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Geofoam Inclusions for Reducing Passive Force on Bridge Abutments Based on Large-Scale Tests

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Abstract

To decrease lateral earth pressures on structures, a zone of compressible material or an "inclusion" can be used as a barrier to decrease lateral earth pressures on structures. The compressible material is typically expanded polystyrene or geofoam. Little guidance is available on the development of passive force with an inclusion. To explore this issue, large-scale passive force tests were conducted with and without a geofoam inclusion acting as a barrier between the backfill soil and a simulated bridge abutment. The presence of the geofoam inclusion reduced the passive force by 70% relative to the sand backfill alone. Although the measured force and failure geometry appeared to conform to a log-spiral mechanism when only sand backfill was used, the geofoam inclusion transforms the failure geometry to a Rankine failure mechanism. This suggests that the geofoam acted to reduce the interface friction between the wall and the backfill sand thereby reducing the passive resistance.

INTRODUCTION

A zone of compressible material or an "inclusion" has been proposed as a barrier to decrease lateral earth pressures on structures (Horvath 1997). The compressible material is typically expanded polystyrene (EPS), also known as geofoam. Although the influence of geofoam inclusions has been investigated for the case of active earth pressure (Ertugrul and Trandafir 2012; Ertugrul and Trandafir 2012; Horvath 1997), very few tests have previously been conducted to examine the effect of geofoam inclusions on passive earth pressure (Bathurst and Zarnani 2013; Horvath, 1997). In some cases, it might be desirable to isolate the bridge structure and abutment walls from the passive backfill force. For example, in the event of liquefaction in an underlying sand layer, lateral spread displacements could cause passive force to develop against the abutment as the overlying backfill soil slides towards the bridge abutment. Alternatively, dynamic forces from inertial earthquake loading could cause structural movement towards a soil backfill leading to large passive pressures on the backwall.

Current design codes and technical literature provide little guidance on passive force-deflection relationships with geofoam inclusions and no field test are available to define performance. To provide some basic information on the behavior of this system, large-scale passive force tests were conducted with and without a geofoam inclusion acting as a barrier between the backfill soil and a simulated bridge abutment. This report describes the properties of the backfill and geofoam materials and the testing procedures employed, and provides results

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from the tests. Test results include passive force-deflection curves, lateral and vertical deformation of the geofoam and backfill soil, shear plane formation and surface cracking patterns, and backfill strain.

GEOMETRY OF SIMULATED ABUTMENT TEST

Figure 1 provides plan and profile drawings showing the layout of the pile cap which simulates a bridge abutment, the geofoam inclusion, the backfill soil and the loading system. The pile cap consists of a reinforced concrete block 3.35-m (11-ft) wide, 1.68 m (5.5-ft) high, and 4.57 (15-ft) long. The pile cap is supported by six 32.4 cm (12.75 in) OD steel pile piles filled with concrete. The piles extend to a depth of approximately 12.2 (40 ft) below the ground surface and ensure that the pile cap does not move vertically. The test layout used by Marsh et al (2013) was identical; however, the inclusion was not present. Load was applied using two MTS hydraulic actuators capable of applying a horizontal force of 5300 kN (1200 kips) in compression. The reaction for the actuators was provided by two 1.22 m (4 ft) diameter drilled shafts along with a 9.1 m (30 ft) deep sheet pile wall tied together by two deep beams as shown in Figure 1.

The backfill zone used for both the tests with and without the geofoam inclusion was approximately 6.4 m (21 ft) wide and 7.9 m (26 ft) long. The backfill was placed directly north of the pile cap and geofoam inclusions. To fully contain a potential log-spiral type failure surface, the soil backfill extended one foot below the pile cap. During placement of the backfill zone, two nuclear density gauge measurements were taken for each lift of soil placed to ensure compaction and to determine the moisture content and unit weight of the soil used. The backfill soil was poorly graded sand and classified as SP soil type according to the Unified Soil Classification System. The maximum density of the soil according to the modified Proctor compaction test (ASTM D1557) was 17.5 kN/m^3 (111.5 lbs/ft^3) with an optimum moisture content of 7.1%. Typical relative compaction was approximately 96%.

Pile cap load was the sum of the two actuator loads and pile cap deflection was the average of four string potentiometers attached to the back corners of the pile cap. Heave of the backfill was measured with a conventional survey level on a grid pattern before and after testing. Backfill displacement was measured using string potentiometers inserted into the geofoam at 0.15 m (0.5 ft) intervals and into the sand at 0.6 m (2 ft intervals). A number of vertical holes were excavated in the backfill and filled with red sand so that the shear plane could be identified.

