Pullout Characterization of Geogrids Embedded in Dredged Material and Steel Slag Fines (DM-SSF) Blends

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ABSTRACT: Dredging of river canals and waterways has resulted in increasing quantities of dredged material (DM) that require management, treatment and/or disposal. The soft, compressible DM could be used for earthwork, provided that concerns associated with comparatively low shear strength are adequately addressed. Blends of DM with granular materials such as steel slag fines (SSF) has been identified to result in mixes with geotechnical properties that are significantly enhanced. This may result in adequate fill material for use with geosynthetic reinforcement. In this paper, results from a large-scale pullout testing program are presented to characterize the interaction between blends of DM-SSF with commercially available geogrids. The testing program included testing of 100% DM and 100% SSF as well as blends with 80/20, 50/50 and 20/80 proportions (dry unit weights of DM reported first). The interaction between a fill material and geogrid is characterized based on its ultimate pullout strength, the ultimate displacement at pullout failure, and interaction parameters. Results show a high pullout performance with the 20/80 DM-SSF blend, with the quality of pullout interaction decreasing with increasing percentage of DM in the blend. The 50/50 and 80/20 DM-SSF media show considerably lower pullout resistance than the 20/80 DM-SSF blend, but still offered a significant improvement over the 100% DM. The results observed with the 20/80 DM-SSF blend are found to be particularly suitable as a cost-effective alternative in earthwork construction.

Keywords: geosynthetic reinforcements, dredged material, steel slag fines, pullout testing, soil-geosynthetic interaction

1 INTRODUCTION

Due to continuous dredging of river canals and navigation channels, the existing Containment Disposal Facilities (CDFs), where the Dredged Material (DM) has conventionally been placed after treatment, have often reached their capacities thereby increasing the need for alternate avenues for disposal. Use of DM as embankment/retaining wall fill material presents a potential cost-effective solution, but the soft, fine-grained DM may not exhibit favorable geotechnical properties that are required of typical backfill materials. However, the geotechnical properties of DM can be significantly enhanced on blending it with industrial by-products such as crushed glass (CG) and steel slag fines (SSF) (Grubb et al. 2006a,b; 2011; 2013; Malasavage et al. 2012). These byproducts may be locally available near major coastal ports and present cost-effective means to enhance the properties of the resulting blend materials. While the potential for beneficial use of these materials are promising, studies are needed to understand their mechanical behavior, including the evaluation of their performance as fill for with geosynthetic reinforcements.

Pullout tests are used to characterize the relevant interaction properties of the geosynthetic layer in reinforced soil structures such as mechanically stabilized retaining walls or reinforced slopes (e.g. Jewell et al., 1984; Palmeira and Milligan, 1989; Wilson-Fahmy et al., 1994; Teixeira et al., 2007). This study presents an evaluation of the performance of the DM-SSF blends in pullout tests with geogrid reinforcements. Pullout tests were conducted with individual DM and SSF materials and their 80/20, 50/50 and 20/80 blends (dry weight percentage of DM reported first). Monterey Sand was also used as a baseline control. Two commercially available uniaxial high density polyethylene (HDPE) geogrids were adopted as reinforcements and tested with all the fill materials at different normal pressures. In this paper, the ultimate pullout resistance and pullout force-displacement behavior observed for the blends was evaluated to assess the prospect for utilizing these blends in reinforced soil structures. Furthermore, aspects of the blend media-geogrid interaction that could have potentially influenced the observed pullout behavior were identified and discussed.

2 CHARACTERIZATION OF THE MATERIALS

2.1 *Fill Materials*

The granular nature of the SSF material makes it well suited for blending with the soft fine-grained DM. The geotechnical properties of the 100% DM, 100% SSF and their blends (80/20, 60/40, 50/50, 40/60 and 20/80) have been reported by Grubb et al. (2011; 2013) and Malasavage et al. (2012). As expected, the specific gravity, loss on ignition, water content, and plasticity index for the blends are influenced by the DM content (Table 1).

