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PSEUDO-STATIC ANALYSIS OF SEISMIC PERFORMANCE OF GEOGRID-REINFORCED PILE FOUNDATION

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ABSTRACT

This paper presents the finite-element (FE) analysis for simulating the performance of a geogrid-reinforced pile foundation system subjected to pseudo-static lateral loads. The FE models were constructed using commercial FE program Plaxis 3D. The FE models were verified against the results of reduced scale physical model tests of a geogrid-reinforced pile foundation system. The calibrated numerical models were then used to conduct a parametric study to investigate the behavior of proposed system. These parameters included the stiffness and the location of the geogrid reinforcement within the granular backfill surrounding the pile foundation as well as the thickness of the granular layer itself. The results indicated that the geogrid-reinforcement reduced the maximum lateral response of the pile foundation significantly. The inclusion of a geogrid layer resulted in reduction of foundation lateral deflections as much as 50% relative to the response in native soil stratigraphy. The amount of reduction in the quantity of engineered backfill was in the order of 67%. Overall, the results indicated that the proposed foundation reinforcement system can be easily implemented and cost effective alternative to the conventional methods that are used to enhance the lateral behavior of foundations.

1. INTRODUCTION AND PROBLEM OVERVIEW

Geogrids are made of polymeric material comprising tensile ribs with openings of sufficient size to allow interlocking with the surrounding soil. This geogrid-soil interlocking mechanism and the tensile strength allow geogrids to work as a reinforcement element, taking over a part of soil stresses. The geogrid mesh embedded within the aggregate engineered fill increases modulus and lateral confinement for the crushed stones interlocked within the apertures of the geogrid. Thus, geosynthetics is widely used in modern construction technology. In several geotechnical engineering applications, geogrids have been widely implemented to reduce lateral wall deflections arising from dynamic loads and uneven settlement of the supporting sub grades and embankments.

Earthquake loads are among the most destructive dynamic loads which have attracted major concerns in the construction industry. Therefore, several researches investigated the use of geogrid-reinforced soils to enhance the seismic resistance of geotechnical structures. These studies include: Bathurst and Alfaro (1996); Cai and Bathurst (1995); Michalowski (1998); Helwany et al. (2001); Ling et al. (2004); Burke et al. (2004); Liu (2009); El-Emam and Bathurst (2007); and Fakharian and Attar (2007). These studies collectively demonstrated the superior performance of geogrid-reinforced walls to resist lateral dynamic loading and provided verified finite element numerical models to analyze their dynamic behavior.

In parallel, several researchers investigated the seismic pile-soil interaction problem through experimental and numerical studies. For example, Yegian and Wright (1973), Angelides and Roesset (1980), Randolph (1981), Faruque and Desai (1982), Trochanis at al. (1988, 1991) Wu and Finn (1997), and Bentley and El Naggar (2000) developed finite element models to analyze the dynamic response of piles. These researches proved that the finite element (FE) method is a powerful tool for analyzing the soil-pile-structure interaction problem.

This paper presents FE analysis for simulating the seismic performance of geogrid-reinforced pile foundation system. FE models were established using the program Plaxis 3D (Brinkgreve et al., 2012). The numerical models were verified against shaking table test results of a model scale geosynthetics-reinforced pile foundation system as described in (Taha et al., 2015). A parametric study was carried out to evaluate the performance of the proposed geogrid-strengthened piled foundation system considering the typical seismic design loads stipulated by the National Building Code of Canada (NBCC, 2010). The objective of the parametric study is to optimize the ground replacement effort (i.e. thickness of engineered backfill).The seismic loading is given by the pseudo-static inertial force generated for 20 m high (6 stories) reinforced concrete building. The parametric study investigates the effects of geogrid depth and tensile stiffness on the lateral pile deflection. The soil profile considered in this study was modified to reflect a practical case of an engineered backfill and a week native soil layer.