The geofoam barrier that was placed between the pile cap and the soil backfill consisted of four blocks of expanded polystyrene (EPS), or geofoam. The bottom two blocks were 1.2 m (4 ft) tall while the upper blocks were 0.6 m (2 ft) tall as shown in Figure 1. These dimensions allowed the geofoam inclusion to extend beneath the pile cap while the top surface of the geofoam remained relatively level with the top of the pile cap. All blocks were 0.9 m (3 ft) thick in the direction of loading, and 2.44 m (8 ft) wide. Thus, the blocks spanned 4.88 m (16 ft) at the face of the backfill zone with a joint in the center of the cap. The geofoam blocks were designated EPS19 which is a medium density geofoam that provides some strength but is also readily compressible when loaded. Geofoam density typically ranges from 12 to 46 kg/m^3. The "19" indicates that the geofoam has a density of 19 kg/m^3 (1.15 lb/ft^3) or about 1/90th of the dry unit weight of the backfill sand (Horvath 1997). The elastic modulus of the EPS19 geofoam is 4000 kPa (580 psi). These geofoam blocks offer 90 kPa (13.1 psi) of compressive resistance at 5% deformation or 16.0 psi at 10% deformation (EPS Geofoam 2012). The blocks were simply stacked on top of each other and not connected using any mechanical or geometric interlocking

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system. The upper blocks weighed approximately 25 kN (55 lbs) while the lower blocks weighed approximately 50 kN (110 lbs).

