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CAPPING BEAM RIGIDITY, ORIENTATION AND SHAPE EFFECTS ON SECANT PILE WALLS BEHAVIOUR

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ABSTRACT

The current research theme is the retaining structures, with special attention to secant pile walls. The deformation of the secant pile wall affects the adjacent building negatively. Accordingly, the overall system rigidity, i.e. capping beam and the piles, should be well investigated and accurately designed. Starting from this perspective, the capping beam lateral rigidity, as wells as its inertia, shape and orientation were covered in details herein. The plaxis 3D is the software used to investigate the above-mentioned design parameters. The pile was modelled by the circular volumetric element with interface element to match the reality as possible. Different excavation shapes were investigated as well as various relative density of the used sandy soil platform. However, several outcomes have been abstracted and discussed throughout the text body. One of the novel conclusion of this study is the aspect ratio and shape of the excavated area that showed a sounding effect on the wall behavior and deformation.

KEYWORDS: Secant Pile, Capping Beam , Sand Soil, Plaxis 3D, Rigidity, Aspect Ratio

تأثير جساءة الكمره الرابطة وتوجيهها وشكل القطاع على الإزاحة الأفقيه للحوائط الخازوقية المتقاطعة

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الملخص

يدور موضوع البحث حول الحوائط الساندة عموماً مع التركيز حصراً علي الستارة الخازوقية المتقاطعة. حيث تؤثر الإزاحة الافقية الناتجة عن حركة الخوازيق المتقاطعة على سلامه المبنى المجاور. الكمره الرابطه لستاره الخوازيق لها فائدتين هما تحسين منحني سهم الازاحة و في المقام الأهم تقليل مقدار سهم الازاحة لجوانب الحفر. من هذا الاعتقاد تم اقتراح موضوع البحث. حيث تم دراسة تأثير جساءة الكمرات الرابطة وتوجيهها وشكل قطاعها بالتفصيل باستخدام النموذج الرقمي للعناصر المحدده بواسطة برنامج PLAXIS 3D والجدير بالاشاره انه تم تمثيل الخوازيق بقطاع دائرى ثلاثى الابعاد والكمرات ممثله أيضاً ثلاثيه الابعاد لتماثل الواقع بقدر المستطاع . ايضا تم دراسه تاثير اشكال الارض المختلفة والكثافات النسبية المختلفة للتربة الرملية علي مقدار الازاحة للحائط. يشتمل البحث علي عده نتائج قيمه تفيد التصميم والتنفيذ ومن الجدير الاشاره الي انه تلاحظ بوضوح ان شكل الحفر ونسبة الطول الى

العرض له لها تاثير ملحوظ على حركة الإزاحة و هذه استنتاج متواضع الا انه غير مسبوق في المراجع السابقة.

الكلمات المفتاحية : الخوازيق المتقاطعة ، الكمرات الرابطة ، تربه رملية ، plaxis 3D ، نسبة الطول الى العرض.

1. INTRODUCTION

The given research paper investigates whether the presence of a capping beam reduces deformation or improves the behavior of the piles, enabling them to act as a single unit. The research strategy consists of five main titles: the literature review, the methodology, the presentation and analysis of parameters, the discussion of results and the recommendations. To address the research question, the study begins with insights from the literature that lead to these research inquiries. The literature is divided into two groups: the first suggests a significant impact, including studies.

Ong et al.[1] highlighted that capping beams restrain pile tops, enabling them to act in unison, which significantly reduces deflection and enhances structural integrity. It recommendeds employing a line load technique for modeling in two-dimensional analysis. Khater et al. [2] found that incorporating capping beams in cantilever secant-pile walls reduces wall displacement by 75%, cautioning that two-dimensional software may overestimate displacements. Xu et al. [3] demonstrated that the restraint provided by capping beams significantly affects lateral deformation, with Bayesian modeling improving prediction accuracy. Chong et al. [4] observed minimal deflection and settlement attributed to capping beams, noting a transition from cantilever to prop behavior following anchor installation.

