Influence of Execution Speed on Displacements of Soil-Nailed Structures with Vertical Face in Urban Areas

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Abstract: This paper presents the study of the execution speed influence on displacements of soil-nailed structures with a vertical face in urban areas, intended as the basements of buildings. Fifteen structures in the Metropolitan Region of São Paulo, Brazil, were evaluated. The main objective was to demonstrate the evolution of the construction technique, making its application possible in conditions considered by the technical community to be unfeasible due to the inevitable resulting displacements. The studied structures ranged from 6.8 to 22.7 m high. Soil-nailed walls were instrumented with displacement gauges (deflectometers) positioned near the top, which monitored the structures' horizontal displacements. The execution time of each work was evaluated in terms of the sectoral excavation advancement, which was 3, 4, or 5 days, as well as the production in square meters per day. The results showed works that were less displaceable than the estimates proposed in the literature. The impact of execution speed also was evidenced, showing that the opening interval of new work fronts resulted in significant differences, with displacements ranging from 20 to 23 mm, from 10 to 15 mm, and from 0 to 6 mm, respectively. Two equations proposed to predict horizontal displacement based on the retaining structure height and daily work productivity are presented. The study can enable works that may be considered impractical if analyzed from the displacement premises of the literature; moreover, this study disseminates design and execution standards to obtain less-displaceable works. **DOI: 10.1061/(ASCE)CO.1943-7862.0002286.** *© 2022 American Society of Civil Engineers.*

Author keywords: Reinforced soil; Retention; Horizontal displacements; Grout injection; Instrumentation.

Introduction

The soil nailing technique has been used for more than 50 years, and improvements to its execution and the understanding of its behavior continue to develop through studies worldwide. Pioneering studies (Clouterre 1991; Gässler 1978; Gassler and Gudehus 1981) helped disseminate the methodology and contractor investments for research involving construction companies, contracting parties, and research centers, mainly because it is a fast, economical, and safe methodology.

Soil nailing can be defined as a reinforcement technique for existing slopes or cuttings, executed via successive excavation phases, concurrently with the installation of passive elements—usually steel bars—in holes, filled with cementitious grout, followed by drainage and face shotcrete coating (Clouterre 1991; Fan and Luo 2008; Farokhzad et al. 2020; FHWA 2015; Sabermahani et al. 2018).

In addition to slope geometry and soil parameters, other factors affect the stability of a soil-nailed structure, such as: nail orientation, nail properties, nail length, and nail spacing.

The use of grout reinjection covering the nails to increase the resistance of the soil–nail interface (q_s) is substantial advance in the execution methodology, in addition to mitigating displacements (Kim et al. 2013; Moayed et al. 2019; Seo et al. 2017; Shahraki Ghadimi et al. 2017).

The installation of vertical nails connected to the concrete face increases the shear strength and stiffness of the foundation, reducing displacements, and is yet another improvement, especially for top-down constructions (Azzam and Basha 2017; Mucheti et al. 2019).

Many studies have pointed out the influence and the great variation of q_s strength, which continues to be the target of studies worldwide, and is due to influence of soil and nail characteristics and execution methodology. Those studies confirmed the need for pull-out tests to validate the design assumptions and qualify the elements installed in the structure (Chen et al. 2020; Shahraki Ghadimi et al. 2017; Tokhi et al. 2018; Zhang et al. 2009).

The development or improvement of the technique does not stand out only in executive aspects, as computational numerical modeling of geotechnical structures has been developed, dealing with different approaches involving different analyses, such as those related to performance (probabilistic or deterministic methods), methods (limit equilibrium or finite elements), and models [two-dimensional (2D) and three-dimensional (3D) analysis], which can predict the performance of the work before it is developed (Moradi et al. 2020; Wang et al. 2020; Zamiran et al. 2012).

Opposed what was cited by Sabermahani et al. (2018), deep excavations in urban areas close to adjacent buildings are carried out using the soil nailing technique to gain space in the basements of buildings (Farokhzad et al. 2020). In urban contexts, studies assessed the behavior of concave and convex corners (excavation vertexes) and found the importance of nail arrangement to achieve satisfactory stability results and smaller displacements, thus improving results (Moradi et al. 2020; Zad and Hejr 2019).

Two important manuals used worldwide provide guidelines for the elaboration of design and performance of soil nailing technique (Clouterre 1991; FHWA 2015). Those manuals estimate the face

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horizontal displacements based on soil type and structure height. Depending on the type of application, the results of an initial analysis may lead to a probable impossibility of employing the technique due to the high displacement that the structure may suffer. Those manuals are based on works that were carried out more than 30 years ago (Bruce and Jewell 1986, 1987; Clough and O'Rourke 1990; Ho et al. 1989; Stocker and Reidinger 1990; Thompson and Miller 1990).

Thus, those estimates should be updated, because the technique has evolved since that time, in terms of design techniques, materials, and construction processes. The most recent works indicate better performance in relation to the magnitude of horizontal displacements compared with the estimates proposed by the manuals.

Excavations with significant heights were carried out in urban areas using the soil nailing technique and showed positive results in terms of cost, versatility, execution speed, and especially performance. Some works have reported lower displacements than those predicted by the manuals (Bridges and Gudgin 2014; Corte et al. 2016; Durgunoglu et al. 2007a, b). Despite the variables involved in the design or execution, the current technique has reached a different format from that of 30 years ago.

It is important that those involved become aware of the new possibilities that the technique demands. The estimates of horizontal face displacements based on manuals can lead to early interpretations that do not allow the application of the soil nailing technique due to the high estimated displacement.

A little-studied point is the influence of the soil nailing technique execution speed on horizontal face displacements. This paper evaluated displacements according to the variation of the imposed execution speed.

To fulfill the objective, 15 soil-nailed works with a vertical face intended as the basements of buildings were designed and developed with various heights, and the face displacements and execution speed were measured. The adopted execution methodology was standardized, except in relation to the opening time of new work fronts (advanced excavations), which varied according to the size of the area to be retained by soil nailing.

The results showed a relevant contribution mainly to the constructive aspects, and demonstrate that using the technique assures less-displaceable works.

Estimate of Soil-Nailed Structure Displacements

In general, the maximum horizontal displacement of a soil-nailed structure with a vertical face occurs at the top. Vertical displacements usually are small, and of the same magnitude as horizontal displacements. Displacements increase with the increase of soil-nailed structures' height, the spacing between nails, the nail inclination, and overload. On the other hand, horizontal displacements decrease with greater wall thickness, increased soil stiffness, and less spacing between nails (FHWA 2015).

Based on the results of five instrumented works, we propose a method to estimate the magnitude of soil-nailed structure displacements using three calculations (Clouterre 1991): δ_0, the horizontal displacement behind the soil-nailed structure; d_h, the face top horizontal displacement; and δ_v, the face top vertical displacement.

Displacement δ_0 is estimated between $4H/10{,}000$ and $5H/10{,}000$, and this value varies inversely to the L/H ratio, and is dependent on the nature of the soil (Clouterre 1991).