Table 1: Properties of various DM-SSF blends (Malasavage et al. 2012)

		Specific gravity	Water content	Loss on ignition	Particle size			Plasticity indices[b]			USCS	AASHTO
		D854 (2002)	D2974 (2000b)	D2974 (2000b)	D422 (1998)			D4318 (2005)				
Media tested[a]		(-)	(%)	(%)	(% gravel)	(% sand)	(% fines)	LL	PL	PI	D2487	D3284
Dredged material (DM)		2.58	122.8	11.76	0.0	1.2	98.8	140	38	102	OH	A-7-6
Blends	80/20 DM-SSF	2.87	106.6	10.10	1.1	15.5	83.4	132	49	83	OH	A-7-6
	60/40 DM-SSF	2.92	76.3	6.87	9.1	29.2	61.7	134	45	89	OH	A-7-6
	50/50 DM-SSF	3.06	67.5	6.80	10.3	41.4	48.3	108	41	67	SM	A-7-6
	40/60 DM-SSF	3.10	59.5	7.89	14.3	43.0	42.7	96	38	58	SM	A-7-6
	20/80 DM-SSF	3.28	32.9	5.94	15.5	62.7	21.7	74	37	37	SM	A-2-7
Steel slag fines (SSF)		3.45	6.95	4.36	35.6	61.1	3.4	NP	NP	NP	SW	A-3

Note: ASTM designations shown where relevant.

[a]Blend nomenclature shows DM content first, dry unit weight % basis.

[b]LL=liquid limit; PL=plastic limit; PI=plasticity index.

The grain size distributions for all DM-SSF blends, adapted from Grubb et al. (2011), are presented in Figure 1. According to the modified proctor test results, the maximum dry unit weight (γ_{dmax}) was found to be approximately 23.6 kPa (150 pcf) and 14.2 kPa (90 pcf) for the 100% SSF and 100% DM materials, respectively. On the other hand, the optimum water content varied from approximately 10% for the 100% SSF to 30% for the 100% DM materials.

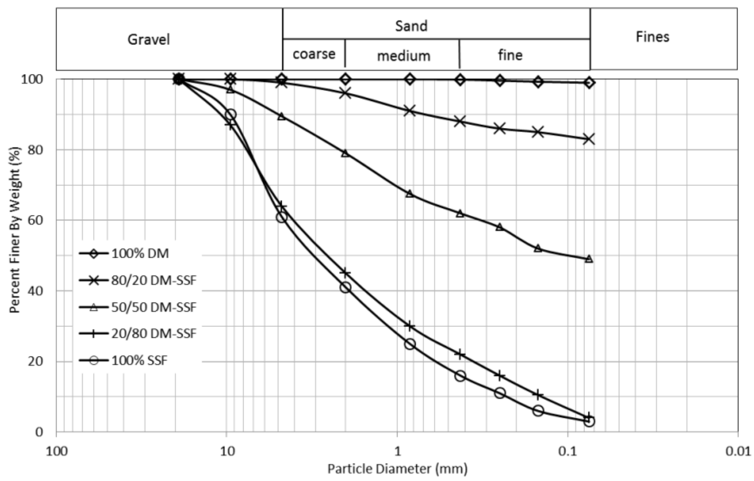

Figure 1: Grain Size Distributions for DM, SSF, DM-SSF blends (Grubb et al., 2011)

In this study, direct shear tests were conducted in accordance to ASTM D 3080-11 to identify the shear strength parameters for Monterey Sand, DM, SSF and DM-SSF blends. Testing conditions including the moisture contents, relative compaction of the specimens, and normal pressures adopted to replicate the test conditions in the pullout tests. The direct shear box used for testing was 75x75 mm in area and accommodated a 35-mm thick soil specimen. All sample material were first sieved through a 4.75 mm opening-size sieve (No.4) to remove the bigger particles, and thereby avoid boundary effects with the side walls of the shear box. Testing conditions involved a shearing rate of 0.5 mm/min under normal stresses of 7, 28, 41 and 55 kPa (1, 4, 6 and 8 psi) for each specimen. Table 2 presents the soil conditioning and the results obtained using direct shear tests conducted for Monterey Sand, DM, SSF and DM-SSF blends.

The 100% SSF and 100% DM materials had friction angles (ϕ) of 40.8° and 31.7°, respectively. The largest friction angle was found to be ϕ=46.7 for the 50/50 DM-SSF blend, while the 20/80 DM-SSF blend showed a ϕ value of 41.1°. The Mohr-Coulomb shear strength failure envelopes for all materials are presented in Figure 2. The high shear strength obtained for the 50/50 blend is probably due to more efficient packing arrangement, with the finer DM particles occupying spaces in between the larger SSF particles, resulting in a greater interlocking between particles. However, it should be noted that all direct shear testing soil samples were sieved to remove particles > 4.75 mm in diameter. This could potentially impact the shear strengths parameters of the blends, especially in the granular-sized SSF particles.