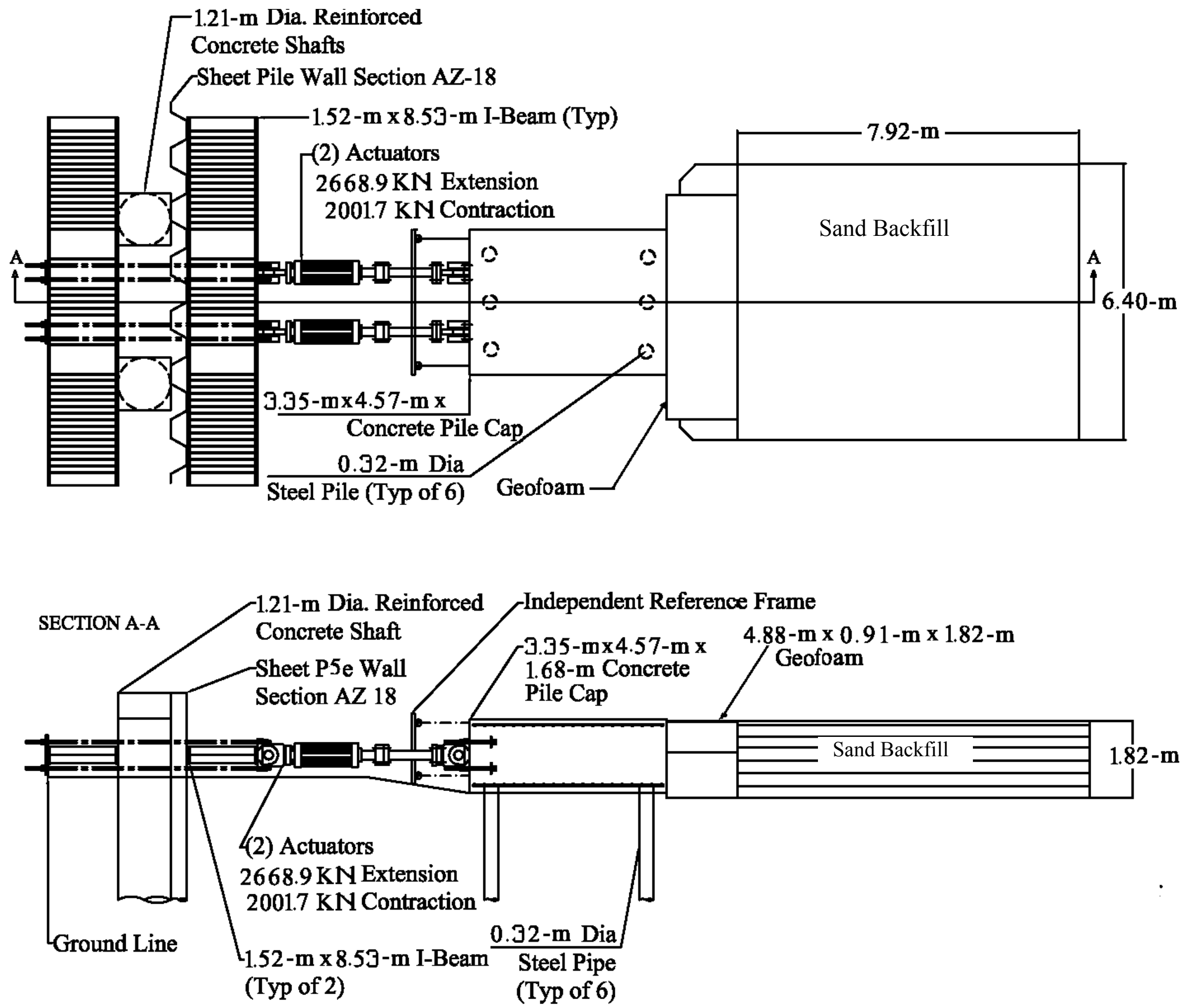

Figure 1. Plan and profile views of the test set-up showing test pile cap, geofoam inclusion, and backfill soil along with the loading system.

LOAD TEST RESULTS

The passive resistance provided by the backfill soil was determined by measuring the total load versus deflection curve and subtracting the "baseline" resistance provided by the pile cap without backfill in place. The load was applied incrementally to produce deflection increments of approximately 6 mm (0.25 in). Marsh et al (2013) reported the passive force vs. deflection curve for the test without a geofoam inclusion previously.

The measured passive force versus deflection curves obtained with and without an inclusion are presented in Figure 2. The peak passive force without an inclusion is approximately 2133 kN (480 kips) and occurs at a pile cap deflection of 5.7 cm (2.24 in) which is about 3.4% of the cap height. This is in good agreement with previously large-scale passive force tests in which the peak developed with displacements equal to 3 to 5% of the wall height

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(Cole and Rollins, 2006). In contrast, the passive force vs. displacement curve with the inclusion does not reach a distinct peak but tends to increase very gradually with displacement. Therefore, at the maximum pile cap deflection of 9.5 cm (3.75 in), the cap was unloaded, shims (plywood sheets) were placed in the gap between the pile cap and the geofoam blocks, then the cap was again loaded to extend the passive force deflection curve to approximately 15 cm (6 in). At a displacement equal to 3.4% of the cap height, the passive force with the inclusion is only about 570 kN (128 kips) which represents a reduction in resistance of 73%. Even at a displacement equal to about 9% of the cap height, the passive force of 800 kN (180 kips) is still about 63% lower than the peak resistance without the inclusion. Clearly, the inclusion significantly reduced passive force.

At the conclusion of the testing, the geofoam blocks were excavated. Figure 3 provides a photograph of the bottom geofoam block on the right side of the cap in the direction of loading. The geofoam is permanently indented by the loading imposed by the pile cap. In addition, shear planes formed along the edge of the pile cap where the geofoam was unable to accommodate the large change in deformation.