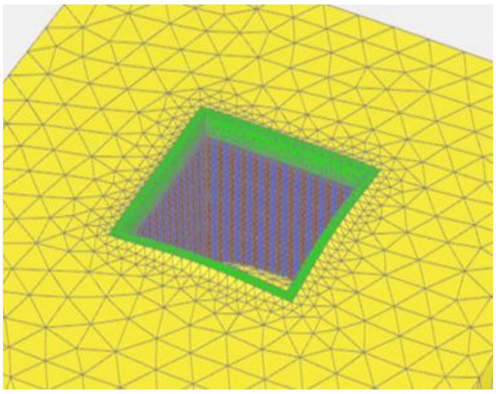
Zhang et al. [5] reported that capping beams reduce maximum lateral deformation by approximately 4.5% and bending moments by 23.1%. Mahesh et al. [6] indicated that capping beams reduce lateral displacement and bending moments, with further minimization achieved by increasing the beam's depth. Ahmed et al. [7]demonstrated that capping beams enhance stability and rigidity, achieving deflections reduced by 40%. Cheng et al. [8] indicated that continuous capping beams decrease loads on adjacent piles, affecting stability and progressive collapse behavior. Abdou et al. [9] observed improvements in structural behavior, noting reductions in horizontal displacement (Ux) of approximately 66% and vertical displacement (Uy) of about 52%, with increased beam depth further enhancing stability. Ong et al. [10] suggested that capping beams mitigate deflections and damage by providing additional rigidity.

Wright et al.[11] found significant reductions in lateral movement and wall deflection, with values decreasing from 146.7 mm to 21 mm and from 193.9 mm to 20 mm due to the beam's effectiveness, thus enhancing stability and reducing construction costs. The second group suggests minimal impact, including Zdravkovic et al. [12] who noted that while capping beams reduce top wall displacement and surface settlements, their impact on lower wall sections and excavation corners is minimal. Ramadan et al. [13] indicated that, although capping beams are used to connect pile heads and control the top movement of the piles, they are not sufficiently rigid to manage the deflection of piles in cantilever secant pile walls, leading to their effect being neglected in this study.

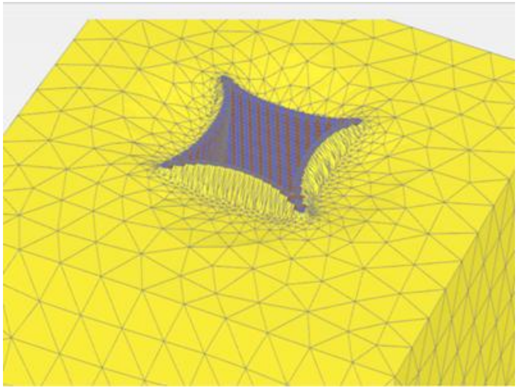
2. METHODOLOGY AND VARIABLE INVESTIGATION

To achieve the objectives of this research, relevant methods and tools have been carefully selected and implemented. The tools employed were briefly described, as they are widely recognized by experts in the field, obviating the need for extensive explanations. The nature of the research is numerical, utilizing finite element analysis through PLAXIS 3D CONNECT Edition V22. The soil model applied is based on the Mohr-Coulomb criteria, while the piles and capping beam were represented as volumetric elements, with the model characterized as linear elastic. The geometry of the finite element (FE) model was designed to ensure that the boundaries were sufficiently distanced to minimize their influence on the system's response.Three distinct cases were examined, differing solely in the geometry of the ground while maintaining all other parameters constant. In the first case, a rectangular land parcel measuring 10.30m in width and 15.90m in length, the model dimensions were set to 30.90m × 47.70m, represented as a volumetric element. The second case, which involved a square plot of land, was analyzed with dimensions of 10.30m × 10.30m.

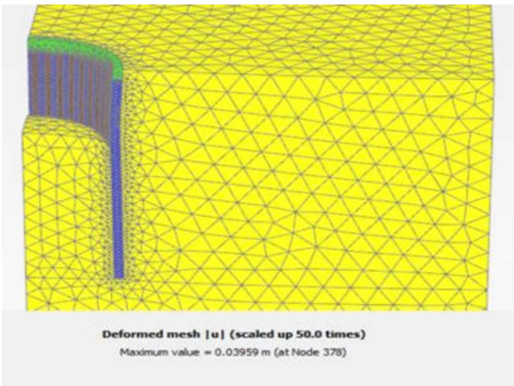
Correspondingly, the model dimensions were set to 30.90m × 30.90m, represented as a volumetric element. To optimize computational efficiency, rectangular and circular model were executed as a quarter model instead of a full model to benefit from the principle of symmetry. Likewise, a single simulation may take up to 30 hours without the capping beam and approximately 8 to 14 hours with the beam included. The dimensions for this model were established at 15.45m × 18.25m. The final case consisted of a circular plot of land with a diameter of 10.30m, which was similarly modeled as a quarter model to enhance computational efficiency, resulting in model dimensions of 15.45m × 15.45m.