Table 2: Material properties and the results of the direct shear tests

Materials	Configuration of Direct Shear Test			Maximum Dry Unit Weight		Relative Compaction/Density		Direct Shear Test Results	
	Water Content	Dry unit weight	Total unit weight	Malasavage et al. (2012) (Laboratory Data)	Malasavage et al. (2012) (Field Data)	Based on ($\gamma_{dmax\text{-}lab}$)	Based on ($\gamma_{dmax\text{ - }field}$)	D3080 (2011)	
	(w) (%)	(γ_d) (kN/m^3)	(γ) (kN/m^3)	($\gamma_{dmax\text{-}lab}$) (kN/m^3)	($\gamma_{dmax\text{ - }field}$) (kN/m^3)	%	%	c (kN/m^2)	ϕ (deg)
Dredged material (DM)	40.6	10.7	15.0	13.4	13.4	80	80	32.3	31.7
Blends									
80/20 DM-SSF	31.0	13.1	17.2	14.6	16.2	89	81	50.5	36.5
50/50 DM-SSF	26.4	14.6	18.5	16.5	18.3	88	80	68.2	46.7
20/80 DM-SSF	15.3	16.9	19.4	20.1	21.1	84	80	35.1	41.1
Steel slag fines (SSF)	9.1	19.1	20.9	23.3	24.7	82	77	29.3	40.8
Monterey Sand	1.5	16.3	16.5	-	-	80	-	0	39.0

2.2 Geogrid Properties

The geogrids used as reinforcements in this study include two HDPE uniaxial geogrids, referred to as GG1 and GG2. Physical and mechanical properties of the two geogrids are reported in the manufacturer's qualification report published in AASHTO NTPEP Report 8507.4 (2010). The two geogrids are very similar in geometry, but the longitudinal and transverse ribs in GG2 are 2.5 to 3 times thicker than that in GG1. Table 3 presents the geometric characteristics of the geogrids including the relevant index properties of the geogrids. The values presented for ultimate tensile strength, T_{ult}, of GG1 and GG2 are 75 kN/m and 175 kN/m, respectively.

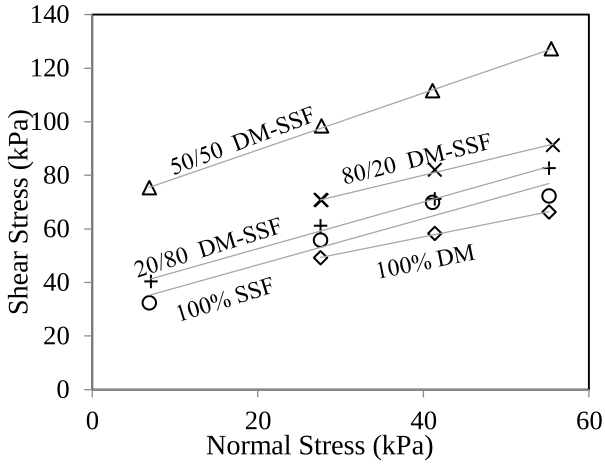

Figure 2: Mohr Coulomb Shear Strength Envelopes of DM-SSF blends

Table 3: Properties of the geogrids used in this study

Properties	Geogrid 1 (GG1)	Geogrid 2 (GG2)
Polymer Composition	HDPE	HDPE
Structure	Punched and Drawn	Punched and Drawn
Mass per unit area (g/m^2)	324.8	873.3
Dimensions in Machine Direction (MD)		
MD Rib Width (mm(in))	5.08(0.20)	5.59(0.22)
MD Rib Spacing (mm(in))	22.1(0.87)	24.13(0.95)
MD Aperture Size (mm(in))	444.5(17.5)	444.5(17.5)
MD Rib Thickness (mm(in))	1.02(0.04)	2.54(0.10)
Dimensions in Transverse Direction (TD)		
TD Rib Width (mm(in))	20.32(0.80)	21.84(0.86)
TD Rib Spacing (mm(in))	464.82(18.3)	467.36(18.4)
TD Aperture Size (mm(in))	17.02(0.67)	18.54(0.73)
TD Rib Thickness (mm(in))	2.79(0.11)	7.87(0.31)
Mechanical Properties in Machine Direction (MD)		
Tensile Strength @5% Strain (kN/m (lbs/ft))	31 (2,130)	75 (5,140)
Ultimate Tensile Strength (ASTM D6637)(kN/m (lbs/ft))	70 (4,800)	175(11,990)
Junction Strength(kN/m (lbs/ft))	66 (4,520)	160(10,970)
Flexural Stiffness (mg-cm)	730,000	9,075,000

3 EQUIPMENT AND EXPERIMENTAL TESTING PROGRAM

3.1 Testing Apparatus

The pullout box used in this study consisted of a steel box with internal dimensions of 1500 mm long, 600 mm wide, and 300 mm deep, with a 75 mm sleeve in the front wall of the box (Figure 3). The box was lined on all inside walls with smooth geomembrane sheets to minimize side-wall friction with the soil. The geogrid specimen is inserted through the sleeve and rolled around a roller grip clamp bar before it is bolted down. The hinge joints of the clamping bar render flexibility to the pullout system and ensure that the geogrid reinforcement is pulled out parallel to the length of the box. Two hydraulic pistons fitted on either side of the box apply the desired constant displacement rate. Figure 4 shows the roller grip on the clamping system, which is interlocked against the piston arrangement. The normal stress setup comprised of a layered arrangement of neoprene mat, plywood pyramids, air cylinders and metallic plates, designed to ensure the uniform distribution of pressure over the entire soil surface area.