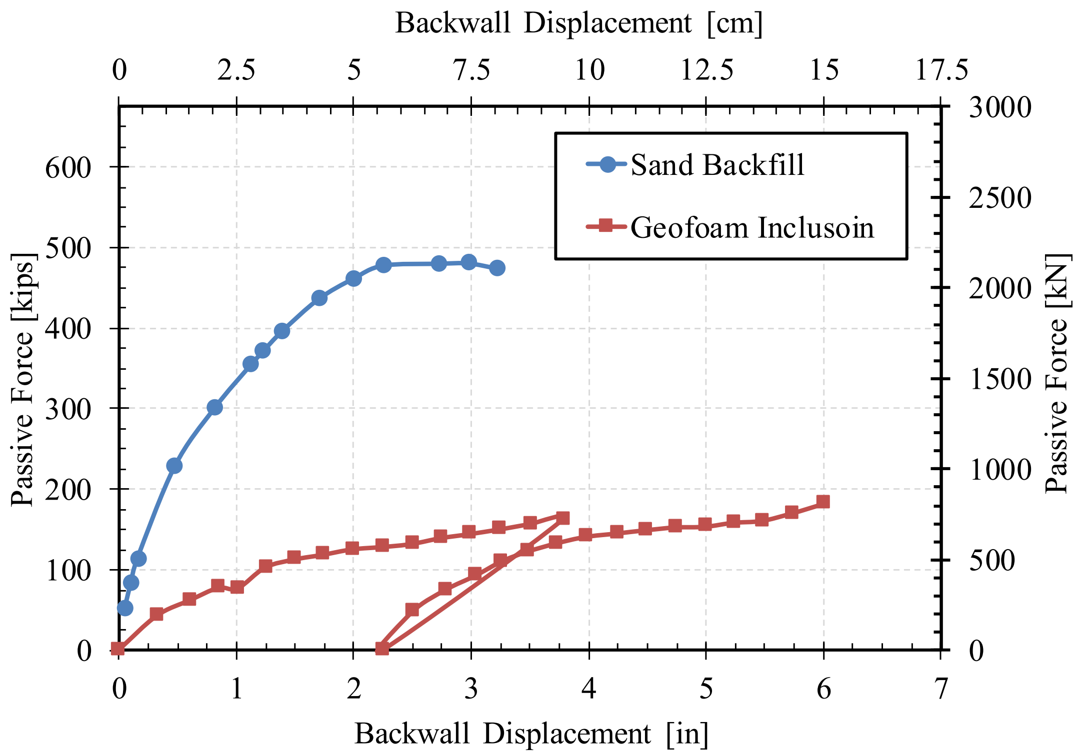

Figure 2. Plan and profile views of the test set-up showing test pile cap, geofoam inclusion, and backfill soil along with the loading system.

The displacement of the backfill with respect to distance from the pile cap face is plotted at five pile cap deflection levels for the test with the geofoam inclusion and the test with sand only in Figures 4 and 5, respectively. In the case of the test with the geofoam inclusion, results are only shown for the first cycle of load to provide a simpler comparison with the test with sand alone. The results indicate that most of the compression of the geofoam occurs in the first 0.15 m (0.5 ft) of the geofoam block behind the pile cap with strains as high as 20% with strains less than 1.0% in the rest of the geofoam. Backfill displacement of the sand behind the geofoam

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typically decreases quite linearly until the pile cap displacement reaches 7.5 (3 in), at which point considerable strain (up to 9%) is developed in the zone from 1.5 to 2.1 m (5 to 7 ft). Backfill displacement decreases to less than 0.5 cm (0.3 in) at a distance of 5.2 m (17 ft). In contrast, in the sand only test, the compression in the 0.6 m (2 ft) behind the pile cap is also substantial but strain does not exceed 6%, whiles strain is less than 1% behind this zone. Backfill displacement at a distance of 5.2 m (17 ft) is more than twice as high as that with the geofoam.

Figure 3. Photograph of the compressed geofoam along with shear plane that developed at the edge of the pile cap.

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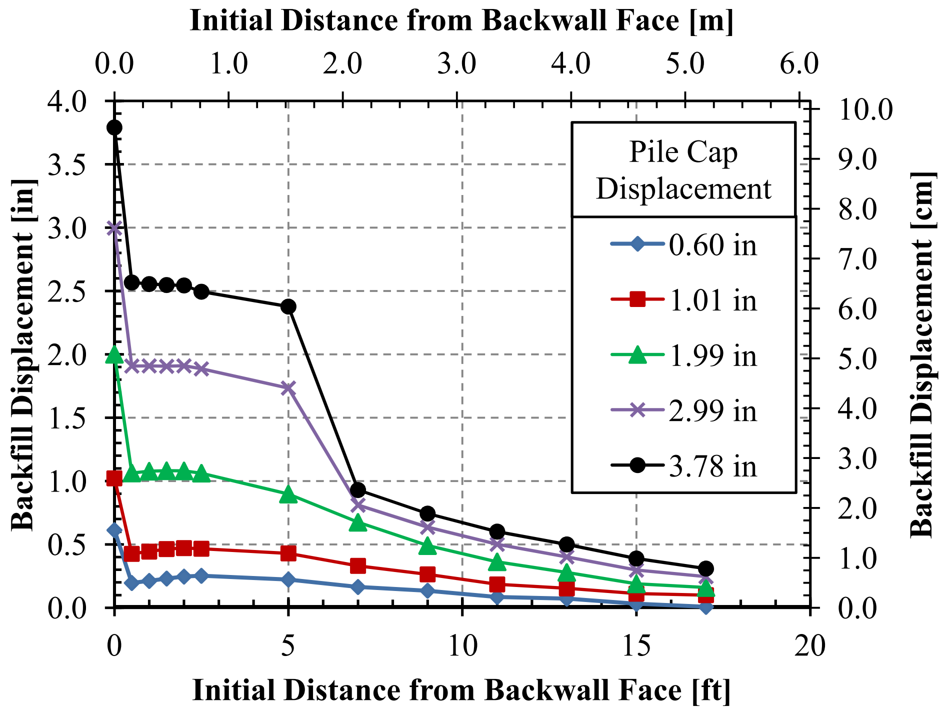

Figure4. Backfill displacement versus distance from the pile cap at selected cap displacements for 1st loading of the geofoam inclusion test.