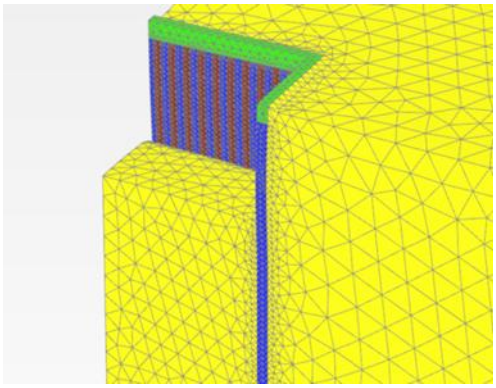
(a) Square model without capping Beam



(b) Square Model With Capping Beam



(c) Circular Model With Capping Beam



(d) Rectangular Model With Capping Beam

Fig. 1: Cases of Models

In the 3D model analysis, the mesh density within the excavation significantly influences the accuracy of the results. A fine mesh was employed for all models. Particular attention was given to the piles and the capping beam in the full models, where the mesh size was set at 0.25 within the piles and capping beam, 0.5 within the excavation, and 1 outside the excavation boundaries. While in the quarter models, the mesh sizes for the piles and the capping beam were adjusted to 0.5, with a mesh of 0.6 within the excavation and 1 outside the excavation boundaries to ensure consistency with the results of the full models. The vertical boundary conditions for the model sides were established to restrict horizontal movement while permitting vertical movement. The boundary condition for the model base was fixed in all directions in the first case. In the quarter models, the boundary conditions were set as the YX Min and YY Min boundaries were fixed, while the YX Max and YY Max boundaries were fixed horizontally. The bottom boundary was fully fixed, and the top boundary was left free.

Thus, the excavation depth was set at H = 6 m, with a single pile diameter of D_p = 0.5 m and a pile length of L = 15 m. The soil was assumed to be homogeneous, isotropic, and extending to infinity. Three different relative densities, D_r(20%, 40%, and 72%), were considered in the analysis, representing a range from loose to dense sand. The parameters for the sand were calculated using the empirical method suggested by [14] in conjunction with [15] PLAXIS 3D numerical modeling is shown in **Table 1**.

Table 1: The Used Variable Values of the Parameters

Property		Sand Relative Density %		
Symbol	**Units**	**Loose Dr=20%**	**Medium Dr=40%**	**Dense Dr=72%**
γ_d	kN/m^3	15.8	16.6	17.88
γ_{sat}	kN/m^3	19.32	19.64	20.15
E	kN/m^2	8100	17161.23	33403
E_{oed}	kN/m^2	12000	2400	43200
φ°	Deg.	30.5	33	37
ψ°	Deg.	1	3	7
C	kN/m^2	1.00	1.00	1.00
K_0	Ratio	0.49246	0.4554	0.39818
μ_s	Ratio	0.33	0.31	0.28

Notation Key:
γ_d: dry denisty - γ_{sat} : saturated density – E :modulus of elasticity - E_{oed} : oed modulus of elasticity - φ° : friction angle - ψ° : dilatancy angle - C: cohesion
K_0 : at rest - μ_s : Poisson ratio
***[14,15] Equations**

In this study, beams of four different heights, h_b(20, 40, 60, and 80 cm), were utilized alongside various cross-sectional shapes, including rectangular, L, T, C, and I sections. All shapes maintained a consistent cross-sectional area of 50 × 80 cm, with the beam height fixed at 80 cm to ensure economic feasibility and isolate the effect of shape alone. Additionally, the impact of rotating the rectangular beam (50 × 80 cm) and the beam (50 × 20 cm) was also investigated, as shown in **Fig. 2** and **Fig. 3**.