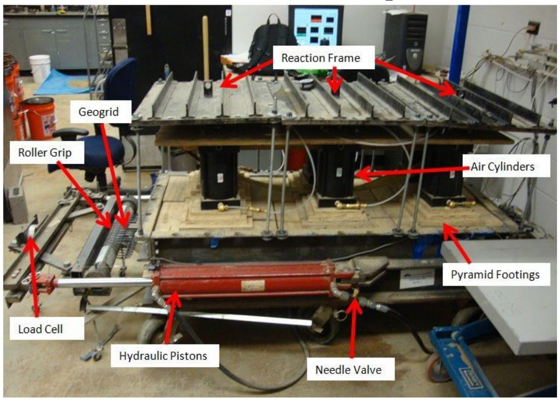

Figure 3: Large pullout box testing equipment used in study

Figure 4: Clamping mechanism and Load cell

3.2 Testing Program

The tested fill materials include Monterey Sand, 100% SSF, 100% DM and the 80/20, 50/50, and 20/80 DM-SSF blends. The pullout box was typically filled in stages with 15 cm thick lifts of material. Compaction was carried out using a hand tamper and a jack hammer in order to achieve uniform density. The pullout tests were performed using normal pressures of 28, 42, and 55 kPa (4, 6 and 8 psi), adopting a constant displacement rate of 1 mm/min. These testing parameters were chosen based on a combination of factors, including allowing pullout failure to develop before the geogrids reached their tensile capacity and prior to reaching the equipment displacement capacity (300 mm). Assuming an average effective backfill unit weight of 10 kN/m^3 (64 pcf), the normal pressure of 55 kPa (8 psi) represents an overburden surcharge of a 5.5 m tall retaining wall. The geogrid specimens used in most tests were 900-mm long and 300-mm wide. A few tests were conducted using 450 mm wide specimens. The dry unit weight and water content conditions for the different blends at the testing stage were the same as those used for the direct shear tests (Table 2). A test was deemed to have failed by pullout when the pullout force stopped increasing or displacements of geogrid were all changing at the same rate and in excess of 300 mm (at which stage the geogrid would have been pulled out close to the capacity of the testing apparatus). Tests where the geogrid failed to tension were not included in the pullout analysis.

4 DISCUSSION OF THE RESULTS

The results of pullout tests in terms of pullout resistance and displacements for the various fill material-geogrid combinations are discussed below.

4.1 Ultimate Pullout Resistance

The ultimate pullout resistance observed with the DM-SSF blends is summarized in Figure 5. In the case of Monterey Sand, the trend of pullout resistance with normal stress passes through the origin. GG1 failed in tension with the 100% SSF materials at 28 kPa (4 psi) and with the 20/80 DM-SSF blend at 55 kPa (8 psi), indicating the pullout resistance exceeds the geogrid tensile capacity. The 100% SSF material was then tested at a reduced normal pressure of 14 kPa (2 psi) with GG1 to achieve pullout failure.

The pullout resistance obtained using the 100% SSF and the 20/80 DM-SSF materials are significantly greater than the rest of the blends. Among the blends, there is a significant decrease in the pullout resistance from the 20/80 to the 50/50 blend (despite the trends shown in Figure 2), which is considerably closer to the pullout resistance in 100% DM. The 100% SSF and the 20/80 DM-SSF blend have pullout resistance that is greater than Monterey Sand while the rest of the blends show lower pullout resistance.

4.2 Load-Displacement Behavior

Figure 6 presents the pullout force-displacement curves for all the DM-SSF materials at 28, 42, and 55 kPa (4, 6 and 8 psi). Evaluation of these results reveals that while the finer materials (100% DM, 80/20 DM-SSF, and 50/50 DM-SSF) reach a pullout load plateau after relatively small displacements, the more granular materials (100% SSF and 20/80 DM-SSF) continuously mobilize pullout resistance up to relatively larger displacements. For example, the pullout force-displacement curves of the 100% SSF and 100% DM materials for both geogrids indicates that 100% SSF clearly develops greater overall pullout resistance than 100% DM. While the 100% SSF material continues to mobilize pullout resistance up to displacements greater than 125 mm (4.92 in), the 100% DM reaches an early plateau after 25 to 50 mm (1 to 2 in) of displacement. As expected, the pullout resistance and the corresponding displacement obtained using GG2 geogrid are consistently greater than those obtained using GG1.