Displacements can be estimated according to Table 1 if the soil nailing technique is performed according to the recommendations in the manuals (Clouterre 1991; FHWA 2015).

Table 1. Displacement estimated as function of soil type

Displacement	Intermediate soils (rocks)	Sand	Clay	Reference
$\delta_v = \delta_h$	$H/1{,}000$	$2H/1{,}000$	$4H/1{,}000$	Clouterre (1991)
$\delta_v = \delta_h$	$H/1{,}000$	$H/500$	$H/333$	FHWA (2015)
λ	(0.8)	(1.25)	(1.5)	Clouterre (1991) and FHWA (2015)

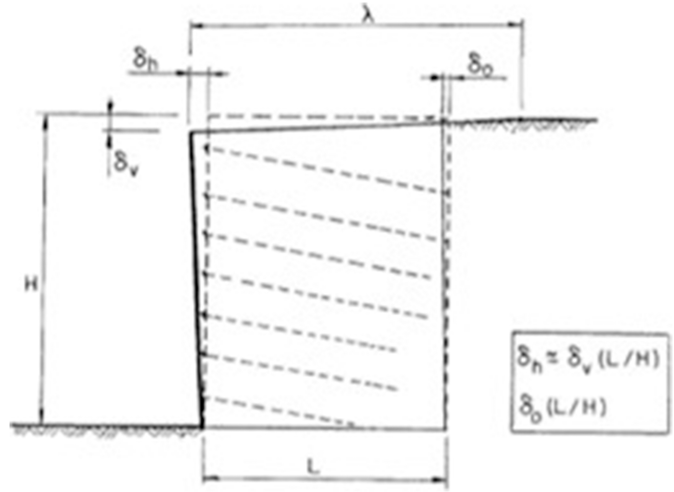

Fig. 1. Displacements according to Clouterre (1991).

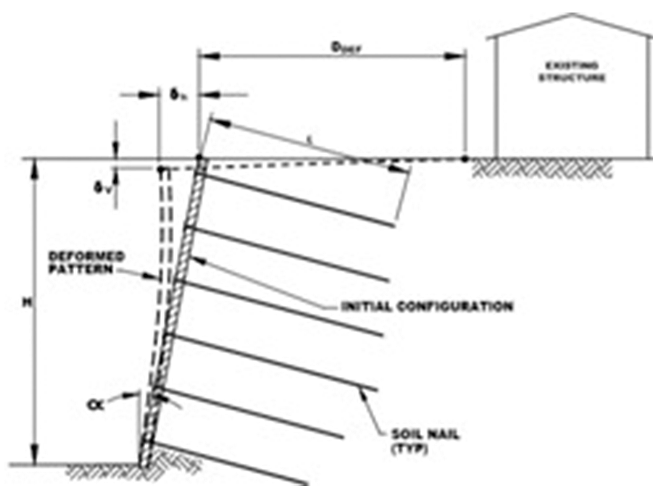

Fig. 2. Displacements according to FHWA (2015).

Parameter λ is used to determine the significant displacement range (D_{DEF}), which corresponds to the end point of the displacement action from the face

$$D_{\text{DEF}} = \lambda(1 - \tan\alpha)H$$

where α = angle of soil-nailed structure face; and λ is a coefficient that depends on the type of soil.

The same indexes are used in the English standard BS 8006-2:2011 (BSI 2011), the French standard NF-P94-270 (AFNOR 2009), and the Nordic soil and embankment guide (Nordic Geosynthetic Group 2005). Figs. 1 and 2 illustrate the position of the estimated displacements according to the literature.

Cases

Fifteen works for the basements of buildings were studied in this paper; the face horizontal displacements and construction time were monitored. The works are located in the cities of Santo André, São Bernardo do Campo, São Caetano do Sul, Barueri, and São Paulo (Figs. 3 and 4).

The geology of the Metropolitan Region of São Paulo (RMSP) is composed of three large types; in stratigraphic order, these are Precambrian basement; Paleogene to Neogene sediments (previously called Tertiary) of the Basin of São Paulo, and Quaternary covers (Negro et al. 2012).

Fig. 3. State of São Paulo, Brazil.

Table 2 presents the set of works monitored by displacement indicators (deflectometers) with the indication of the location, execution year, soil type, retaining structure height, total area of soil-nailed section, nail mesh, and length of upper and lower nails of the retaining structure. The mesh size ($S_h \times S_v$) was 1.0×1.0 m, and the face thickness was 100 mm. With the exception of Works 9 and 13, which were the highest, the L/H ratio (nail length to soil-nailed structure height) was 0.9 for upper nails and 0.6 for lower nails.

In other works, the ratios were between 1.0 and 1.3 for upper nails and between 0.7 and 1.6 for lower nails. The works are located mainly on fine-grained soils; nine works are on silty clay, two works are on sandy clay silt, three works are on sandy silt, and one work is on silt embankment.

Table 3 presents the execution time, daily and monthly production, and face displacement at the end of the execution for soil-nailed structures.

Fig. 5 shows the horizontal displacement of each work and the influence of execution speed on displacements based on monthly production.

There was a linear increase in displacements as the monthly production increased. This index is important because soil-nailed works generally are economically viable with production of at least 250 m^2/month for each team allocated to the work; thus, works with larger perimeters allow the opening of a greater number of excavation fronts, maintaining a reduced execution speed (smaller displacements) but with a productive yield which justifies a lower labor cost.

Design Concept and Execution Sequence

The projects followed a standardization using the recommendations of Clouterre (1991), FHWA (2015), and Nordic Geosynthetic Group (2005) as starting points, but adapting them to obtain better results regarding face displacement and characteristics, similar to those described in Fig. 6.

An important feature regarding the nails is the use of three sectoral grouting phases after the sheath is finished. Polypropylene

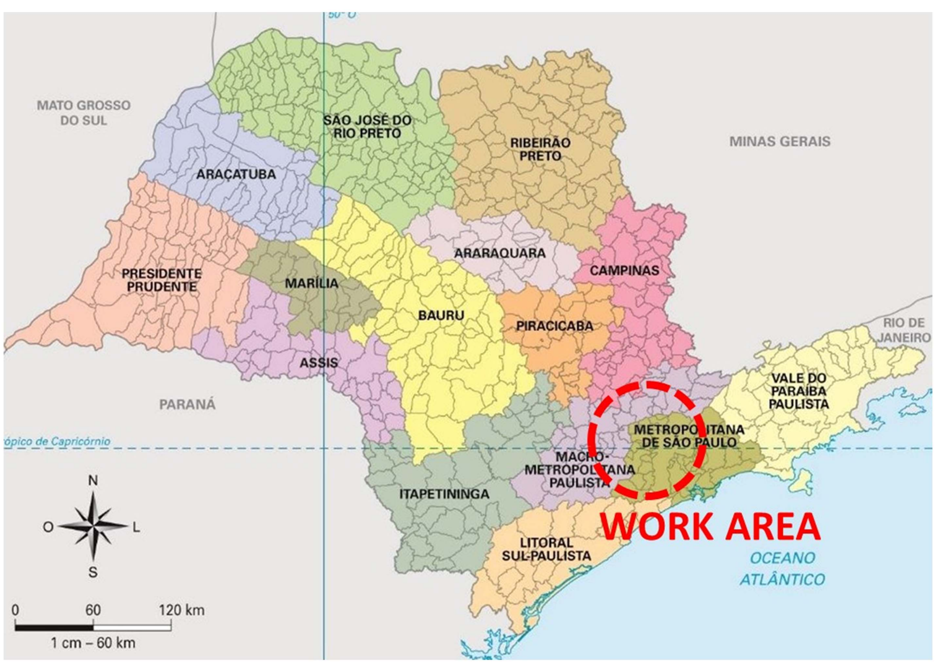

Fig. 4. Site locations.