2. BUILDING, PILE CAP MODEL AND GEOGRID

The geosynthetics-reinforced pile foundation system is assumed to support a multistory building located in Vancouver, BC. The total building height is 20.0 m covering an area of 22.5 m X 22.5 m. The building is supported on a raft 0.5 m thick and supported by 100 steel piles spaced at 2.5 m centre-to-centre. The piles were 12 m long, 0.5 m in diameter and had 9.5 mm wall thickness. The pile raft was supported on the soil surface over an interface mesh which allows maximum free translation in the direction of loading. For the purpose of reducing the analysis time, only an area of 4 m X 4 m within the core of the building was modeled. The core of the building was assumed to support part of the lateral seismic load through two shear walls in the direction of the seismic loading. Therefore, only one pile group (2X2) was considered in the analysis.

The soil model boundary and geogrid width were extended 4.5 and 4.5 m in the lateral direction beyond the line of symmetry. The piles, pile cap, and soil finite element mesh characteristics and model were all similar to the ones presented in the (Taha et al., 2015) prototype dynamic study. Figures 1 and 2 show the vertical shear walls, pile cap and geogrid layout plus the soil profile in 2D and 3D views.

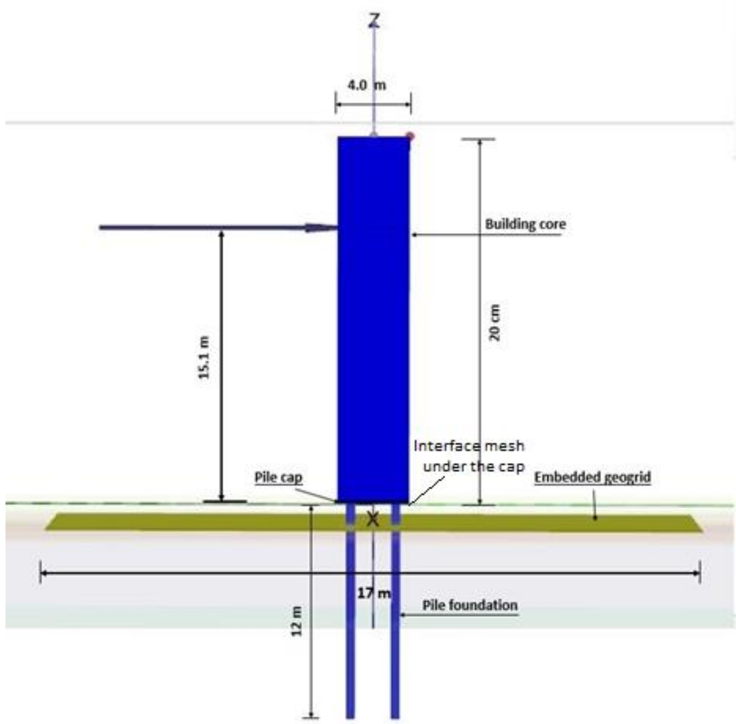

Figure 1: Pile, cap, geogrid and superstructure model

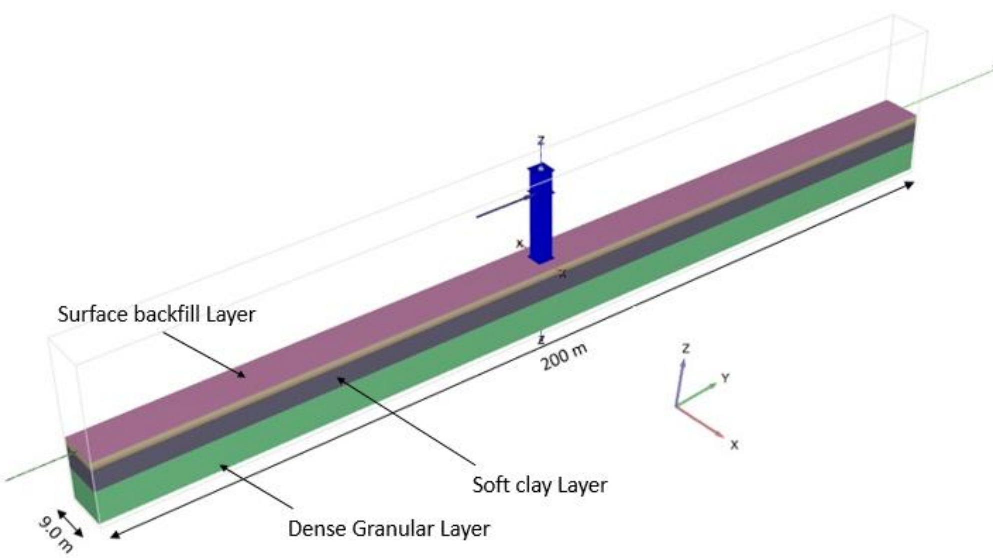

Figure 2: 3D Plaxis model of soil layering and building core

The method of analysis for the nonlinear soil model was similar to that adopted in (Taha et al., 2015) dynamic prototype study. However, for practical consideration, the shear wave velocity Vs of the backfill used in this study was increased to 300 m/s and a softer clay layer with Vs equals 113 m/s was used to simulate a weaker native soil. The nonlinear stress-strain behaviors of the soil layers were modeled using the Plaxis built-in Hardening Soil (HS) model with small strain stiffness (HSSMALL model).