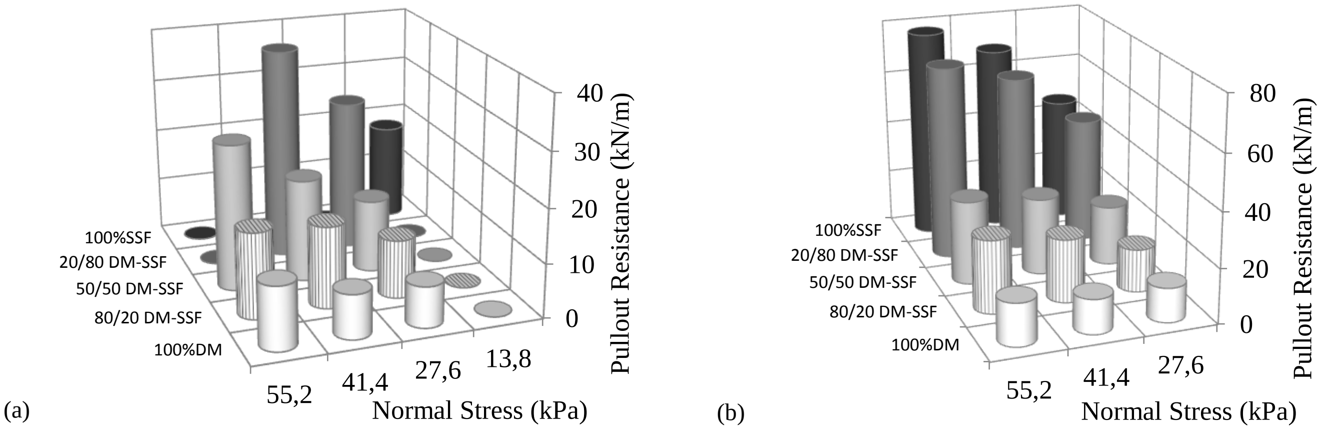

Figure 5: 3-Dimensional representation of pullout resistances of DM-SSF blends at different normal stresses (a) GG1 and (b) GG2