Table 2. General and design characteristics

Work	Location	Year	Soil type	Height (m)	Area (m^2)	Upper nails (m)	Lower nails (m)
1	SCS	2010	SE	8.5	1,139	10.0	6.0
2	SBC	2012	SCS	9.0	458	11.0	7.0
3	SBC	2012	SCS	11.8	787	12.0	8.0
4	SCS	2012	SC	9.0	923	11.0	6.0
5	SCS	2013	SC	8.9	670	11.0	8.0
6	SBC	2015	SC	8.8	610	9.0	6.0
7	SA	2015	SC	8.6	762	9.0	6.0
8	SA	2015	SC	8.6	437	9.0	6.0
9	SBC	2015	SS	22.7	2,200	20.0	14.0
10	BA	2015	SS	6.8	500	7.0	7.0
11	SA	2017	SE	11.5	1,917	12.0	10.0
12	SA	2017	SC	8.3	188	10.0	8.0
13	BU	2019	SS	16.0	344	14.0	10.0
14	SA	2020	SC	9.5	765	12.0	14.0
15	SCS	2020	SC	7.6	771	10.0	12.0

Note: SCS = São Caetano do Sul; SBC = São Bernardo do Campo; SA = Santo André; BA = Barueri; BU = Butantã; SC = silt clay; SCS = sandy clay silt; SS = sandy silt; and SE = silt embankment.

Table 3. Execution data

Work	Time (days)	Production (m^2/day)	Production (m^2/month)	Displacement (mm)
1	176	6.5	194	10
2	88	5.2	156	6
3	103	7.6	229	10
4	90	10.3	307	20
5	160	4.2	125	0
6	155	3.9	118	0
7	125	6.1	182	5
8	106	4.1	123	2
9	441	5.0	149	5
10	72	6.9	208	13
11	170	11.3	338	23
12	33	5.7	170	5
13	45	7.6	229	15
14	223	3.4	102	0
15	151	5.1	153	2

tubes ½-in. in diameter were installed (Fig. 7). Grouting valves are small openings in the pipes, every 0.5 m, plugged with adhesive tape. Sectorization was chosen to ensure valve opening in the desired section. The recorded injection pressures ranged from 700 to 1,000 kPa for valve opening and from 200 to 600 kPa during the grouting process.

In general, the execution sequence followed the recommendations of Clouterre (1991), FHWA (2015), and Nordic Geosynthetic Group (2005) but with some different implementations and details

- in all works, vertical nails were used with a 5° inclination relative to the face, and 4.0 and 6.0 m long, depending on the soil-nailed structure height;
- the new excavation fronts were opened only after the nails in the upper line had been installed and regrouted and the shotcrete had been applied; and
- the execution proceeded according to Fig. 8.

To mitigate displacements, following Azzam and Basha (2017) and Mucheti et al. (2019), vertical nails were installed at pre-established points according to the structure height. The nails had two sectoral grouting phases and were arranged as in Fig. 9.

Displacement gauges were installed near the top of retaining structures to control horizontal face displacements. The gauges were metal rods equipped with a free section and an anchored section (such as a bond); the free section was protected with a rigid PVC tube, and the anchorage was carried out by grout injection. For each rod, a metal plate was fixed to the shotcrete face as a reference for the readings.

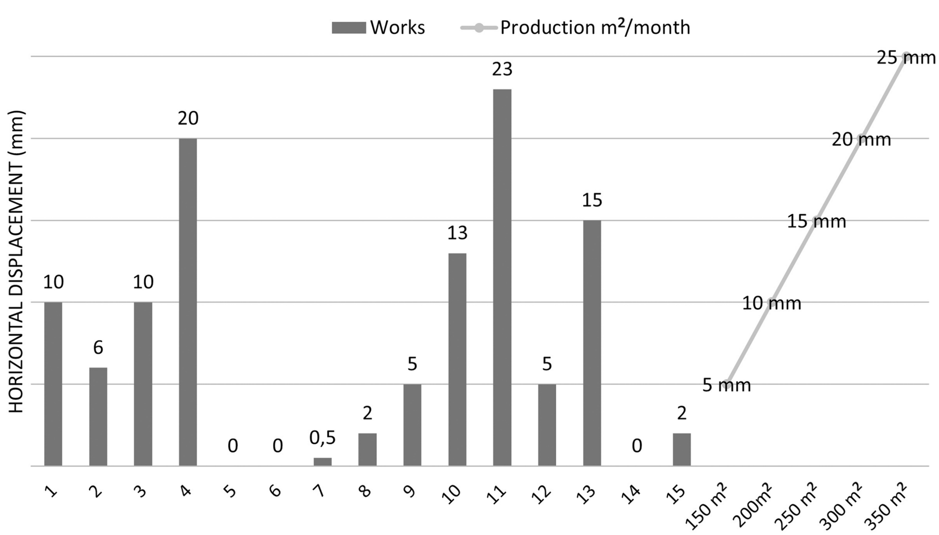

Fig. 5. Displacement per work and displacement as a function of monthly production.

J. Constr. Eng. Manage., 2022, 148(7): 04022048

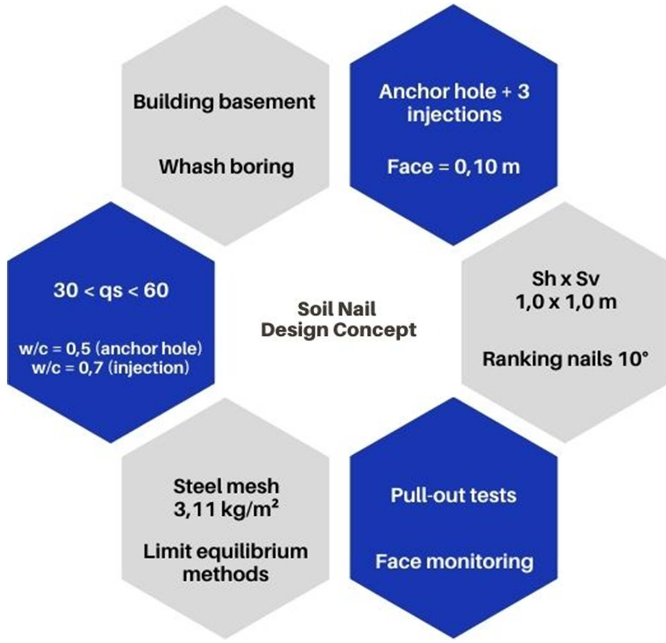

Fig. 6. Standard characteristics of projects involved.