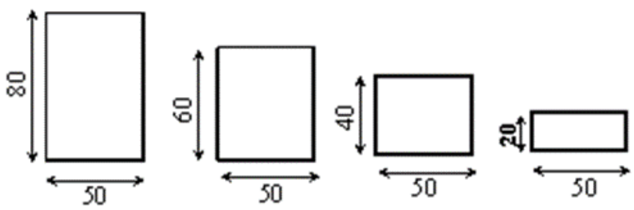


Fig. 2. Capping Beam Depth

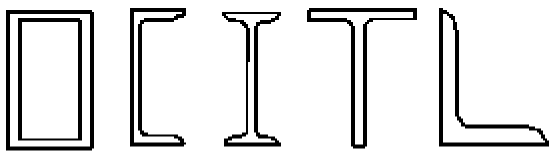


Fig. 3: Capping Beam Shapes

3. PRESENTATION AND ANALYSIS OF RESULT VARIABLE PARAMETRIC STUDY

This modest work consists of five subsections, each addresses one of the primary factors that influence the behavior of the capping beam and consequently, its design and analysis. The discussion begins with the excavated aspect ratio, followed by the influence of sand density. The study examines the effects of capping beam rigidity, as well as the effects of its orientation and shape. Figures have been included as beneficial aids to enhance the reader's understanding.

3.1 Excavation Aspect Ratio

As a start, the shape of the excavated pit seems to have a minor effect on pile top deformation. This uncertainty sparked the research curiosity to investigate and clarify this thought. Accordingly, a limited pilot study has been performed, and its results surprisingly proved that the opposite is true, i.e., it has a major effect.

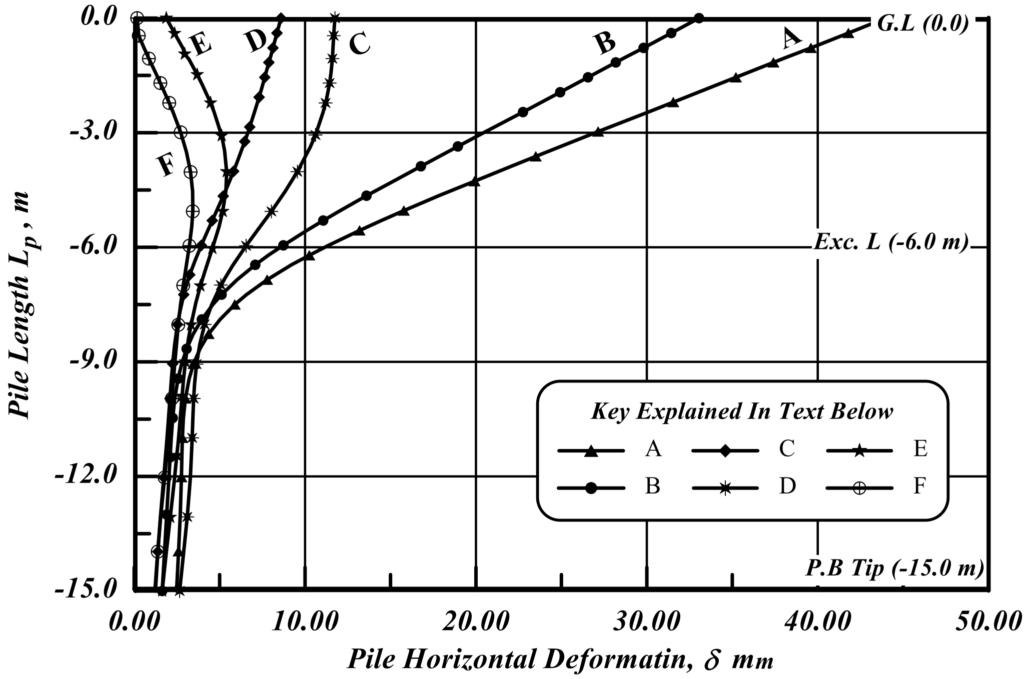


Fig. 4: Pile C.L Deformation Along Its Length, Per Three Different Excavation Shapes

However, the six curves shown in **Fig. 4** proved that not only the existence of the capping beam affects the pile top deformation, but also the shape of the excavation affects the top deformation of the pile.

Curves A, B, C present pile without capping beam, while curves D, E, F present pile with rectangular capping beam measuring 50 *80 cm. Furthermore, curves A&D are plotted for rectangular excavation pit, curves B&E are plotted for square excavation pit, and curves C&F are plotted for circular excavation pit.

Curve A is adjusted to be curve D just due to the existence of the capping beam with a reduction of the pile top movement by 73%. The same pattern is repeated for B and E, also C and F, 94% and 97% respectively.

The surprising notice is the deformation of the pile top for case of rectangular, i.e., curve A became curve B, then C. This is just due to the change of the excavation shape, even all cases were done for the same depth of the excavation. This proved that the excavation shape has a major effect on the pile deformation.