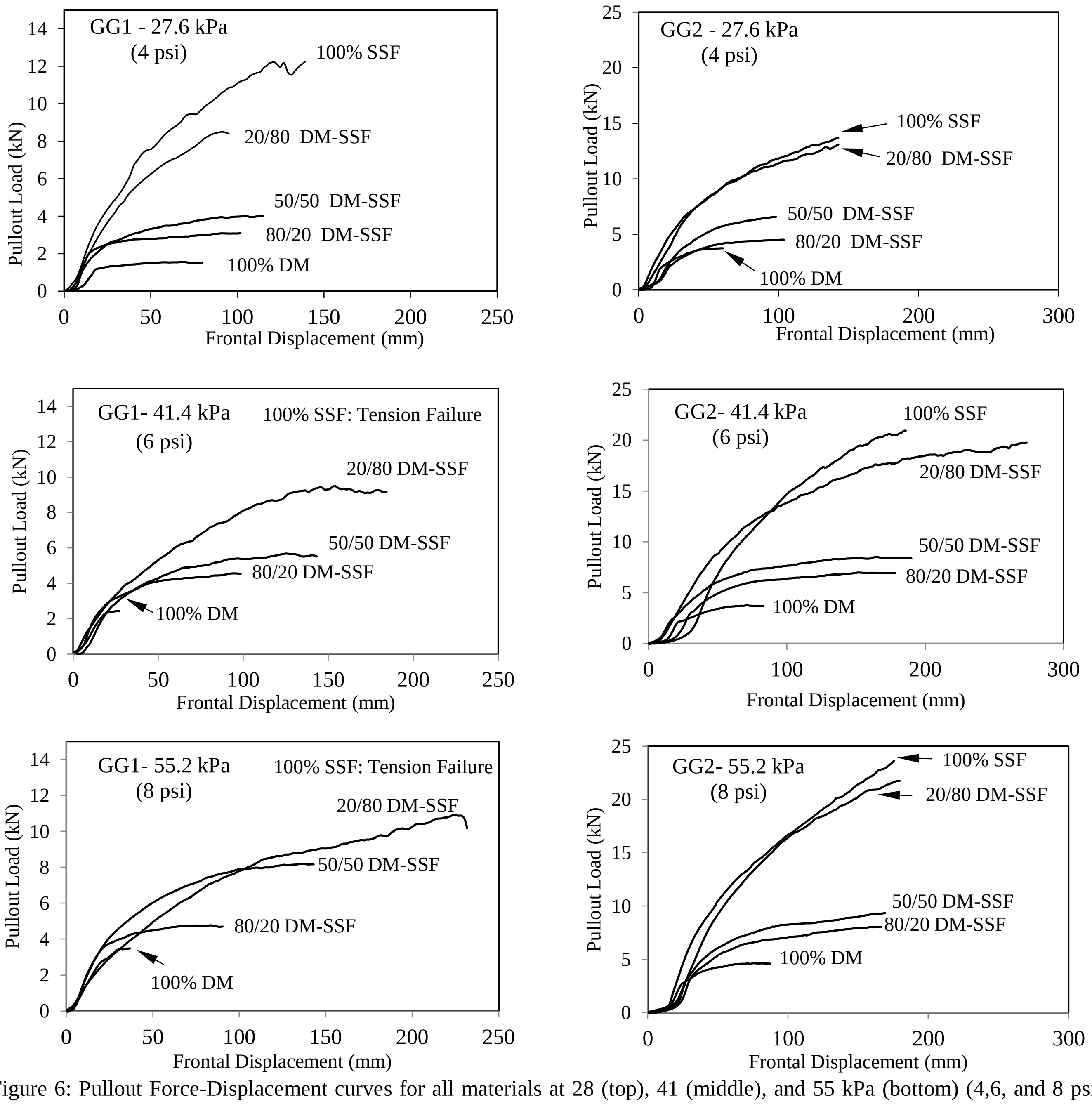

Figure 6: Pullout Force-Displacement curves for all materials at 28 (top), 41 (middle), and 55 kPa (bottom) (4,6, and 8 psi)

normal pressure

The differences in the observed pullout behavior of the various DM-SSF blends with both geogrids can be attributed to several factors. The total pullout resistance can be expressed as the sum of the frictional resistance on the surface area of the geogrid in contact with the fill material, and the bearing resistance at the transverse ribs. Palmeira (2008) reported that the bearing resistance decreases as the ratio of transverse rib thickness, B, to the mean grain size, D_{50}, increases and then remains constant. For the fill materials used in this study, the ratio of B/D_{50} increased with increasing DM content, indicating a much greater contribution of bearing resistance towards the total pullout resistance in case of the granular materials versus the finer materials. Furthermore, Wilson-Fahmy et al. (1994) showed the bearing resistance mobilizes at greater displacements when compared to the frictional resistance. Hence, as indicated by the pullout force-displacement curves, the granular materials, which mobilize greater bearing resistance as compared to the finer materials, showed an increasing trend in pullout resistance even at relatively greater displacements. Specifically, in geogrids with large spacing between the transverse ribs (this study), after overcoming the initial friction barrier at the interface, the transverse rib was continuously pulled through undisturbed zones in the material leading to continuous mobilization of resistance. Since the granular materials mobilize greater bearing resistance than the finer blends, larger pullout displacements are observed as compared to the finer blends. This mechanism has also been investigated by Palmeira and Milligan (1989) for grids with various ranges of S/B ratios [Spacing between the transverse ribs (S) to the thickness of the transverse ribs (B)] in a large pullout box and concluded that the grids with large S/B ratios (this study) do not show peak resistance in their pullout response.

In summary, it may be concluded that in the case of the granular fills (i.e. 100% SSF and 20/80 DM-SSF), the bearing resistance of the transverse ribs dominated the pullout response. With the finer-grained fills (100% DM, 80/20 DM-SSF, and 50/50 DM-SSF), the bearing resistance is relatively small. Therefore the geogrid did not mobilize pullout resistance at greater displacements after the initial frictional resistance and the small bearing resistance was exceeded.

4.3 Interaction Parameters

Interaction coefficients provide the percentage of soil shear strength mobilized at the soil-geogrid interface allowing for easy comparison between the various blends. One of the parameters used for this purpose is the coefficient of interaction (c_i), which is expressed as the ratio of the slope of the interfacial shear strength envelope (tan δ) to the slope of the internal soil shear strength (tan ϕ) envelope (Koerner, 2005). This expression was originally developed for cohesionless soils, as a measure of the fraction of the soil strength that is mobilized at the soil-geosynthetic interface, thereby quantifying the efficiency of interaction. The soil-geosynthetic interface shear is then expressed as pullout resistance per unit area thus yielding an expression that is a function of the pullout resistance (Pr), embedment length of geogrid specimen (Le), and the soil shear strength is expressed as (σ tan ϕ). The c_i can be calculated as:

$$c_i = \frac{\tan(\delta)}{\tan(\phi)} = \frac{P_r / 2Le}{\sigma \tan\phi} \tag{1}$$