The displacement gauges were anchored with three different lengths to enable the identification of the region that separated the active zone from the resistant zone (Fig. 10).

Other than Work 11 (on sandy silt embankment soil), Displacement gauge 1 measured the displacements of the works, and it was verified that the critical failure surface is located at the point at which the highest loads act on the nail, at a distance $0.3H$ to $0.4H$ from the retaining structure top. For Work 11, the displacement was noted in Gauge 3, which was observed in the field from a crack in the neighboring floor and extending longitudinally to the end of the nails. Fig. 11 illustrates the movement observed according to the displacement gauges.

Results and Analyses

Based on results, it was possible to analyze the relevant data to understand the behavior of the horizontal displacement of soil-nailed structures with a vertical face in urban areas.

Execution Time

Execution time control was carried out for all the works, which made it possible to establish the production in square meters

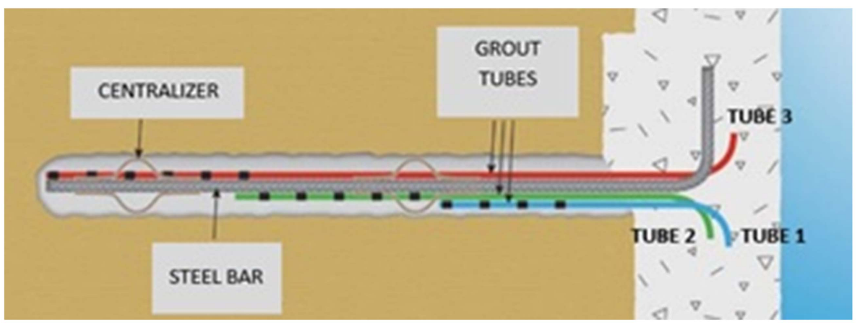

Fig. 7. Detail of re-injection system.

CONSTRUCTION SEQUENCE	SITES 22, 5, 6, 7, 8, 9, 12, 14 AND 15	SITES 1, 3, 10 AND 13	SITES 4 AND 11
DAY 1	NAIL (ANCHOR BORING)	NAIL (ANCHOR BORING)	NAIL (ANCHOR BORING)
DAY 2	1st + 2nd INJECTION	1st + 2nd INJECTION	1st + 2nd + 3rd INJECTION + SHOTCRETE
DAY 3	3rd INJECTION + SHOTCRETE	3rd INJECTION + SHOTCRETE	NEW EXCAVATION
DAY 4	CURING	NEW EXCAVATION	
DAY 5	NEW EXCAVATION		

Fig. 8. Execution sequence.

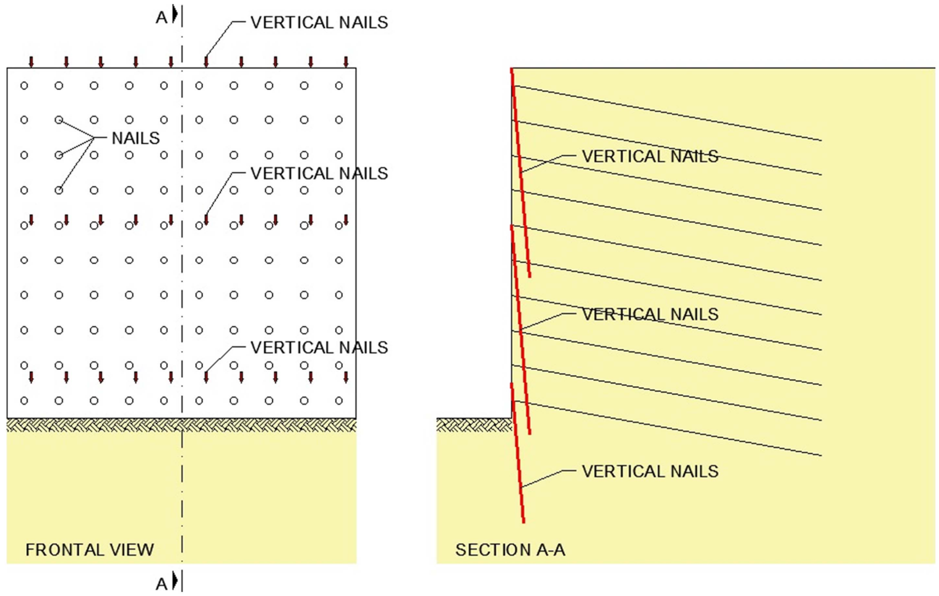

Fig. 9. Detail of vertical nails.

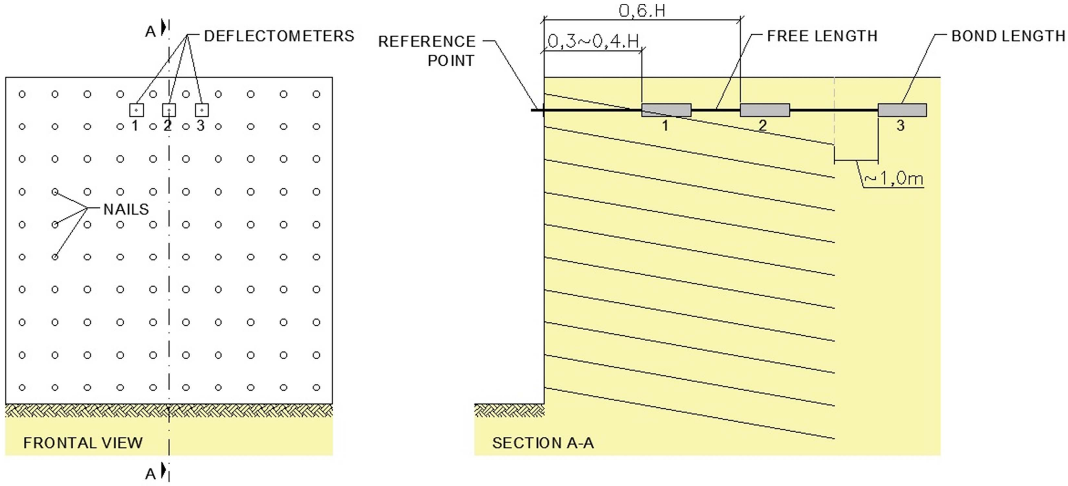

Fig. 10. Detail of displacement indicators.