The deformation of the circular excavation is a significant outcome. It proves to be smaller than the other curves and it reaches approximately zero value. It is due to ring action.

3.2 Effect of Relative Density

Fig. 5 presents the horizontal deformations of the secant pile center line versus pile length for rectangular excavation pit at different relative densities. Curves A, B, and C represent the deformation values for loose, medium and dense sand, respectively, in the absence of a capping beam. Curves D, E, and F illustrate the deformation values with a rectangular capping beam (50 × 80 cm) for loose, medium and dense sand. The behavior of curve A is consistent with that of curves B and C; however, curves D, E, and F exhibit differences in deformation values. A notable observation is that the presence of the capping beam reduces the elastic line values along the length of the pile.

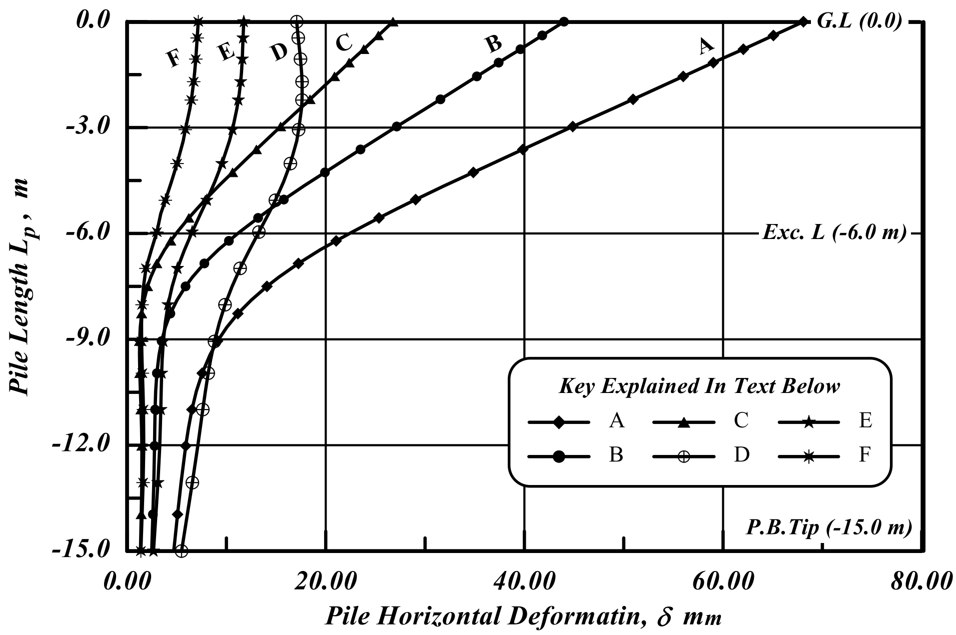


Fig. 5: Pile C.L Deformation Along Its Length, Per rectangular Excavation Pit

Results in the rectangular-excavated pit show decreased deformation in loose sand from 68 mm to 17 mm, resulting in a 95% reduction, as illustrated by curves A and D. Medium-density sand decreased from 44 mm to 11.8 mm, resulting in a reduction of 73%, as represented by curves B and E. In dense sand, deformation decreased from 27 mm to 7.17 mm, a reduction of 73%, represented by curves C and F. These findings indicate that the presence of the capping beam significantly impacts deformation, irrespective of the type or density of sandy soil.

3.3 Capping Beam Rigidity V.S Deformation

Fig. 6 illustrates the effect of varying capping beam depths on deformation values. Curve A represents the deformation of the secant pile in medium-density sandy soil without the capping beam. Curve B depicts the deformation with a rectangular capping beam of dimensions 50 × 20 cm, Curve C with a beam of 50 × 40 cm, Curve D with a beam of 50 × 60 cm, and Curve E with a beam of 50 × 80 cm. Upon analyzing the five curves, it is evident that the behavior differs significantly between Curve A and Curves B, C, D, and E, as the deformation values markedly decrease in the presence of the capping beam. The results show that the deformation decreased from 11.8 mm to 13.3mm, 16 mm, 19.8 mm, and 44 mm for beam depths of 20 cm, 40 cm, 60 cm, and 80 cm, respectively. The percentage of reduction is 55%, 63%, 69% and 73%, respectively. These findings underscore the importance of selecting an appropriate beam depth, as the reduction in deformation becomes more pronounced with increasing beam depth.

