ON THE SIGNIFICANT DESIGN PARAMETERS OF SELF-CENTERING CONCRETE BRIDGE PIERS

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ABSTRACT

This study develops a 3D Finite Element model of a self-centering concrete bridge pier to examine itsbehaviour under lateral load. The model is validated with the experiments conducted by Hewes andPriestley at the University of California, San Diego. The developed FE model is used to conducta detailed parametric study on the high aspect ratio bridge piers of Hewes and Priestley. Usingthe developed model, the effects of the prestress force, material properties and the pier cross-sectionalarea on the load carrying capacity have been determined. The result shows that the compressive strengthof the concrete and the prestress force have a substantial effect on the lateral responses, whereas ductdiameter has a negligible effect. The findings suggest that compressive strength of concrete and prestress force are the significant design parameters of the self-centering bridge piers.

Keywords:*Cyclic loading, finite element, force-displacement response, self-centering pier*

1. INTRODUCTION

In conventional seismic design, collapse prevention of structures is the primary goal in an earthquakeevent. Though the seismic resistant structures may resist collapse, these often sustain severe damage.The cost of repairing damages can be enormous, and in some cases, structures may require completedemolition. Hence, to enhance the seismic resilience of structures, a new concept named self-centeringhas been emerged. This structural system aims to minimize earthquake-induced damages and preventcollapse by allowing a bridge pier to return to its original position after an earthquake event.

A self-centering pier possesses two key characteristics: a post-tensioning system and prefabricatedconcrete segments. The pier is constructed by stacking precast segments, enabling rapid erection andminimizing damage during an earthquake. Unlike conventional piers, the self-centering system reducesresidual deformation to zero when no external force is applied. This re-centering capability distinguishesit from traditional designs and ensures superior performance. During an earthquake, the self-centeringpier exhibits movement and rotation without being fixed to the foundation. Once the lateral forces areremoved, the pier returns to its original position. The re-centering force is generated by post-tensioningforces and dead loads, including self-weight. Tendons, anchored in the base, introduce post-tensioningforces into the system.

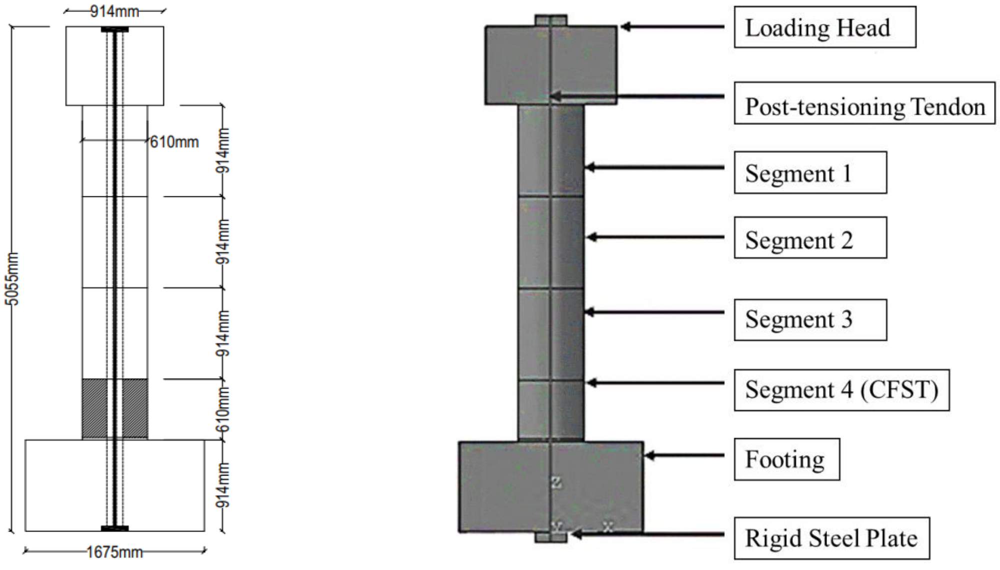
Researchers conducted both experimental and numerical studies in this field. Hewes and Priestley (2002)performed an experiment of self-centering pier by varying jacketing steel thickness and prestress force.Shim et al. (2008) performed experimental research on prestressed segmental concrete (PSC) withbonded threaded prestressing bars. ElGawady et al. (2010) tested PSCs with glass fiber-reinforcedpolymer (GFRP) tubes under cyclic loading and compared the performance to that of a monolithicreference column. Li et al. (2017) numerically investigated the effect of bonding conditions of thetendon in self-centering bridge pier. Li et al. (2017) discovered that the column with bonded tendonhad higher strength but lower ductility, and it experienced a larger residual displacement due to thestress concentration in the bonded tendon resulting in tendon yielding and loss of post-tensioned force.Hassanli et al.(2017), Zhang, Q. &Alam M. S.(2016) investigated the pier by varying the strength ofmaterials, the thickness of the jacketing steel, the level of axial stress, and the diameter of the pier. Somestudies also investigated different types of rocking columns, using energy-dissipating bars, and tryingout different materials like crumb rubber concrete (CRC), shape memory alloy (SMA), and fiberreinforced concrete (FRP).