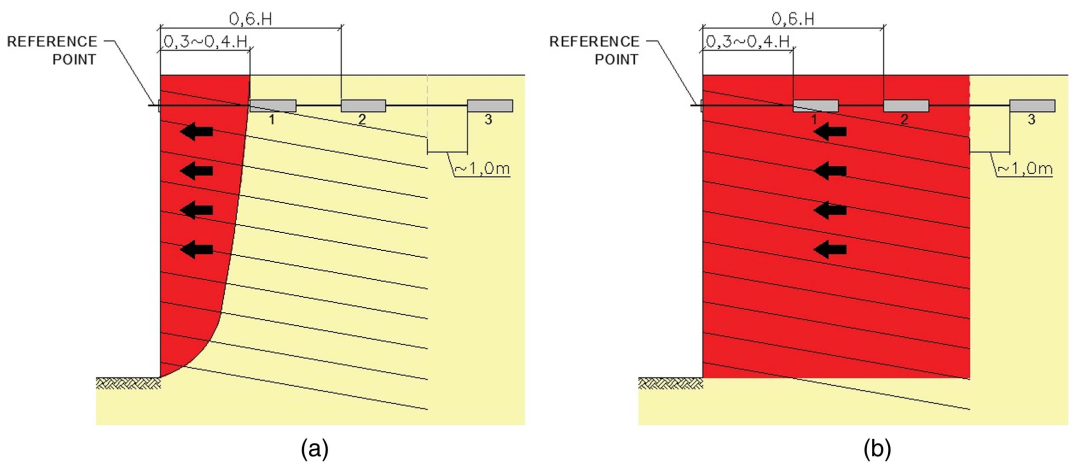

Fig. 11. (a) General observation; and (b) Work 11.

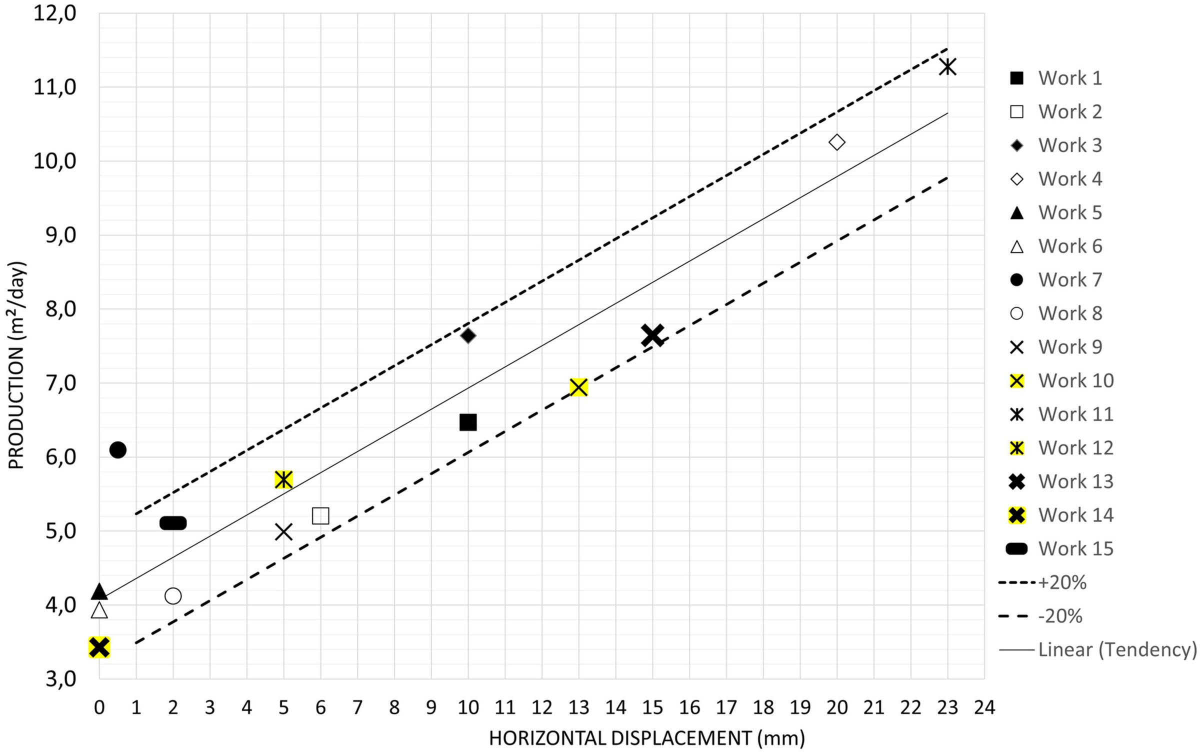

Fig. 12. Horizontal displacement versus daily production.

per day. There was a linear increase in horizontal displacement with the increase in daily production (Fig. 12). Works with a larger construction perimeter enable the opening of simultaneous work fronts, allowing for a reduced execution speed, with no labor cost per square meter, and also enabling less displacement.

It is possible to establish an equation that enables estimating horizontal displacements as a function of daily production, from a minimum 4.0 m^2/day production. The 20% variation in the trend line of the analyzed works is indicated, and good agreement with the results was noted. The coefficient of variation obtained was 36%; according to the OCDI (2009), this is classified as low but acceptable. Clouterre's (1991) proposal to estimate the displacement of soil nailing walls was based on the analysis of 5 instrumented works, linked to the type of soil and height of retainment, whereas in the present work the influence of the execution speed was incorporated in the concept based in 15 instrumented works

$$\delta_h = \frac{p - 4,0}{0,30} \quad (\pm 20\%)$$

δ_h = horizontal displacement (mm); and p = production (m^2/day).

In addition to predicting horizontal displacements, the equation allows the construction company and the project manager to estimate the execution deadline and link it to the construction performance; based on this, they can prepare a joint action strategy in advance to obtain better results. They also can anticipate planning, being aware of the minimum execution period, avoiding the increase in execution speed to recover schedule delays.

Displacement Assessment

Figs. 13 and 14 show the estimated horizontal displacements as a function of the soil type and soil-nailed structure height according to Clouterre (1991) and FHWA (2015). In the case of fine-grained soils, which accounted for most of the works studied, the smallest displacements obtained were close to 1/3 ratio, a very significant result, proving the improvement of the technique compared with works carried out 30 years ago.

Because the displacement estimates proposed by Clouterre (1991) and FHWA (2015) take into account the retaining structure height, Works 9 and 13, which were the highest—22.7 and 16.0 m, respectively—had displacements of as much as 91 and 64 mm for clayey soils, and 45 and 32 mm for sandy soils, respectively. Contradicting the premises of the literature, which present 5- and 15-mm displacements; thus it is assumed that the higher the structure, the greater is the forecast error.

Comparing the displacements in Fig. 14, even with execution speed ranging between 3.4 and 11.3 m^2/day, all the results obtained at the end of the retaining structures execution were lower than the estimates in the literature; eight works had displacements of as much as 5 mm, three works had displacements of as much as 10 mm, two works had displacements of as much as 15 mm, one works had displacements of as much as 20 mm, and one works had displacements of as much as 23 mm, the latter of which was on landfill soil.