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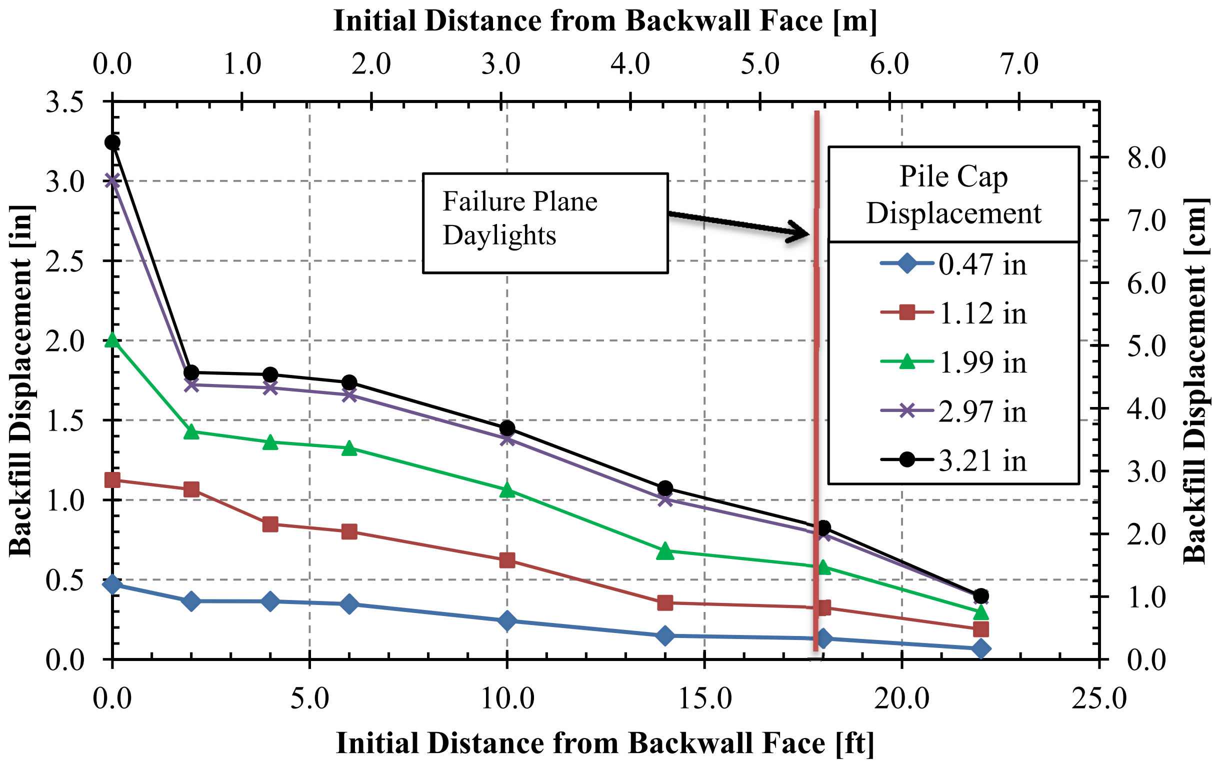

Figure 5. Backfill displacement versus distance from the pile cap at selected cap displacements for test without inclusion (sand backfill only).

Heave measurements and crack patterns for the sand backfill indicate that the failure plane extends to a distance of about 5.5 m (18 ft) behind the pile cap. In contrast, heave patterns for the backfill with geofoam indicate that the failure plane would daylight at about 3.3 m (10 ft) behind the pile cap. Columns of red sand were installed in the backfill behind the cap for both tests and the offset in columns indicates a log-spiral shape of the failure surface for the sand only backfill, but a linear "Rankine" type failure surface for the geofoam. Because the top block of geofoam was only 0.6 m (2 ft) thick, intermediate failure planes clearly developed behind these shallow blocks. This also likely explains why there was a significant decrease in the backfill displacement behind this intermediate failure wedge.