Based on the studies, it is decisive that tendon prestress force,concrete compressive strength and duct diameter are efficacious parameters which affect the base reaction of self-centering bridge piers.In this study, the values are taken aiming to optimize the material strength and maximize the efficiency of design section.

2. GEOMETRY

The experimental program conducted by Hewes and Priestley (2002) consisted of piers with both high and low aspect ratios. The pier with a high aspect ratio was divided into four distinct circular sections, whereas the pier with a low aspect ratio only occupied two sections. The variation in the length of the piers can be attributed to the differing number of segments. Following a cycle of subsequent loading, each column underwent a process of being jacketed with fiber reinforced plastic in order to restore the damaged CFST section and prepare for another round of lateral loading. Consequently, four sets of columns were analysed, specifically labelled as JH11, JH12, JH21, and JH22.

Following the experimental program, the analysis and modeling of the designated pier is limited to a high aspect ratio. The base and loading head of the structure are connected to four circular hollow concrete pieces through a tendon that passes through the duct. The tendons are structurally linked to the base and loading head using strong base plates. The concrete section includes both longitudinal and spiral reinforcements, which are, however, divided into distinct parts.



(a) (b)

Figure 1: (a) Geometry, (b) FE Model

The dimensions of different elements are followed by the experimental program in order to accurately account for their impacts. The Footing has a square shape measuring 1675 mm on each side and 914 mm in thickness. The circular segments have a diameter of 610 mm and a height of 914 mm. The loading head is also square-shaped, measuring 914 mm in both length and width. The anchor plates serve as a supportive component for the tendons, preventing them from penetrating the concrete elements when prestress is applied. The CFST segment is encased by a 6 mm steel jacket, which has an identical diameter as the other circular segments but a height of 610 mm.

3. FINITE ELEMENT MODELING AND ANALYSIS

A numerical model has been developed to predict the force displacement responses of a self-centering bridge pier. Three-dimensional material and geometric nonlinearities are incorporated into the model. The investigation model of the cyclic loading experiment specimen is comprised of the concrete bridge pier, loading head, post-tensioning (PT) strands, and footing connected to a strong floor, while the majority of the parts are modeled with conventional techniques using solid and truss elements.

Concrete was modeled using eight noded Solid element, which is a general purpose and fully integrated linear brick element. A damage plasticity model was used for concrete modeling. For loading head and circular segments, Mander's (1988) model has been used and for steel tube confined concrete, Han's (2014) model has been incorporated. Reinforcement and prestressing steel have been modeled using two nodedTruss Element and the jacketing steel plate has been modeled using four nodedShell Element. The utilization of a steel jacket was implemented to enhance the strength of the lowermost circular segment. The perfect bond between the steel and concrete has been taken into account. The model doesn't take into account the fact that concrete and reinforcing steel can slip against each other because of embedded constraints.

Appropriate boundary conditions are applied in the developed FE model to simulate the experimental condition. All the nodes of the footing bottom face are constrained in all direction to simulate the connection between the laboratory strong floor and the footing. Different mesh sizes have been used for the different parts of the developed FE model of the self-centering pier. Appropriate mesh sizes have been chosen to keep the model computationally efficient.

The precast segments of the pier were placed one over another and approximately 10 mm epoxy was provided in between the joints. The joints between the precast segments are simulated using the node to surface contact. A friction coefficient of 0.5 is used as suggested by Dawood et al. (2013) for simulating the contact for both between the concrete-concrete interface and the steel-concrete interface

The displacement-controlled cyclic loading as shown in Fig. 2 is appliedat mid-height of the loading head (at point A of Fig. 2). The static analysis is performed and the rate-dependent effect is neglected because of the fact that the loading rate effect on the responses is not significant. The analysis method is acceptable as the simulation results are comparable with the experiments which is further discussed in Section 3.1.