An equation for predicting displacements as a function of execution speed, height, and soil characteristics is suggested, from a minimum 4.0 m^2/day production

$$\delta_h = \frac{p - 4,0}{0,30} + 0,08 \cdot H \cdot s$$

where δ_h = horizontal displacement (mm); p = production (m^2/day); H = soil-nailed structure height; and s = soil type, where $s = 1.2$ for clays and silts and $s = 0.75$ for sandy soils.

Figs. 15 and 16 show the effect of execution speed on horizontal displacements for different retaining structure heights. The proposal

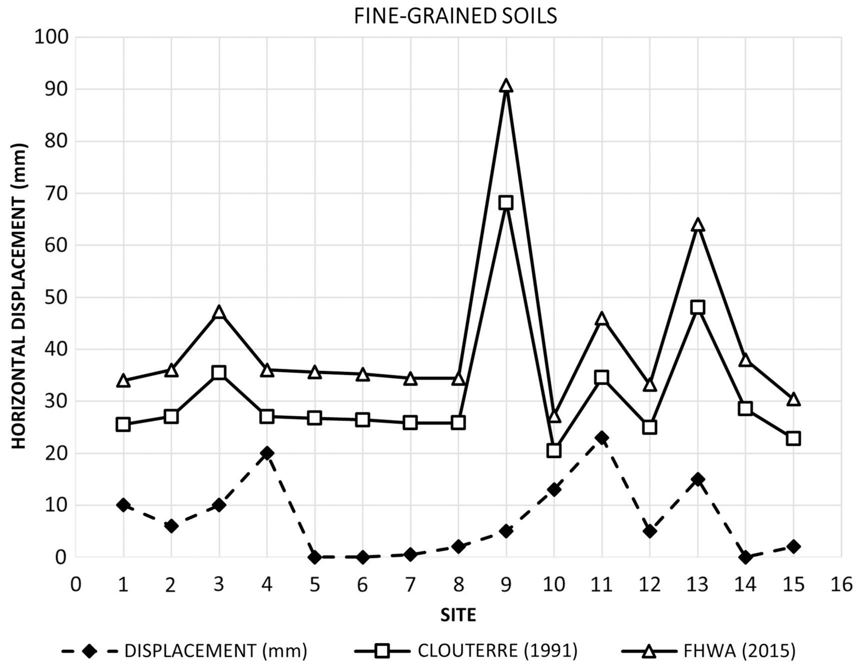

Fig. 13. Displacements in fine-grained soils.

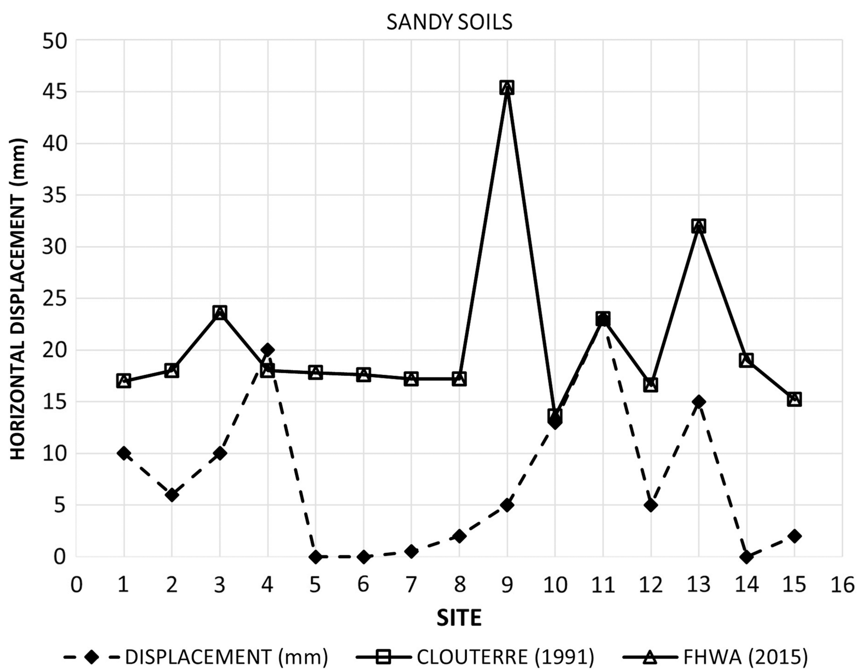

Fig. 14. Displacements in sandy soils.

refers to structures with vertical faces ranging from 3.0 to 24.0 m high.

In the set of 15 works analyzed, 9 works were between 8.5 and 9.5 m high, observing the interval between the heights of 9.0 to 12.0 m in Fig. 15, it appears that 7 works fit close to this variation, which represents a reasonable agreement for these structures. For sandy soils, the adjustment was checked based on the variation of displacements in Fig. 14, and it was determined that in granular soils the same displacements allowed higher structures.

Analysis with Historical Cases

Comparing the horizontal displacements measured in the 15 works with the results of historical cases, it was found that 11 works had displacements less than $H/1{,}000$, 1 work had a result slightly above $H/1{,}000$, and 3 works had results close to $2H/1{,}000$ (Fig. 17).

The work that had displacements just over $H/1{,}000$ (Work 1) and the works with displacements of $2H/1{,}000$ (Works 4, 10, and 11) had the highest execution speed, with production greater

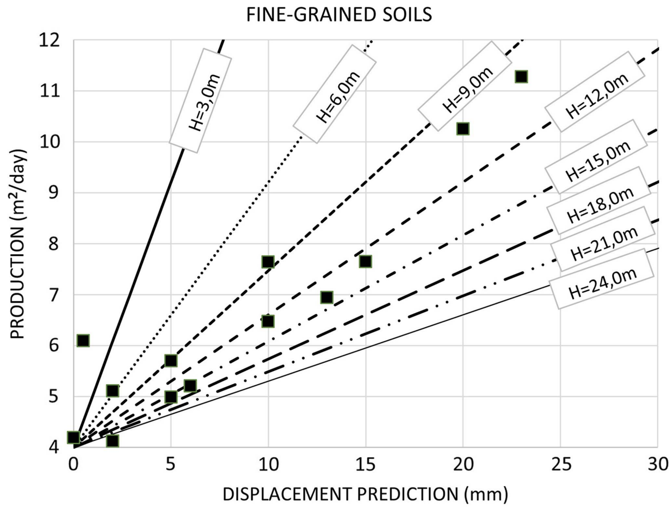

Fig. 15. Effect of height on fine-grained soils.

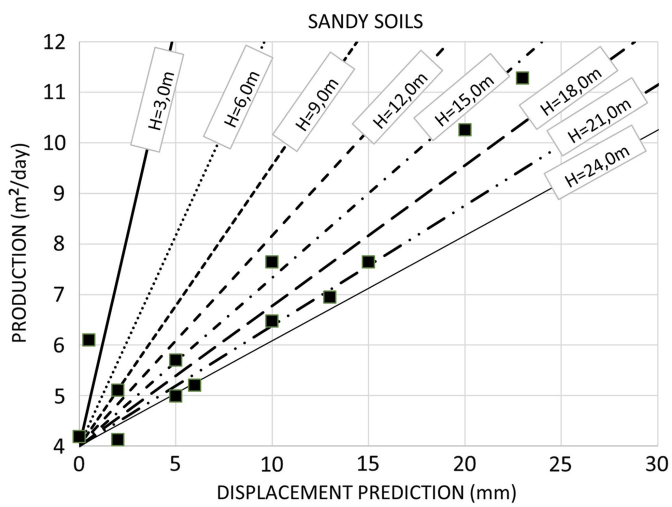

Fig. 16. Effect of height on sandy soils.

than 7.5 m^2/day, and construction sequence each 3 days for Works 4 and 11, and each 4 days for Works 1 and 10 as shown in Fig. 8.