Analysis of Test Results

The ultimate passive force can be computed using a variety of methods including: Rankine, Coulomb, and Log-Spiral. The Rankine method assumes no interface or wall friction between the pile cap and backfill while the Coulomb and Log-Spiral methods consider wall friction. Both the Rankine method and the Coulomb method assume a linear failure surface while the log-spiral approach assumes a log-spiral zone immediately behind the pile cap which transitions to a triangular Rankine failure wedge near the ground surface. The ultimate passive force has been computed using all three of these methods for the backfill with geofoam inclusion and for the backfill with sand only. Table 1 summarizes the predicted and measured passive force values from the sand test while Table 2 shows the predicted and measured passive force value for the

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geofoam inclusion test. In computing the ultimate passive force, the moist unit weight (γ) was taken as 18.4 kN/m^3 (117 lbs/ft^3), the sand friction angle (ϕ) was assumed to be 38.5º, and wall friction (δ) was assumed to be 0.70 for the Log-Spiral and Coulomb methods, and 0º for the Rankine method. The effective width of the failure wedge transverse to the direction of loading was 18.5 ft for the sand backfill using a 3D width correction factor proposed by Brinch-Hansen (1966). For the geofoam inclusion test, the effective width of the shear zone was also assumed to be 18.5 ft based on the observed shear crack patterns, but the wall height was taken as 6 ft to match the height of the geofoam block wall. All other parameters were the same as for the sand backfill test.

Table 1. Calculated and measured passive forces for sand backfill test.

Method	Passive Force Per width	Total Passive Force	Total Passive Force
	kN/m (kips/ft)	kN (kips)	Percent Error
Log Spiral	32.7 (24.1)	2105 (474)	-1.50%
Coulomb	48.6 (35.9)	3138 (706)	47%
Rankine	13.2 (9.7)	849 (191)	-60%
Sand Test	33.1 (24.4)	2138 (481)	N/A

Table 2. Calculated and measured passive forces for geofoam inclusion test.

Method	Passive Force Per width	Total Passive Force	Total Passive Force
	kN/m (kips/ft)	kN (kips)	Percent Error
Log Spiral	32.7 (24.1)	2105 (474)	154%
Coulomb	48.6 (35.9)	3138 (706)	278%
Rankine	13.2 (9.7)	849 (191)	2.4%
Geofoam Inclusion Test	12.9 (9.5)	831 (187)	N/A

As shown in Table 1, the Log Spiral method, which is commonly considered to be the most theoretically sound method, provides the most accurate estimate of the measured passive force for the sand backfill tests. However, the Coulomb method significantly overestimated passive force while the Rankine theory significantly underestimated the passive force that was measured. However, as shown in Table 2, the Rankine theory was the most successful at explaining the results obtained from the geofoam test while the Log-spiral and Coulomb methods greatly over predicted passive resistance. One potential explanation for the success of the Rankine theory in predicting the geofoam inclusion test results is the reduction in interface friction between the geofoam and the backfill wall or the soil backfill and the geofoam. Based on the failure surface geometry and the reduced passive force, it appears that the presence of the geofoam inclusion reduces the effective interface friction to a value close to zero which is the value assumed by the Rankine earth pressure theory.

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CONCLUSION

Based on the field test results and the computer analyses, the following conclusions can be drawn:

1. Geofoam inclusions appear to be very effective at reducing the ultimate passive force which develops at abutments with sand backfills. In this case, the geofoam inclusion reduced the passive force by about 70% relative to the backfill composed only of sand.
2. Although the failure mechanism for a sand backfill typically involves a log-spiral failure surface, the governing failure mechanism for a sand backfill with a geofoam inclusion appears to be a linear shear failure similar to that described by the Rankine earth pressure theory.
3. The log-spiral method was able to predict the peak passive resistance for the sand backfill with an error of less than 10% assuming a friction angle of 38.5º with wall friction equal to 70% of the friction angle, while the Rankine method significantly underestimated resistance. In contrast, the Rankine method predicted the peak passive resistance for the backfill with the geofoam inclusion within 10%, assuming a wall friction of zero, while the log-spiral method significantly overestimated resistance.
4. The reduction in passive force produced by the geofoam inclusion appears to result from a reduction of the effective interface friction to about zero rather than excessive compression of the geofoam.
5. In computing the peak passive force for a sand backfill with a geofoam inclusion, the wall friction should be assumed to be zero and the Rankine method should be used.

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