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Measurement of Shear Strength and Interface Parameters by Multi-Stage Large-scale Direct/Interface Shear and Pull-out Tests

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ABSTRACT

It is essential to measure the shear strength of soils and interface parameters between soils and geosynthetics for the safe design and stability analysis of geosynthetic-reinforced soil structures. These parameters recommended for engineering projects are normally measured by laboratory single-stage direct/interface shear and pull-out tests. The conventional single-stage tests are carried out on at least three representative specimens under three different normal stresses. However, a large quantity of specimens is required for large-scale tests, with tedious sample preparation procedures, so that large-scale single-stage testing becomes very labour intensive, time consuming and expensive. Given that the multi-stage testing method is able to measure the shear strength parameters by testing only one representative specimen, this paper investigates the feasibility, reliability and applicability of the multi-stage testing method in large-scale direct/interface shear and pull-out tests. Two compacted soils and a geogrid were tested using both single-stage and multi-stage tests. It was found that the shear strengths obtained from the multi-stage tests were slightly lower that those obtained from the single-stage tests, and the inferred apparent cohesion and friction angle matched closely. In addition, the limitations of the multi-stage testing method were highlighted. The measured direct shear strength of the soils, the interface shear strength and pull-out shear strength between the soils and the geogrid are also compared and discussed in this paper.

KEYWORDS: measurement, shear strength, interface parameters, laboratory testing, direct shear, pull-out

List of Symbols

τ_s	direct shear strength of soil alone
τ_{ds}	interface shear strength between the geogrid and the soil
τ_p	pull-out shear strength between the geogrid and the soil
f_{ds}	direct shear interface coefficient
f_b	pull-out interface coefficient
α	scale effect correction factor
ϕ	internal friction angle
δ_0	friction angle between soil and geogrid ribs
δ	interface friction angle
α_{ds}	the proportion of the surface area of the geogrid ribs in contact with soil
σ_n	normal stress
c	apparent cohesion of soil
c_a	apparent adhesion between the geogrid and the soil
P_R	pull-out resistance per unit width
P_{RS}	frictional component of pull-out resistance
P_{RB}	bearing component of pull-out resistance
L_R	reinforcement length in the anchorage zone
S	spacing between geogrid bearing members
L_R/S	the number of geogrid bearing members
α_B	the fraction of total frontal area of geogrid available for bearing resistance
B	bearing member thickness
σ_b	bearing stress against the geogrid bearing members

Introduction

Direct/interface shear and pull-out tests are commonly used laboratory techniques to measure the shear strength parameters of soils and the interface parameters between soils and geosynthetics. These parameters are necessary for the safe design and stability analysis of geosynthetic-reinforced soil structures. The interface shear test is the most appropriate experimental method for the analysis of soil-geosynthetic interaction when the sliding of the soil mass on the reinforcement surface is likely to occur. However, the pull-out test is more relevant to the study of soil-geosynthetic interaction when the failure surface shears through the geosynthetic in the anchorage zone (Change et al. 2000; Palmeira, 2009; Lopes, 2012; Bathurst and Ezzein 2015; Ferreira et al. 2015; Mosallanezhad et al. 2015; Xu et al. 2018a). Nonetheless, both the two testing methods can be adopted in the laboratory to measure the interface parameters between the soil and the geosynthetic, such as interface friction angles, apparent adhesions and interface coefficients. However, the relationship between the interface shear stress and pull-out shear stress mobilised along the soil-geosynthetic interface in these two testing methods is still a very controversial topic and may produce significantly different interface parameters for design. (Bergado et al.1994; Alfaro et al. 1995; Mallick et al. 1996; Lopes and Silvano 2010; Hsieh et al. 2011).

Mallick et al. (1996) demonstrated that the surface roughness of the geosynthetic and the interlocking between the soil and geosynthetic could influence the frictional resistance in interface shear tests. Apart from the two factors, the geosynthetic extensibility should be taken into account in pull-out tests. The maximum extension of the geosynthetic in an interface shear test is much smaller than that in a pull-out test. This is because the geosynthetic is usually fixed and clamped on the shear box for interface testing, while the geosynthetic is embedded in the soil with its end being pulled for pull-out testing. Lopes and Silvano (2010) have shown that the average pull-out interface coefficients are approximately 55% of the direct shear interface coefficients for a residual granite soil-geotextile interface in their study, indicating that the pull-out shear strengths obtained from the pull-out tests were much lower than the interface shear strengths obtained from the direct shear tests. By contrast, Hsieh et al. (2011) compared the direct shear and pull-out test results for different types of soil-geosynthetic interfaces and observed that the interface shear stress and pull-out shear stress were close for the crushed stone geotextile interface, while the pull-out shear stress was much higher than the interface shear stress for the crushed stone-geogrid interface. In addition, they also concluded that there existed a linear relationship between the interface shear stress and the applied normal stress for the interface shear tests between crushed stone and geogrid, but the pull-out shear stress appeared to have no consistent relationship with the applied normal stress for the pull-out tests.

