 8m, and 10m is 133,445 $, 294,209 $, and 560,084 $, respectively. The cost of labors in PT flat slab buildings for spans 6m, 8m, and 10m is 130,885 $, 277,645 $, and 528,860 $, respectively. Savings in cost of labors are 2,560 $ (2%), 16,564 $ (6%), and 31,224 $ (6%) for spans 6m, 8m, and 10m, respectively.

- Cost of concrete

The cost of concrete in traditional flat slab buildings for spans 6m, 8m, and 10m is 205,111 $, 450,729 $, and 858,516 $, respectively. The cost of concrete in PT flat slab buildings for spans 6m, 8m, and 10m is 192,602 $, 402,676 $, and 763,853 $, respectively. Savings are as follows 12,509 $ (6%), 48,053 $ (11%), and 94,663 $ (11%) for spans 6m, 8m, and 10m, respectively.

- Cost of non-prestressed reinforcement

The cost of non-prestressed reinforcement at the whole building level in traditional flat slab buildings for spans 6m, 8m, and 10m is 295,247 $, 711,291 $, and 1,403,459 $, respectively. The cost of non-prestressed reinforcement at the whole building level in PT flat slab buildings for spans 6m, 8m, and 10m is 177,621 $, 350,467 $, and 686,101 $, respectively. Hence, savings in non-prestressed steel are 117,625 $ (40%), 360,823 $ (51%), and 717,358 $ (51%) for spans 6m, 8m, and 10m, respectively.

- Cost of prestressed and non-prestressed reinforcement.

The cost of prestressed and non-prestressed reinforcement at the whole building level in traditional flat slab buildings for spans 6m, 8m, and 10m is 295,247 $, 711,291 $, 1,403,459 $, respectively. The cost of prestressed and non-prestressed reinforcement at the whole building level in PT flat slab buildings for spans 6m, 8m, and 10m is 260,765 $, 522,748 $, and 943,878 $, respectively. Hence, savings in steel reinforcement is 34,482 $ (12%), 188,543 $ (27%), and 459,581 $ (33%) for spans 6m, 8m, and 10m, respectively.

4.3. Time Analysis

The project duration is one of the important aspects in the field of construction. Therefore, a time analysis is performed for the construction of each building by using the productivity rate (PR) of each activity. In this analysis the number of labors is assumed to be the same for all buildings to obtain fair comparison. Hence, based on quantities take-offs and productivity rates, the time duration for each activity is obtained according to the following equation:

$$\text{Duration} = \frac{\text{Quantity}}{\text{Production rate}}$$

The productivity rate varies slightly from one place to another, so this rate has been compiled from several contracting firms and assigned to each activity. The number of crews is assumed in a logical manner for all activities, as shown in Tables 6.

After obtaining the duration of each activity for all buildings, a time schedule was made for all construction phases, whether sub-structure or super structure activities using Primavera program. The purpose of creating the time schedule is to find the timeline for the implementation of each building.

Time spent to construct the traditional flat slab buildings for spans 6m, 8m, and 10m is 324 days, 502 days, and 741 days, respectively; while time spent to construct the PT slab buildings for spans 6m, 8m, and 10m is 242 days, 314 days, and 548 days, respectively. Time savings when using the PT system for spans 6m, 8m, and 10m are 82 days (25%), 188 days (37%), and 193 days (26%), respectively, Fig. 6.