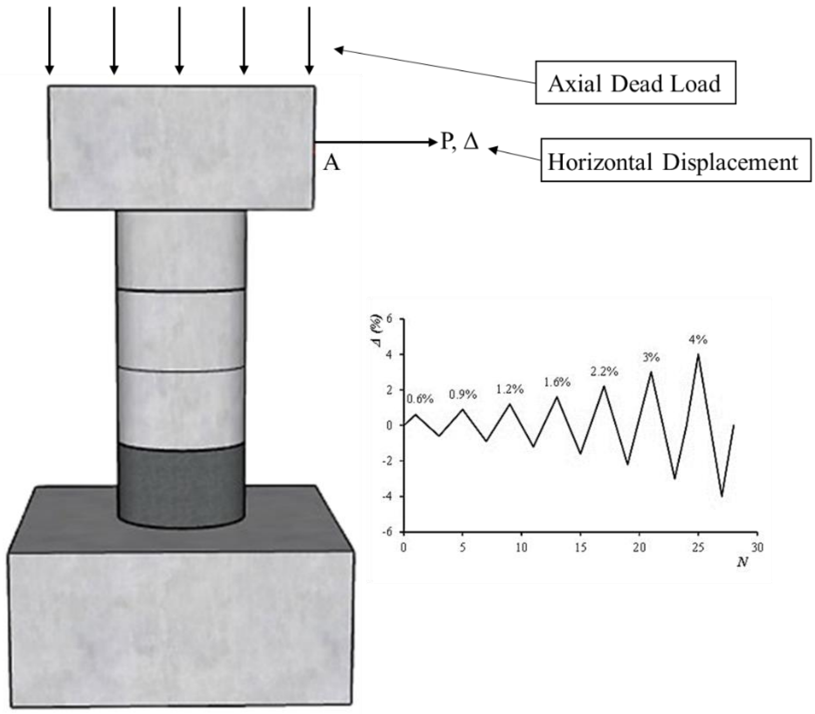


Figure 2: Schematic diagram of the bridge pier loading

3.1 Model Validation

The model was validated following the experimental response conducted by Hewes and Priestley (2002). The test was performed at University of California, San Diego. In the experimental program, the bridge pier model was cyclically loaded from the side after a constant axial load was applied on the pier head.

In the FEM program, both the axial dead load and the lateral cycle load were applied on the loading head of the pier. In three steps, the load was placed on. The prestressing forces were applied through the truss elements on the pier as the initial condition. The constant axial dead load was placed on the loading head afterward. Finally, the loading head was subjected to cyclic lateral load.In the FE program, the full load was applied in a displacement-controlled situation to make modeling easier and make the program run faster.The results were compared to the experimental program of Hewes and Priestley(2002). The obtained deformed shape, opening of the segments due to horizontal load, force displacement response, etc. are taken into account.

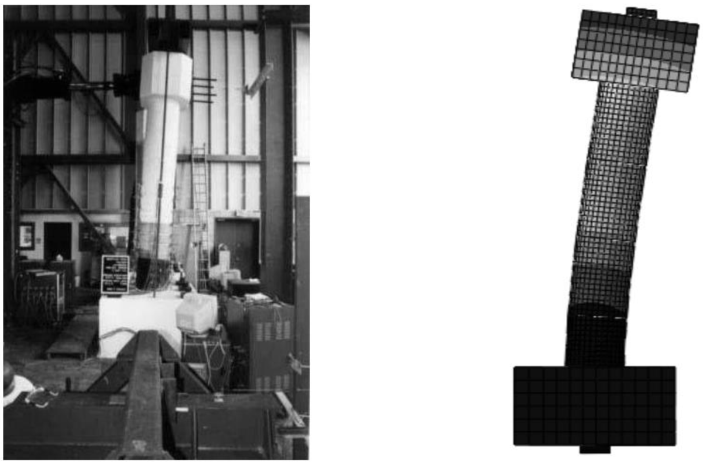


Figure 3: Comparison between deformed shape

The pieces of the pier were not connected structurally. Since the pieces were being loaded from the side, they opened up as expected.