The Plaxis (HSSMALL) model accounts for the stiffness degradation for different types of soils when subjected to primary deviatoric loading (Brinkgreve et al., 2012). The HSSMALL model uses the Hardin and Drenvich (1972) hyperbolic law to relate the shear modulus at large strains to small-strain properties. The Hardin and Drenvich (1972) hyperbolic law is formulated as:

$$\frac{G_s}{G_0} = \frac{1}{1 + \left|\frac{\gamma}{\gamma_r}\right|}$$

where the threshold strain γr is given by: $\gamma_r = \frac{\tau_{max}}{G_0}$

The model calibration details were discussed in Taha et al.(2015).

Table 1 summarizes the HSSMALL model parameters used in this investigation. The soil layers depths were modified so that the total depth of native clay layer is 6 m and the depth of the bedding layer is 13 m. The backfill layer replaced the native clay layer in three stages: 2, 4 and 6 m.

Table 1: HSSMALL Soil parameters of each soil layer adopted for the equivalent static study

Parameter	Symbol	Top Backfill layer	Interface Layer	Soft clay layer	Dense Granular layer
Soil unit weight (kN/m3)	γ	20	20	17	20
Shear wave velocity (m/s)	Vs	300	405	113	220
Secant stiffness in standard drained triaxial test (kN/m2)	E_{50}^{ref}	58.8 X 103	107 X 103	2.17 X 103	31.6 X 103
Tangent stiffness for primary oedometer loading (kN/m2)	E_{oed}^{ref}	47.0 X 103	85.7 X 103	1.74 X 103	25.3 X 103
Unloading/reloading stiffness (kN/m2)	E_{ur}^{ref}	176.0X 103	321.0 X 103	6.51 X 103	94.8 X 103
Power for stress-level	m	1	1	1	1
Cohesion	c'_{ref}	5	5	5	NA
Friction angle	φ	40	40	25	40
Reference shear modulus at small strains (kN/m2)	G_0^{ref}	184.0 X103	335.0 X103	22.1X103	98.8X103
Poisson's ratio	ν'_{ur}	0.2	0.2	0.2	0.2

There were two types of geosynthetics considered in the pseudo-static analysis. The first is the polymer strips with stiffness of 44,000 kN/m. The second is a conventional geogrid with a stiffness of 2900 kN/m at 2% strain. The geogrid layers were embedded in the backfill layer under the pile cap as shown in figure 1 and 3. The goegrid elements were connected to the pile shell elements and the soil tetrahedron elements and share the translational degrees of freedom at the connecting nodes as shown in Figure 3.

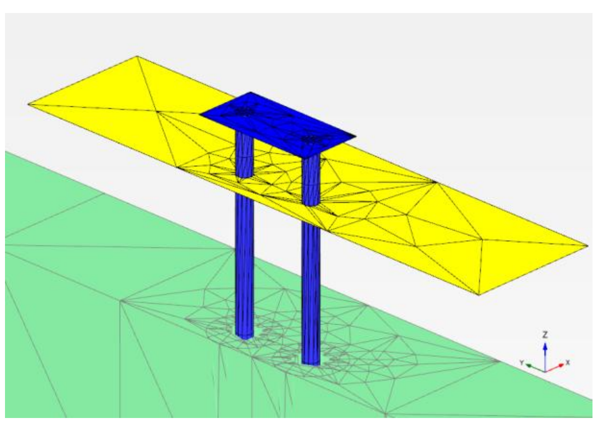

Figure 3: Pile-Cap–geogrid finite element mesh.