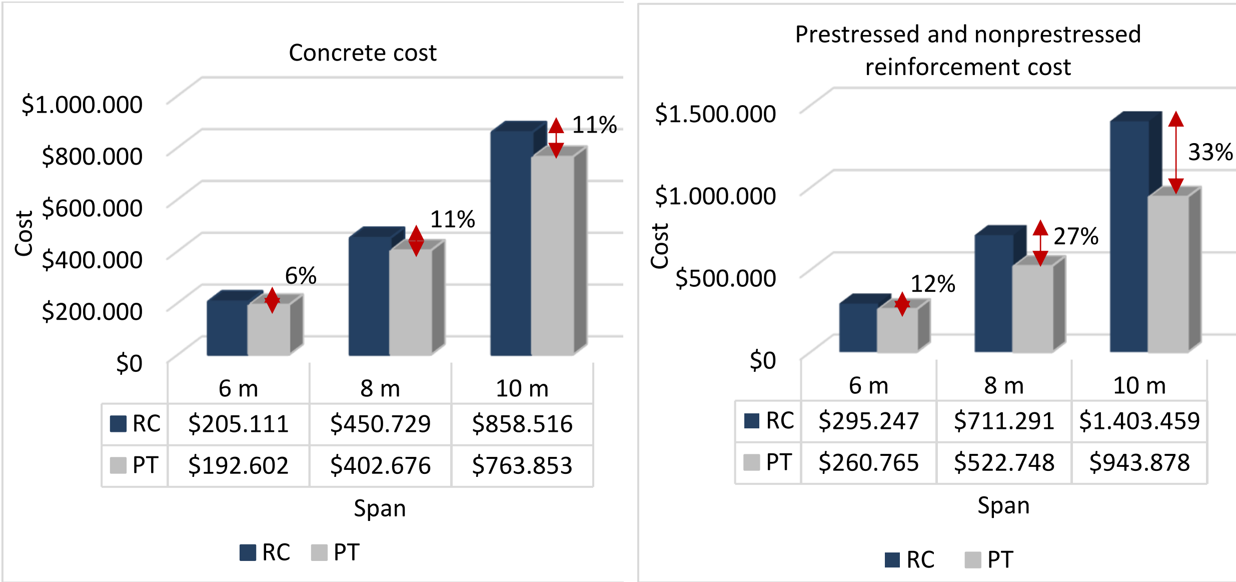

Figure 5. Cost of Concrete and Reinforcement.

Table 6. Activities, Productivity Rate and Total Crew Number.

Activity		Unit	Productivity Rate (Unit/Day)	Total Crew Number
Excavation works		m³	400	2
Backfilling and compaction		m³	500	1
Insulation works		m²	100	4
Pouring	PC Raft foundation	m³	300	1
	RC Raft foundation	m³	300	4
	Slab on grade	m³	300	1
	Slabs	m³	300	2
	Columns and walls	m³	200	1
Shuttering	PC Raft foundation	m³	50	2
	RC Raft foundation	m³	50	10
	Slabs	m³	5	15
	Columns	m³	1.65	15
	Walls	m³	3	8
De-shuttering	Raft foundation	m³	150	15
	Slabs	m³	10	15
	Columns and walls	m³	11.5	7
Steel fixing	Raft foundation	m³	5	30
	Slabs	m³	3	30
	Columns	m³	2.5	10
	Walls	m³	3	8
Post Tension Slabs				
Shuttering slab		m³	5	15
De-shuttering		m³	10	15
Steel fixing		m³	9	30
Pouring slab		m³	300	2
Tendons marking		ton	6	1
Tendon’s erection		ton	3	1
Stressing works		ton	6	1
Grouting		ton	6	1

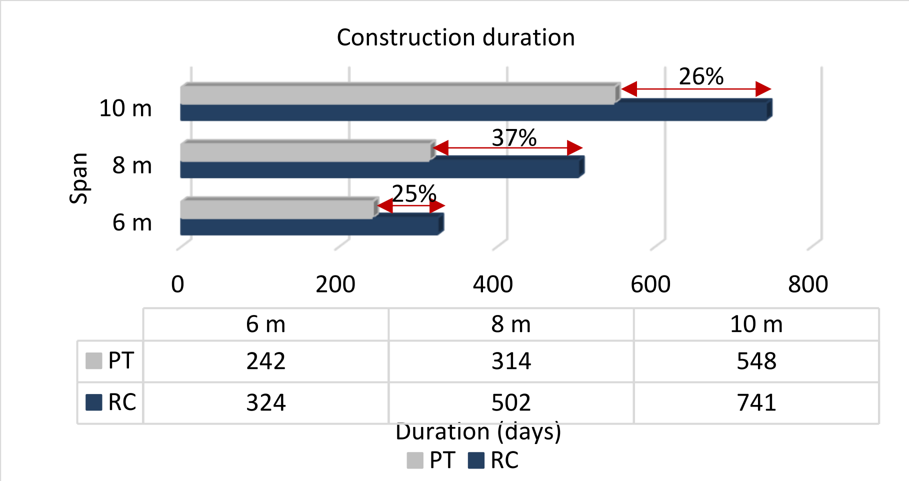

Figure 6. Construction Duration.