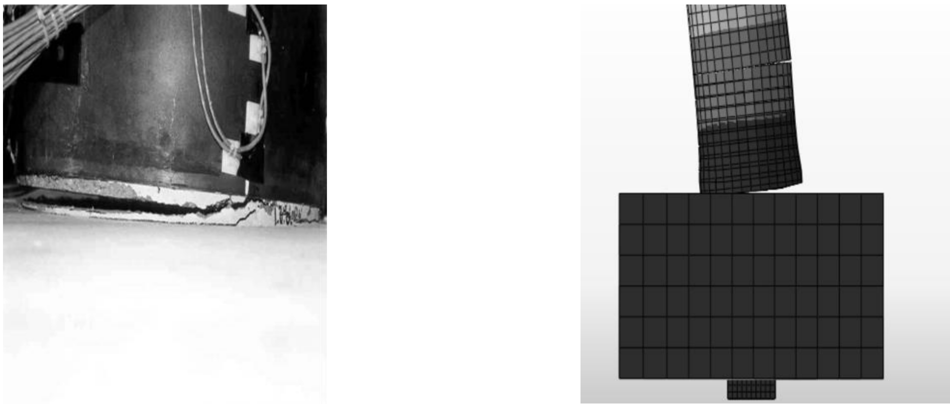
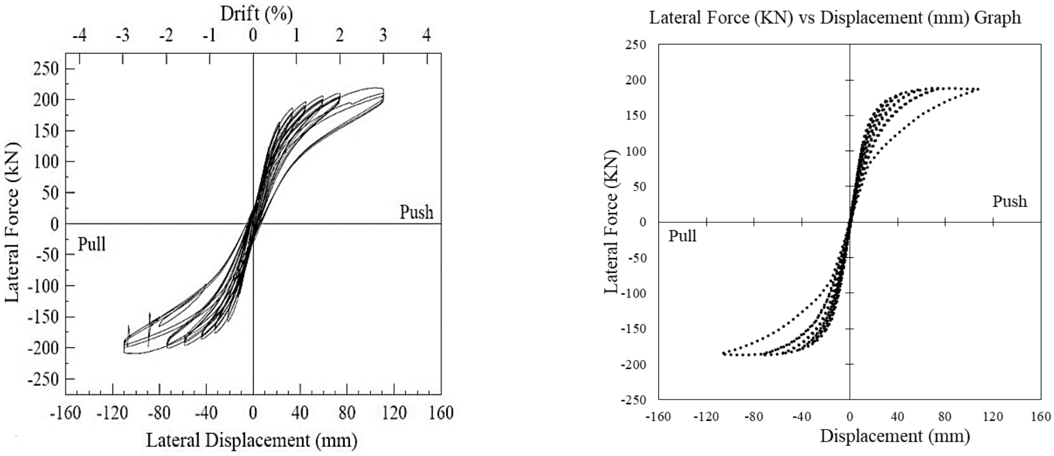


Figure 4: Separation between foundation and CFST section

The force-displacement response from the experimental program by Hewes and Priestley(2002), had a hysteresis shape. The base reaction gradually followed the displacement, and the residual deformation was very small. The developed FE model showed the same behavior.



(a) (b)

Figure 5: Comparison of force displacement response; a) Expeimental, b) Numerical

3.2 Parametric study

For Axial load ratio is an important factor for changing the behaviour of self-centering bridge pier. Axial load ratio depends on three factors i.e., axial load, cross section of the circular segment and compressive strength of concrete.

$$\text{Axial load ratio} = \frac{f_c}{f_c'}$$

$$= \frac{P}{A_c \times f_c'}$$

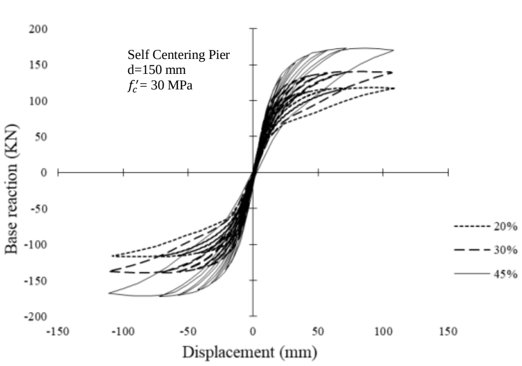
The axial load ratio changes as P, A_c and$f_c^{'}$ change. In this study, the value of $f_c^{'}$ was varied to 30, 40, and 50 Mpa. The cross-sectional area changed as the duct size changed. The size of the duct had been thought to be 150 mm, 200 mm and 250 mm. Also, the prestress force had been considered to be 20%, 30% and 45% of the ultimate prestress strength.According to Hewes and Priestley (2002), the first stressing of the model was done with 45% of the tendon's ultimate strength. Following the experiment, initial stress had been given (0.45 × 1860= 837) 837 MPa. The parameters were proposed based on the factors that were considered significant in determining the seismic response of the pier. Based on the three mentioned parameters, the hysteresis curve for all the possible combinations wasanalysed.