The conventional geogrid stiffness was taken from the technical data sheet of TMP Geosyenthetics – Uniaxial Geogrid GG200PE. Table 2 shows the specification of the conventional geogrid.

Table 2 : Uniaxial Geogrid GG200PE specifications

Index Properties	Test Method	Units	MD Value
Polymer	-	-	HDPE
Minimum Carbon Black	ASTM D 4218	%	2
Tensile Strength @ 2% Strain	ASTM D 6637	kN/m (lb/ft)	58 (3.970)
Tensile Strength @ 5% Strain	ASTM D 6637	kN/m (lb/ft)	116 (7,950)
Ultimate Tensile Strength	ASTM D 6637	kN/m (lb/ft)	200(13,700)
Strain @ Ultimate Strength	ASTM D 6637	kN/m (lb/ft)	11.5
Junction Efficiency	GRO GG2-87	kN/m (lb/ft)	90

3. PSEUDO-STATIC SEISMIC LATERAL LOADING CALCULATION

The equivalent seismic base shear has been calculated as per the NBCC (2010) provisions. The site was assumed to be located in Vancouver area with soft soil and site Class E classification (NBCC 2010, Table 4.1.8.4.A). The strength level design base shear is given by:

$$V = \frac{S(T_a)\, M_v\, I_E}{R_d R_0}\, W \qquad \text{(NBCC 4.1.8.11)}$$

Where

- The Fundamental period of the structure in seconds Ta = 0.05 (hn)3/4 = 0.5 sec (Cl.4.1.8.11.3(c)).
- For Vancouver, Canada, the 5% damped spectral response acceleration ratios, Sa(T), are provided in Table-C2 of NBCC2010 and shown her in Table 3 :

Table 3 : Spectral response acceleration at Vancouver Area

Sa(0.2)	Sa(0.5)	Sa(1.0)	Sa(2.0)	PGA
0.95	0.65	0.34	0.17	0.47

- The design spectral acceleration value S(T):

  From Table 4.1.8.4.b, the value of acceleration-based site coefficient, Fa = 0.9.

  From Table 4.1.8.4.c, the value of velocity-based site coefficient, Fv = 1.8.

  For T=0.5 sec, S(T) = Fv . Sa(0.5) or S(T) = Fa. Sa(0.2), Smallest S(T) = 0.855.

  Therefore, for T=0.5 sec, S(T) = 0.855

- From Table 4.1.8.11, Sa(0.2)/Sa(2.0) = 0.95/0.17 = 5.6 < 8.0, Therefore higher mode factor Mv = 1.0.
- The seismic importance factor was set at 1.5.
- From Table 4.1.8.9, and considering the building has limited ductility shear walls, Rd = 1.5, Ro = 1.5.
- Seismic dead load W = 15220 kN.
- Total lateral seismic force is obtained from the Eq (NBCC 4.1.8.11): V= 8726.13 kN

The calculated base shear force was applied at the vertical centroid of the distributed lateral floor forces. The vertical centroid was calculated from the division of the total seismic overturning moment by the total base shear. Table 4 shows the distribution of the lateral earthquake forces Fi and determines the total overturning moment and the vertical centroid.

Table 4: Equivalent static forces and overturning moment calculation

Floor height	W(kN)	wiXhi	LTFi*(kN)	LFi**(kN)	OM***(KN.m)
20	3961.25	79225.00	3546.41	141.85	0
15	3961.25	59418.75	2659.80	106.39	709.28
10	3961.25	39612.50	1773.20	70.92	1950.52
5	3336.25	16681.25	746.72	29.87	3546.40
Total	15220.00	194937.50	8726.13	349.05	5291.63

* Total lateral force over 100 piles

**Lateral force over 4 piles

***Overturning moment over 4 piles

The vertical centroid = 5291.63/349 = 15.16 m

4. SUMMARY OF NUMERICAL PSEUDO-STATIC ANALYSES

This section describes the cases investigated in this parametric study. The equivalent static load was applied to the model geogrid-strengthened foundation system considering various soil profiles and different configurations for the geosynthetics reinforcement including: embedment depth and tensile stiffness. Table 5 summarizes the different cases analyzed.