Among the advantages of saving time is the use of the facility quickly and obtaining a return from its use, which is called the return on investment (ROI). It is known that the return on investment in real estate in Egypt is approximately 8% of the building cost per year. Therefore, the time savings between the two alternatives is converted into a monetary value that can be deducted from the original building price.

Hence, considering the return on investment in the total building cost, the savings of investment for spans 6m, 8m, and 10m are 10,920 $, 52,871 $, and 104,044 $. The cost of PT flat slab buildings after deducting the savings of investment for spans 6m, 8m, and 10m will be 596,696 $, 1,230,237 $, and 2,355,544 $, respectively, instead of 607,616 $, 1,283,108 $, and 2,459,588 $, respectively.

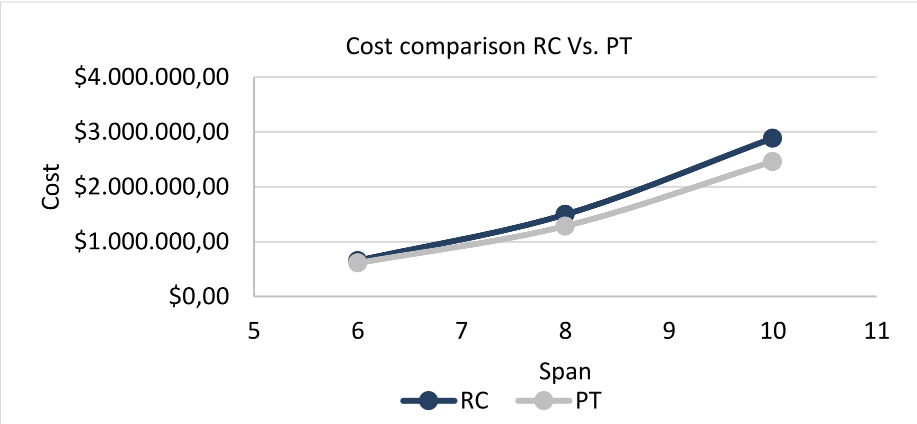

Figure 7. Cost Comparison for Building with Various Spans.

As shown in Fig. 7, a minor savings obtained in the comparison of span 6m. On the other hand, a considerable savings occurs in span 8m, 10m which proves that post tensioned slab can be recommended for multi storey buildings with spans over 6m.

5. Conclusions

The following conclusions are drawn from the present case study:

1- Post-tensioned PT buildings have a better behavior against seismic load. This is shown by stiffness values which affect the inter storey drift of post-tensioned buildings.
2- Post-tensioned slabs have lower value for deflection than the traditional flat slab.
3- Higher punching shear strength can be obtained in PT systems by using an appropriate layout for tendons due to the vertical component and axial compression stress from tendons.
4- The price of the slabs represents about 64% of the total building cost in the case studies used in this research.
5- The price of material represents about 78%, while labor cost represents 22% of the total building cost.
6- Post-tensioning slabs with spans over 6m offer direct cost reduction in:
    - Concrete by (6% to 11%).
    - Non-prestressed reinforcements by (40% to 51%).
    - Prestressed and non-prestressed reinforcement by (12% to 33%)

- Material by (9% to 24%).
- Labor by (2% to 6%).
- Slabs by (9% to 19%).
- Columns and walls by (4% to 14%).
- Raft foundation by (3% to 5%).
- Total building by (7% to 15%).

7- Post-tensioning slabs with spans over 6m offer direct reduction in construction duration by (25% to 37%).
8- When considering the time return on investment, the total savings in building cost will be (9% to 18%) instead of (7% to 15%).

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Conflict of Interests
The Authors declare no conflict of interest.

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Nomenclature

PT	Post tension.
RC	Reinforced Concrete.
Vp	Vertical Component Force of Tendon.
Fpc	Prestressing Stress.
Vc	Concrete Shear Strength.
Vu	Ultimate Shear Strength.
PC	Plain Concrete.
ROI	Return on Investment.
PR	Production Rate.
ACI	American Concrete Institute.
ECP	Egyptian Code of Practice.
L/D	Span/Depth.