The comparison of the works carried out in the Metropolitan Region of São Paulo shows that the execution speed interferes with the horizontal face displacements, and the beneficial impact of using a system of grout reinjection to cover the nails, and of using vertical nails to mitigate the displacement.

Conclusions

- The variation of the construction sequence showed the influence of execution speed on soil-nailed structure face displacement. The opening interval of new work fronts in 3, 4, and 5 days resulted in significant differences, with displacements ranging from 20 to 23 mm, from 10 to 15 mm, and from 0 to 6 mm, respectively.
- To comply with the proposed estimates, the following design characteristics must be taken into account: vertical face, mesh of nails sized 1.0×1.0 m (with 15% acceptable variation), the nails must be prepared with sectored reinjection phases, and the stability analyses must satisfy the limit equilibrium methods.
- The execution speed of the soil-nailed structures and the displacements also are related to the curing of the cement slurry of the nails and the shotcrete of the face. The cement characteristic must be evaluated and considered to define the opening speed of the new excavation fronts.
- Works with larger construction perimeters benefit when a construction sequence with lower excavation speed is applied, because it allows the simultaneous opening of more excavation fronts; on the other hand, works with smaller construction perimeters deal with two situations: the first is related to productivity, that is, low productivity increases the labor cost; the second is an increase in the execution speed, which increases face displacement. Execution speed between 10 and 15 m^2/day (approximately 220–300 $m^2/month$) usually is the pace established by construction companies to ensure a competitive labor cost per square meter.
- The works carried out in the RMSP generally were less displaceable than was assumed in the literature, whether for clayey or sandy soils, which shows the importance of a more careful assessment of displacements so as not to make the construction methodology unfeasible before analyzing the influence of execution speed.
- This paper proposes an adaptation of the horizontal displacement estimates proposed by Clouterre (1991) and FHWA (2015) from the analysis of works carried out in the RMSP. The equation incorporates the influence of execution speed, a factor that

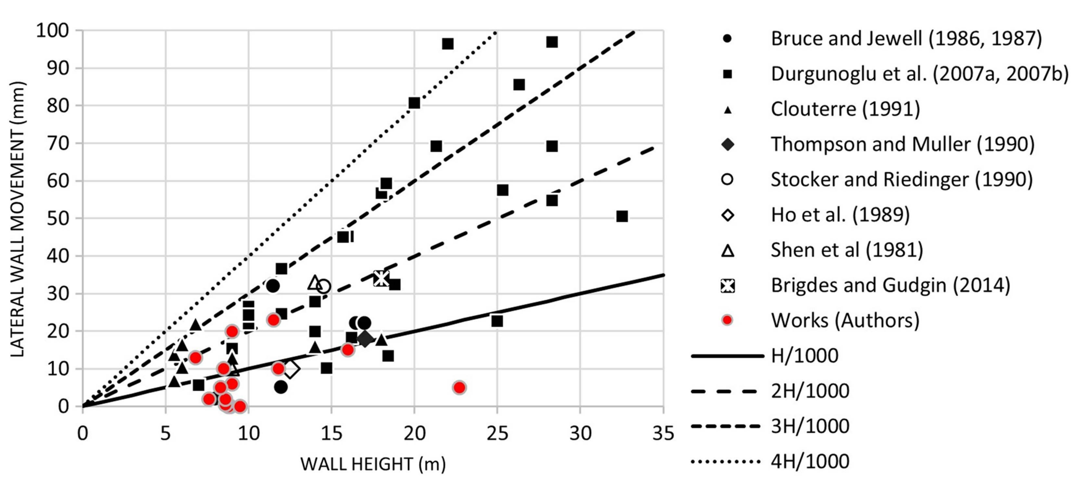

Fig. 17. Comparison of results obtained with historical cases.

greatly affects displacements, which was the main target of this study. In addition to forecasting displacements, the new proposal supports the estimation of deadlines and costs for works, which are crucial aspects for decision-making regarding the application of the soil nailing technique.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

References

AFNOR (Association Française de Normalisation). 2009. *Norme Fançaise—Calcul géotechnique—Ouvrages de soutènement—Remblais renforcés et massifs en sol cloué*. NF-P94-270. Paris: AFNOR.

Azzam, W. R., and A. Basha. 2017. "Utilization of soil nailing technique to increase shear strength of cohesive soil and reduce settlement." *J. Rock Mech. Geotech. Eng.* 9 (6): 1104–1111. https://doi.org/10.1016/j.jrmge.2017.05.009.

Bridges, C., and J. Gudgin. 2014. "A soil-nailed excavation for the Brisbane Airport Link project, Australia." *Proc. Inst. Civ. Eng. Geotech. Eng.* 167 (2): 205–216. https://doi.org/10.1680/geng.13.00040.

Bruce, D. A., and R. Jewell. 1986. "Soil nailing: Application and practice—Part 1." *Ground Eng.* 19 (8): 10–15.

Bruce, D. A., and R. A. Jewell. 1987. "Soil nailing: Application and practice—Part 2." *Ground Eng.* 24 (4): 21–33.

BSI (British Standards Institution). 2011. *Code of practice for strengthened/reinforced soils: Part 2: Soil nail design*. BS 8006-2:2011. London: BSI.

Chen, Z., M. Que, L. Zheng, X. Li, and Y. Sun. 2020. "Effect of mortar constraint conditions on pullout behavior of GFRP soil nails." *Adv. Mater. Sci. Eng.* 2020: 11. https://doi.org/10.1155/2020/4170363.

Clough, G. W., and T. D. O'Rourke. 1990. "Construction induced movements of in situ walls." In *Proc., Conf. on the Design and Performance of Retaining Structures*, 439–470. Reston, VA: ASCE.

Clouterre. 1991. *Recommendations CLOUTERRE 1991, soil nailing recommendations—1991 for designing, calculating, constructing, and inspecting earth support systems using soil nailing*. Washington, DC: Federal Highway Administration.

Corte, F. H., A. S. Mucheti, and P. J. R. Albuquerque. 2016. "Modelagem Numérica de Contenção em Solo Grampeado em Área Urbana, Um Caso de Obra." In *Proc., 18th Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica*. Chicago: American Board of Medical Specialties.