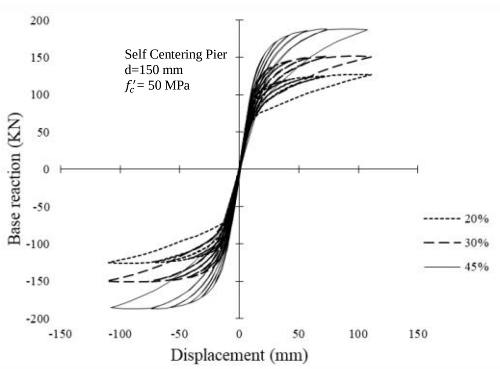
Table 1: Simulation variables

Prestress (%)	**Concrete Strength, $f_c^{'}$ (MPa)**	**Duct Diameter,d(mm)**
20	30	150
30	40	200
45	50	250

4. SIMULATION RESULTS

The base reaction vs. displacement curves are shown in Figure 6 for variable duct diameter and variable concrete compressive strength.When the prestress force is low, the base reaction is also low. However, as the prestress force increases, the base reaction rises correspondingly.This indicates that higher prestress forces contribute to improved resilience and ductility of the pier under seismic loads. The graphs also depict the impact of the compressive strength of concrete on the elastic behaviour of the pier. When the compressive strength of concrete is 30 MPa, the elastic area appears to be scattered. However, as the compressive strength of concrete increases, the scatteredness decreases. This suggests that higher compressive strengths contribute to more consistent and reliable self-centering behaviour of the pier, particularly under higher prestress forces.