Table 5: Equivalent static analysis cases

Case No.	case description
1	Native soil, no backfill without geosynthetic reinforcement
2	2 m backfill without geosynthetic reinforcement
3	4.0 m backfill without geosynthetic reinforcement
4	6.0 m backfill without geosynthetic reinforcement
5	2.0 m backfill with one high tensile geogrid mesh placed at 1.0 m depth
6	2.0 m backfill with one high tensile geogrid mesh placed at 1.25 m depth
7	2.0 m backfill with two high tensile geogrid mesh placed at 1.0 and 1.5 m depth
8	2.0 m backfill with one polymer strips placed at 1.25 m depth

5. RESULTS AND DISCUSSION

The results of the parametric study are presented and discussed in this section. The results are discussed with respect to the effect of geosynthetic material tensile stiffness, depth and length on: the building maximum lateral displacement, pile head maximum deflection, pile maximum bending moment and pile maximum shear.

Table 6 provides the results of cases 1-8 with respect to building maximum lateral drift, pile head maximum deflection, pile maximum bending moment and pile maximum shear. Figures 4 shows the results in a bar chart.

Table 6: Cases 1-8 results comparison.

Case No.	Max pile cap vertical deflection (mm)	Max pile cap lateral deflection (mm)	Max pile bending moment (Nm/m)	Max pile shear (kN/m)
1	19.4	19.6	209	208.0
2	17.4	14.3	215.7	268.3
3	16.1	12.2	265.7	279.2
4	15	11.3	259.4	272.6
5	16	11	146	285
6	16.2	12	135	260
7	15.7	10.4	150.4	272.3
8	16.3	9.4	133.1	291

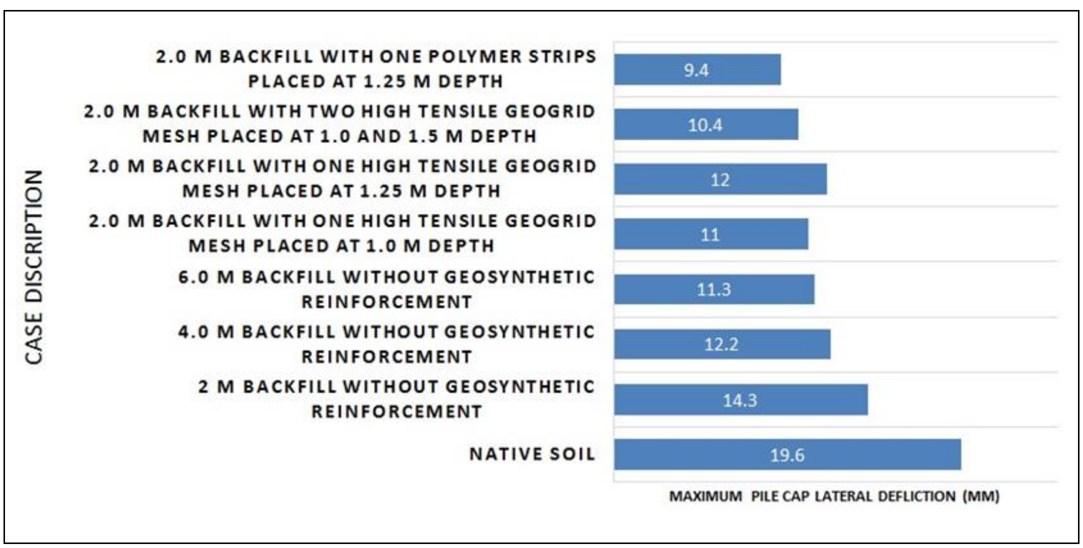

Figure 4: Parametric study results, pile cap lateral deflection (mm)

It can be noticed from the results of cases 1-3 that the pile cap lateral deflection decreases as the conventional backfill depth increases. Also, the results show that increasing the backfill induced higher bending moment and shear force in the piles.