However, when the tested media exhibits cohesion the expression should be modified to account for this component of shear strength. As part of this study, a modified coefficient of interaction ($c_{i,mod}$) was adopted as the ratio of the interfacial shear strength at the soil-geogrid interface (τ_{g-s}) and the internal soil shear strength (τ_s), where the soil shear strength accounts for the cohesion (Equation 2). Figure 7 qualitatively depicts the two failure envelopes for better clarity. Accordingly, $c_{i,mod}$ can be calculated as:

$$c_{i,\mathrm{mod}} = \frac{\tau_{g-s}}{\tau_s} = \frac{P_r / 2Le}{c + \sigma \tan\phi} \tag{2}$$

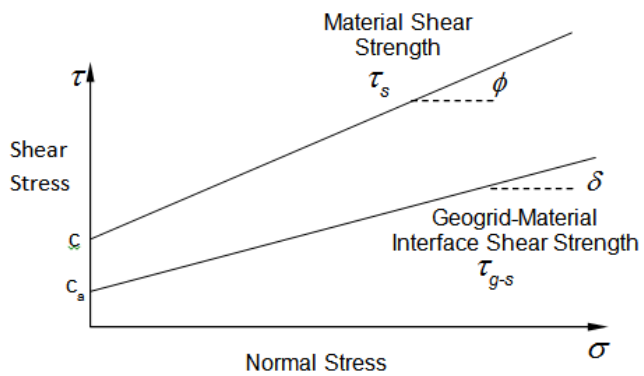

Figure 7: Coefficient of Interaction for Cohesive soils

The coefficient of interaction (c_i) for all the blends and geogrids (Figure 8) show a general decreasing trend with increasing normal stress for all DM-SSF media. This indicates the presence of adhesion between the geogrid and the particles, which is also observed as an intercept on the Y-axis in the pullout resistance-normal stress plot. When using granular materials (100% SSF and the 20/80 DM-SSF blend), c_i values were found to be notably larger than when using Monterey Sand for both the geogrids. For example, in GG2, c_i values range from 1.0 at 42 kPa to 0.8 at 55 kPa normal pressure whereas the maximum c_i value for Monterey sand was found to be 0.76. The finer materials (50/50 DM-SSF, 80/20 DM-SSF, and 100% DM) show values of c_i ranging from 0.2 to 0.4 for the two geogrids, and all lie very close to each other.

Evaluation of the interaction between fill materials and geogrids using the modified coefficient of interaction, $c_{i,mod}$, is illustrated in Figure 9. Because of the comparatively high cohesion values in the DM-SSF blends, the $c_{i,mod}$ values were found to be comparatively low, generally below 0.5. As indicated in this figure, the interaction performance of the 20/80 DM-SSF blend was very close to that obtained using 100% SSF. These two materials showed $c_{i,mod}$ values close to the baseline fill material, i.e. Monterey Sand, whereas the rest of the blends showed notably lower performance. The interaction of the performance of the finer materials (i.e. 50/50 DM-SSF, 80/20 DM-SSF, and 100% DM), were very close to each other in terms of $c_{i,mod}$ values, and were about 0.10 with GG1 and 0.15 with GG2. This indicates a comparatively lower interaction between the geogrids and the finer blend materials.