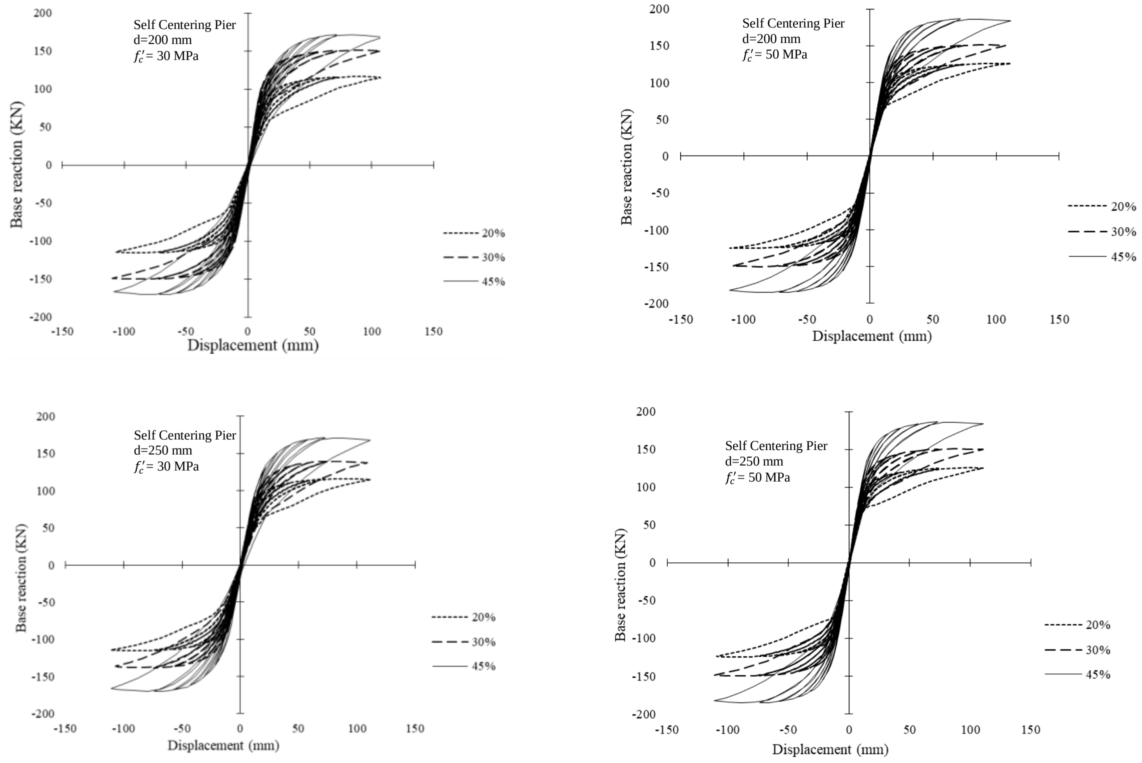


Figure 6: Base Reaction vs Displacement

Another variable of the study is the duct diameter. Figure 7 shows that changing the duct diameter does not have a significant effect on the base reaction.For a specific compressive strength, such as a certain value, the base reaction for different duct diameters, such as 150 mm, 200 mm, and 250 mm, remains within a certain range or band. As the compressive strength of the concrete increases, the base reaction generally increases, but the bands for each duct diameter remain separated. The reason behind this behavior is the substantial dead load that the pier carries in the absence of prestress force. The dead load contributes to the base reaction, and as the compressive strength of the concrete increases, the overall load-carrying capacity of the pier improves, resulting in higher base reactions. However, the variations in the base reaction for different duct diameters remain within certain bands, indicating that the duct diameter itself does not have a significant influence on the base reaction.

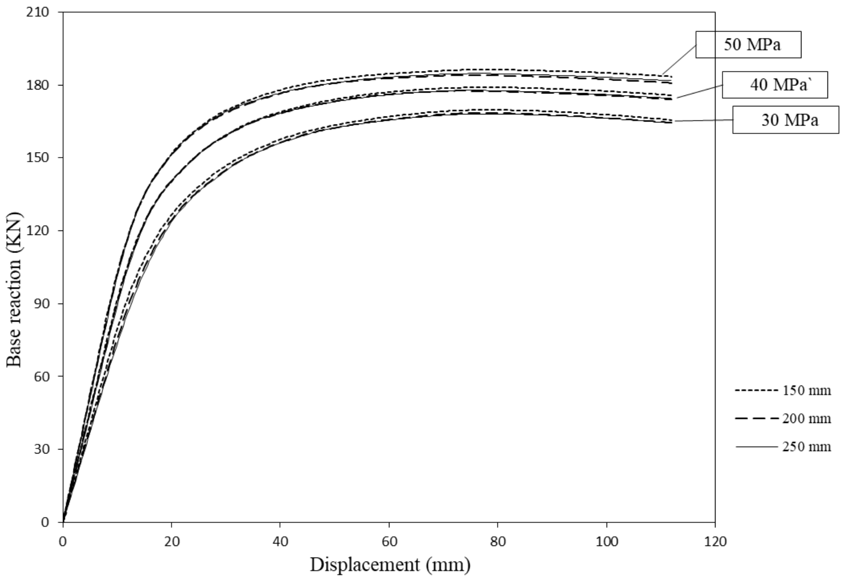


Figure 7: Base Reaction vs Displacement graph for variable duct diameter.

Axial load ratio, being an effective factor for the variation of base reaction, shows simultaneous relation with base reaction. Table 2 shows the relation between axial load ratio and base reaction with other parameters. For a certain prestress force, maximum base reaction is found when the axial load ratio is minimum. Also higher prestress force results in higher base reaction.

The Study discusses the effect of axial load ratio on the force displacement response of self centering bridge pier depending on prestress force, concrete compressive strength, and duct diameter. Results show that with different combination of simulation matrix maximum increase in base reaction is found for 45% prestress force and concrete compressive strength 50 MPa compared to 30 MPa.

Table 2: Increase in base reaction (MPa) for 45% prestress force

	Base Reaction (MPa) Increment	
Duct Diameter, d (mm)	**40 MPa**	**50 MPa**
150	2.9	8.6
200	4.1	9.8
250	5.9	11.8

5. FINDINGS AND CONCLUSION

The findings from the study are as follows:

- Increasing the compressive strength of concrete leads to a higher base reaction, indicating improved resistance to lateral loads and deformations. Higher compressive strength is recommended for better performance.

- Higher prestress forces result in an increased base reaction, indicating an enhanced ability to withstand horizontal loads. Greater pretension force also leads to larger energy absorption capacity as well as more damage in the case of lateral seismic loading.

- The size of the duct has a limited effect on the base reaction capacity. However, larger duct sizes offer material and cost savings. It is important to consider the duct size while balancing material requirements and cost considerations. For the protection of the tendons from deteriorating during horizontal loading, the duct size should maintain a minimum dimension.

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