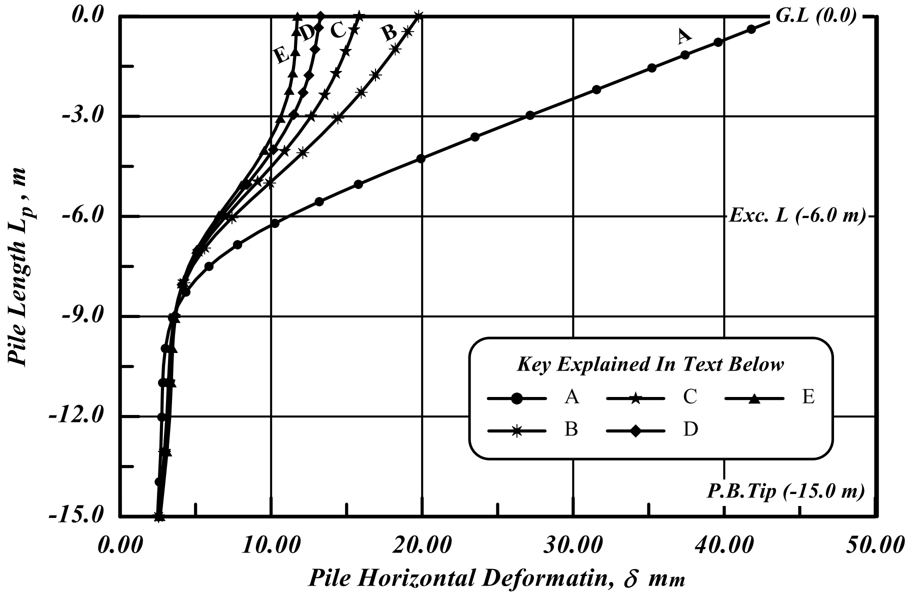


Fig. 6: Pile C.L Deformation Along Its Length, Per rectangular Excavation Pit

3.4 Cross Section of Capping Beam Orientation Affect

Fig. 7 illustrates the effect of capping beam rotation on deformation. Curve A represents the deformation of the pile without a capping beam, while Curve B depicts the deformation of the pile with a rectangular capping beam of dimensions 50 × 80 cm. Curve C presents the deformation of the pile with a rotated rectangular capping beam of dimensions 80 × 50 cm.

The results indicate that despite maintaining a constant capping beam dimensions while varying the width through orientation, there was a notable impact on deformation values. This finding underscores the importance of considering beam orientation in the design and reinforcement distribution in both directions.

When the capping beam was rotated to 50 × 80 cm, the deformation decreased from 1.1.8 mm to 6.8 mm, a reduction of 42%.

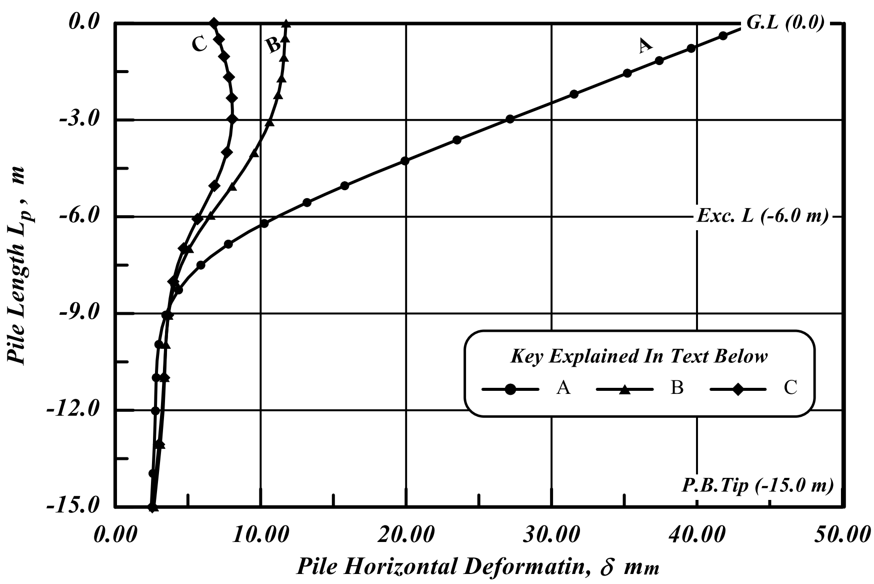


Fig.7: Pile C.L Deformation Along Its Length, Per rectangular Excavation Pit

3.5 Shape Effect of Capping Beam

Fig. 8 displays five graphs, each represents the deformation of a secant pile subjected to various capping beam shapes, dimensions, and moments of inertia. Curve A illustrates the deformation of the secant pile without a capping beam. Curve B depicts the deformation with a rectangular capping beam measuring 50 × 80 cm. Curve C represents the deformation with I-shaped capping beam, Curve D shows the deformation with a C-shaped capping beam, Curve E presents the deformation with T-shaped capping beam, and Curve F illustrates the deformation with L-shaped capping beam.