Durgunoglu, H. T., H. B. Keskin, H. F. Kulac, S. Ikiz, and T. Karadayilar. 2007a. "Performance of soil nailed walls based on case studies." In *Proc., 14th European Conf. on Soil Mechanics and Geotechnical Engineering*, 557–564. London: International Society for Soil Mechanics and Geotechnical Engineering.

Durgunoglu, H. T., H. B. Keskin, H. F. Kulac, S. Ikiz, and T. Karadayilar. 2007b. "Performance of very deep temporary soil nailed walls in Istanbul." In *Proc., TC17 Ground Improvement Workshop, XIV Conf. of the Int. Society for Soil Mechanics and Geotechnical Engineering*, 1–16. London: International Society for Soil Mechanics and Geotechnical Engineering.

Fan, C.-C., and J.-H. Luo. 2008. "Numerical study on the optimum layout of soil-nailed slopes." *Comput. Geotech.* 35 (4): 585–599. https://doi.org/10.1016/j.compgeo.2007.09.002.

Farokhzad, F., M. J. Shabani, and A. Hasanpou. 2020. "Investigating stabilized excavations using soil nailing method in urban context." *J. Rehabil. Civ. Eng.* 8 (2): 126–138. https://doi.org/10.22075/JRCE.2019.10841.1175.

FHWA (Federal Highway Administration). 2015. "Soil nail walls reference manual." Accessed April 8, 2022. https://www.fhwa.dot.gov/engineering/geotech/pubs/nhi14007.pdf.

Gassler, G., and G. Gudehus. 1981. Soil nailing—Some aspects of a new technique." In Vol. 3 of *Proc., 10th Int. Conf. of Soil Mechanics and Geotechnical Engineering*, 665–670. London: International Society for Soil Mechanics and Geotechnical Engineering.

Gässler, G. 1978. Large scale dynamic test of in situ reinforced earth." In *Proc., Dynamical Methods in Soil and Rock Mechanics*, 333–342. Rotterdam, Netherlands: A.A. Balkema.

Ho, C. L., H. P. Ludwig, R. J. Fragazy, and K. R. Chapman. 1989. "Field performance of a soil nail system in loess." In *Foundation engineering: Current principles and practices*, 1281–1292. Reston, VA: ASCE.

Kim, Y., S. Lee, S. Jeong, and J. Kim. 2013. "The effect of pressure-grouted soil nails on the stability of weathered soil slopes." *Comput. Geotech.* 49 (Apr): 253–263. https://doi.org/10.1016/j.compgeo.2012.12.003.

Moayed, R. Z., M. Hosseinali, S. M. Shirkhorshidi, and J. Sheibani. 2019. "Experimental investigation and constitutive modeling of grout–sand interface." *Int. J. Geomech.* 19 (5): 04019024. https://doi.org/10.1061/(asce)gm.1943-5622.0001384.

Moradi, M., A. Pooresmaeili Babaki, and M. Sabermahani. 2020. "Effect of nail arrangement on the behavior of convex corner soil-nailed walls." *J. Geotech. Geoenviron. Eng.* 146 (5): 1–12. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002235.

Mucheti, A. M., P. J. R. Albuquerque, and J. R. Garcia. 2019. "Contribuição de Grampos Verticais Injetados na Estabilidade e Deslocamentos de Obras de Solo Grampeado." In *Proc., 9o Seminário de Engenharia de Fundações Especiais e Geotecnia*. São Paulo: ABEF—Associação Brasileira de Empresas de Engenharia de Fundações e Geotecnia.

Negro, A., M. Namba, A. S. Dyminski, V. L. Sanches, and A. C. M. Kormann. 2012. *Twin Cities: Solos das Regiões Metropolitanas de São Paulo e Curitiba*. São Paulo: D'Livros.

Nordic Geosynthetic Group. 2005. "Nordic guidelines for reinforced soils and fills (revision B)." Accessed April 8, 2022. https://sgy.fi/wp-content/uploads/2017/04/nordic-guidelines-for-reinforced-soil-anf-fill.pdf.

OCDI (Overseas Coastal Development Institute). 2009. "The overseas coastal area development Institute of Japan, index." In *Technical standards and commentaries for port and harbour facilities in Japan*. Tokyo: OCDI.

Sabermahani, M., F. Ahimoghadam, and V. Ghalehnovi. 2018. "Effect of surcharge magnitude on soil-nailed wall behaviour in a geotechnical centrifuge." *Int. J. Phys. Modell. Geotech.* 18 (5): 225–239. https://doi.org/10.1680/jphmg.16.00022.

Seo, H.-J., L. Pelecanos, Y.-S. Kwon, and I.-M. Lee. 2017. "Net load–displacement estimation in soil-nail pullout tests." *Proc. Inst. Civ. Eng. Geotech. Eng.* 170 (6): 534–547. https://doi.org/10.1680/jgeen.16.00185.

Shahraki Ghadimi, A., A. Ghanbari, M. Sabermahani, and M. Yazdani. 2017. "Effect of soil type on nail pull-out resistance." *Proc. Inst. Civ. Eng. Ground Improv.* 170 (2): 81–88. https://doi.org/10.1680/jgrim.15.00038.

Stocker, M. F., and G. Reidinger. 1990. "Bearing behaviour of nailed retaining structures." In *Proc., Conf. on the Design and Performance of Earth Retaining Structures*, 612–628. Reston, VA: ASCE.

Thompson, S. R., and I. R. Miller. 1990." Design, construction and performance of a soil nailed wall in Seattle." In *Design and Performance of Earth Retaining Structures*, Geotechnical Special Publication 25, edited by P. Lambe. Reston, VA: ASCE.

Tokhi, H., G. Ren, and J. Li. 2018. "Laboratory pullout resistance of a new screw soil nail in residual soil." *Can. Geotech. J.* 55 (5): 609–619. https://doi.org/10.1139/cgj-2017-0048.

Wang, B., X. Jiang, and Q. Liu. 2020. "Study on the supporting features of composite soil nailing wall." In Vol. 455 of *Proc., IOP Conf. Series: Earth and Environmental Science*, 12111. Bristol, UK: IOP Publishing. https://doi.org/10.1088/1755-1315/455/1/012111.

Zad, A. A., and M. M. Hejr. 2019. "Investigation of corner effects of deep excavations using the combination of soil nailing ANG ground-anchors

J. Constr. Eng. Manage., 2022, 148(7): 04022048

methods." In *Proc., 13th Australia New Zealand Conf. on Geomechanics*, 536–537. St. Ives, NSW, Australia: Australian Geomechanics Society. https://doi.org/10.1007/978-3-319-73568-9_174.

Zamiran, S., H. Ghojavand, and H. Saba. 2012. "Numerical analysis of soil nail walls under seismic condition in 3D form excavations." *Appl. Mech. Mater*. 204–208 (Oct): 2671–2676. https://doi.org/10.4028/www.scientific.net/AMM.204-208.2671.

Zhang, L. L., L. M. Zhang, and W. H. Tang. 2009. "Uncertainties of field pullout resistance of soil nails." *J. Geotech. Geoenviron. Eng*. 135 (7): 966–972. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000014.