Cases 4 and 5 compare the 6 m plain backfill results to the results of the 2 m backfill with high tensile geogrid embedded at 1.0 m depth. It can be noticed that embedding the high tensile geogrid at 1.0 depth within 2m of backfill resulted in the same performance as the case of 6m backfill, while reducing the bending moment of the piles by 44%. However, the shear force increased by 5 %. This comparison indicates that by using the geogrid, the backfill depth can be reduced by 67% while achieving the same reduction in the lateral displacement (i.e. 44 % reduction in lateral displacement).

The results of Cases 5 and 6 demonstrate the effect of the geogrid layers depth on the performance of geosynthetics-reinforced pile foundation system. It can be noticed that embedding the geogrid mesh at depth of 1.25 m has reduced the bending moment and shear forces while improving the serviceability of the foundation system. Case 6 demonstrates that by using the geogrid reinforcement, the backfill depth can be reduced by 67% (compared to Case 3) while achieving 39 % improvement in lateral pile foundation performance relative to the native soil case.

In addition, the comparison of Cases 6 and 7 indicates that the lateral performance of the foundation can be improved further by increasing the number of geogrid layers. Also, the comparison of Cases 1, 4 and 7 indicates that through using 2 layers of geogrid, the backfill depth can be reduced by 67% while achieving 47 % improvement in the lateral pile foundation performance and reducing the bending moment and shear forces in the piles.

Moreover, comparing Cases 4, 6 and 8 indicates that the lateral performance of the pile foundation with polymer strips embedded in 2 m backfill was better than that of the pile foundation system with 6.0 m backfill and the 2 m backfill enhanced with one geogrid layer. Using the polymer strips, the backfill depth can be reduced by 67 % while achieving 52 % improvement in the lateral pile foundation performance. In addition, using the polymer strips as reinforcement induced the least bending moment, but polymer strips induced bigger shear force in the piles. This behavior can be attributed to the large tensile stiffness of the polymer strips resulting in high lateral force at the pile shell nodes.

6. SUMMARY AND CONCLUSIONS

This paper presents the pseudo-static analysis of geogrid-reinforced pile foundation system. A numerical dynamic model of geogrid-reinforced pile foundation system was calibrated using the results of the experimental dynamic model. A parametric study was carried out to study the effect of the seismic inertial loading on the geogrid piled foundation system. The parametric study also evaluated the efficiency of pile foundation-geogrid against the performance of a conventional pile foundation with ground replacement (i.e. deep engineered backfill). The following conclusions may be drawn from the results:

The pseudo-static analysis showed that, as expected, the lateral performance of the pile foundation was improved as the thickness of the conventional backfill increased. However, increasing the backfill thickness induced higher bending moment and shear force in the piles.

The pseudo-static analysis indicated that the dynamic performance of the pile foundation when embedded in 6 meter engineered backfill is almost equivalent to the dynamic performance of the same piles embedded in 2m thick engineered backfill with the high tensile geogrid introduced at 1.0 m depth. This means that introducing the geogrid reinforcement can reduce the need for deep backfill by 67% while achieving the same improved dynamic performance (i.e. 44% reduction in lateral displacement and pile bending moment). However, the shear force in the piles increases by 5 %.

Embedding the geogrid mesh at a depth of 1.25 m, within 2m backfill, reduced the bending moment and shear forces of the piles while improving the performance of the foundation system (39 % reduction in lateral pile foundation displacement).

The lateral performance of the pile foundation can be improved further by adding another geogrid layer. It was found that using two layers of geogrid, the backfill thickness can be reduced by 67% while achieving 47 % reduction in lateral displacement of the pile foundation, and reduced bending moment and shear force in the piles.

The lateral performance of the pile foundation reinforced with polymer strips embedded in 2 m thick backfill was better than the performance of the pile foundation with 6m thick backfill and that with the 2 m backfill strengthened with one and two geogrid layers.

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