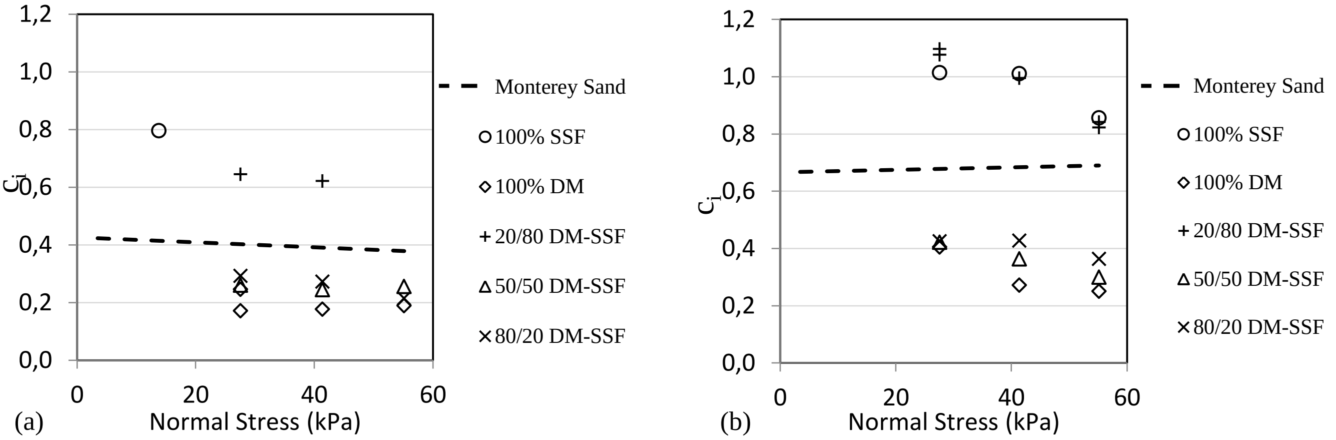

Figure 8: Coefficient of Interaction against normal stress for DM-SSF blends (a) GG1, (b) GG2

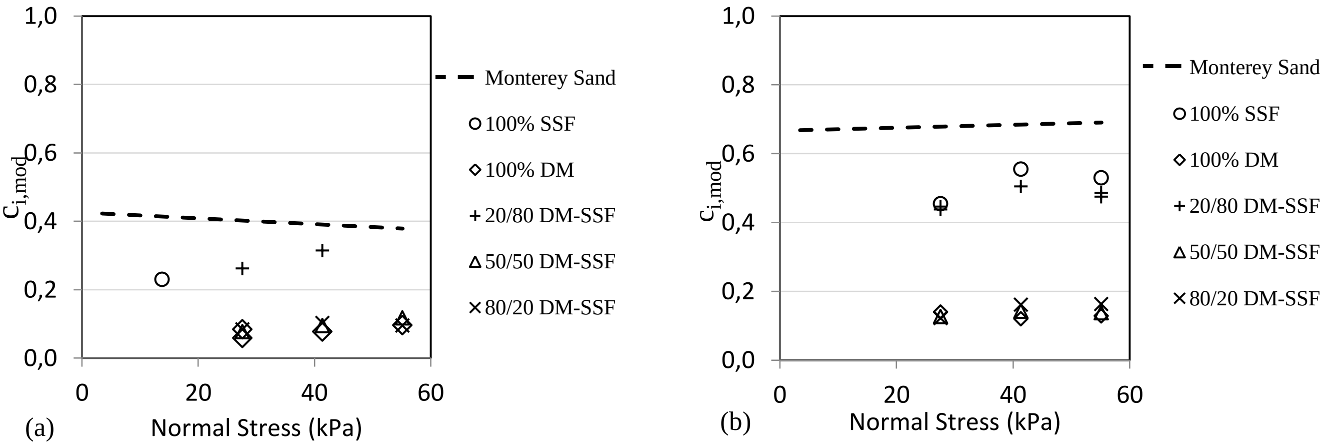

Figure 9: Modified coefficient of Interaction against normal stress for DM-SSF blends (a) GG1, (b) GG2

5 CONCLUSIONS

Large-scale pullout tests were conducted on blends of dredged materials (DM) and steel slag fines (SSF) with two commercially available uniaxial geogrids. The tested materials included 100% SSF and 100% DM materials and their 80/20, 50/50 and 20/80 blends (dry weight of DM reported first). The main findings drawn from this investigation include the following:

- The pullout force-displacement curves of the coarse materials (i.e. 100% SSF and 20/80 DM-SSF) continuously increased resistance up to large displacements (>150 mm of frontal displacement). In the finer materials, the rate of mobilization of pullout resistance dropped significantly beyond 50mm of frontal displacement in most cases. The 100% DM was characterized by a low, early plateau in the pullout force-displacement, indicating that little resistance was mobilized.

- The 100% SSF and 20/80 DM-SSF materials had a pullout resistance about twice the value observed with Monterey Sand for both geogrids while the rest of the blends showed lower pullout resistance. Therefore, it was observed that the addition of 20% of DM to the SSF material does not seem to alter the pullout interaction behavior of the resulting blend by much.
- The quality of interaction between the materials and the geogrids was investigated using the coefficient of interaction (c_i) and the modified coefficient of interaction ($c_{i,mod}$), which accounts for the cohesive component of interaction. Significant differences were found in the values and the trends of the two coefficients. Accordingly, the use of coefficient of interactions in the design procedures should be considered carefully.

Overall, the results of this study revealed that, while dredged material show poor pullout interaction with the geogrid reinforcements, steel slag fines can significantly improve its pullout performance. However, the percentages of the mix should be carefully designed. The 20/80 DM-SSF blend proved to be a very promising mix in order to retain the efficiency in pullout performance of the 100% SSF, while also providing an avenue for the disposal of the dredged material.

ACKNOWLEDGEMENTS

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