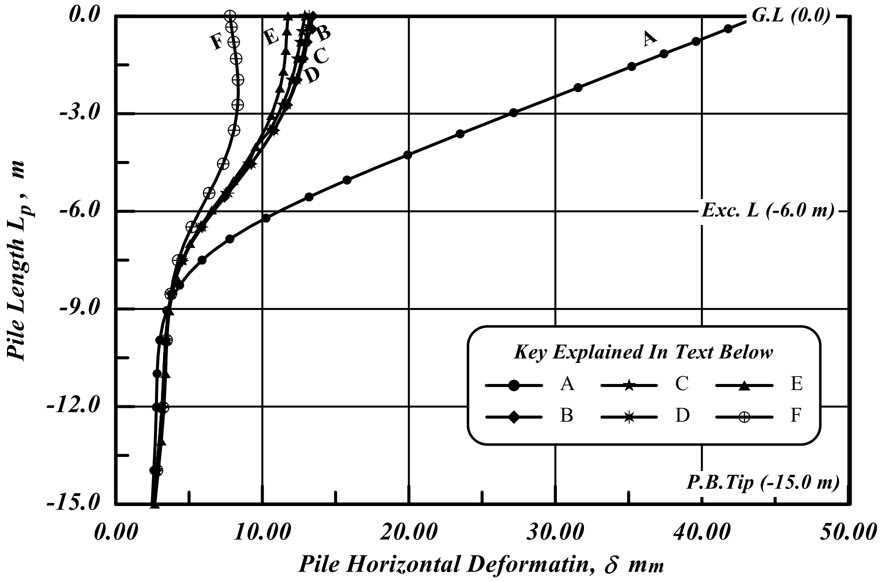


Fig. 8. Pile C.L Deformation Along Its Length, Per rectangular Excavation Pit

The results indicate that the L-shaped capping beam demonstrated the most significant performance, as the deformation decreased by 82%. The deformation values for the rectangular C, I, and T-shaped capping beams were similar, suggesting that these configurations had a comparable impact on the deformation of the secant pile.

4. DISCUSSION AND CONCLUSIONS

The following summarizes the proposed procedure for analyzing the effects of the rigidity and orientation of the capping beam (C.B) of the secant cantilever wall on deformation values:

1. The capping beam reduces the curve arrow of the piles without capping beam.
2. The maximum deformation with the capping beam presented occurs at 5 meters for both square and circular excavation shapes. In contrast, for the rectangular excavation shape, maximum deformation remains at the top of the pile.
3. The incorporation of a capping beam significantly reduces the horizontal deformation of secant piles across various excavation shapes (square, rectangular, and circular).
4. In case of rectangular-excavation shape, the reduction in deformation due to the capping beam is 73%, for square-shaped ground case the reduction is 94%; and for circular ground, it reaches 97%, with the "ring action" phenomenon providing additional constraint.
5. The presence of a capping beam effectively reduces the deformation in all types of sand density, i.e., (loose, medium, and dense), achieving reductions of up to 73% in medium-density sand, 73% in dense sand, and 95% in loose sand for rectangular-shaped ground.

6. Increasing the capping beam height cross section reduces the horizontal deformation. It decreases from 19.8 mm to 16 mm, 13.3 mm, 11.8 mm, and 44 mm for h_b, 20cm, 40cm, 60cm and 80cm, respectively.
7. In rectangular-excavation ground, changing orientation of the capping beam to 80 × 50 cm reduces deformation by 42% with respect to its orientation before this change.
8. The width of the capping beam significantly affects deformation values as shown in **Fig. 7**.
9. The L-shaped provided in **Fig. 8** is considered the most effective, as it reduces deformation by 82% in rectangular-excavation shaped, thus, it is recommended to be used.
10. Other shapes (rectangular, C, I, and T) exhibited similar performance in deformation reduction; however, the L-shape provided the greatest impact.

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