The earliest literature concerning multi-stage testing that could be found is a Master's thesis written by Gullic in 1970, at the University of Missouri-Rolla, USA. Gullic (1970) performed a series of multi-stage direct shear tests on a cohesionless soil using a small shear box with a diameter of 62.0 mm and a specimen height of 25.8 mm. Five different multi-stage direct shear testing procedures were studied and compared with conventional single-stage results. Later, Gan and Fredlund (1988) proposed a multi-stage direct shear testing method for unsaturated soils by applying multiple matric suctions on the same specimen. More recently, Hormdee et al. (2012) performed the multi-stage direct shear testing of loess soil under drained conditions using a conventional small direct shear apparatus. Petro et al. (2017) carried out the standard and limited displacement multi-stage direct shear tests on rough rock joints, corresponding to the two multi-stage testing procedures. In general, a good agreement was observed based on their obtained plots of shear stress versus shear displacement. However, it would be very difficult to determine when to cease the shearing or when a peak stress has been achieved, especially for brittle rock samples.

Similar to the multi-stage direct shear testing, there is also very limited multi-stage pull-out testing research work available. For instance, a Master's thesis written by Pradhan, at The University of Hong Kong, China, can be cited. Pradhan (2003) performed both single-stage and multi-stage pull-out tests on soil nails in completely decomposed granite fill and compared the peak pull-out resistances obtained. He concluded that the peak pull-out resistances obtained from the single-stage tests were higher than those from the multi-stage tests. This is because a continuing reduction in the length of the nail embedded in the soil in the later stages of the multi-stage tests caused a significant reduction in the soil-nail contact surface. Therefore, the peak pull-out resistance obtained was lower than that obtained from the single-stage test under the same normal stress. Another multi-stage pull-out testing method proposed by Moraci and Cardile (2009) was actually a cyclic tensile loading test, which differed from the multi-stage testing method in Pradhan (2003) and that proposed in this paper. Overall, previous studies have not applied the multi-stage testing method in the large-scale interface shear and pull-out tests on the soil-geosynthetic interfaces. Therefore, the application of the multi-stage testing to both large-scale direct/interface shear and pull-out tests deserves further investigation.

In summary, the main aims of this paper are: 1) to investigate the feasibility, reliability and applicability of the multi-stage testing in large-scale direct/interface shear and pull-out tests by testing the compacted soils and a geogrid, 2) to construct an empirical relationship between the single-stage and multi-stage test results based on the collected data; 3) to study the process of shear stress mobilisation during the shearing and pulling in the direct/interface shear and pull-out tests; and 4) to develop empirical relationships between the measured direct shear strength of the soil, the interface shear strength and pull-out shear strength between the soil and geosynthetic so that they could be predicted from one another.

Soil-geogrid Interaction Mechanism

112 The stability of geosynthetic-reinforced soil structures is highly dependent on the soil-geosynthetic interfaces. The interaction mechanism between the soil and geotextile (or other simple sheet types of geosynthetics) is only attributed to the frictional resistance mobilised along the continuous geotextile surface. However, due to the presence of apertures in geogrid products, the interaction mechanism between the soil and geogrid is much more complex than that between the soil and geotextile.

118 The direct shear resistance between the soil and the geogrid in direct shear tests has two components: (1) frictional resistance between the soil and the geogrid ribs along the single shear surface; and (2) frictional resistance between the soil and the soil in the geogrid apertures. This mechanism can be theoretically interpreted using the following equation (Jewell et al. 1984):

123 $$\tau_{ds} = f_{ds}\sigma_n \tan\phi = \sigma_n\left[\alpha_{ds}\tan\delta_0 + (1-\alpha_{ds})\tan\phi\right] \quad (1)$$

124 where ϕ is the internal friction angle of the soil, δ_0 is the friction angle between the soil and geogrid ribs, f_{ds} is the direct shear interface coefficient, α_{ds} is the proportion of the surface area of the geogrid ribs in contact with the soil, i.e., the area of ribs (longitudinal and transverse) relative to the total geogrid area, σ_n is the normal stress and τ_{ds} is the interface shear strength between the geogrid and the soil.

129 From the experimental results of interface shear tests, the interface shear strength τ_{ds} can be interpreted by the Mohr-Coulomb criteria:

131 $$\tau_{ds} = c_a + \sigma_n \tan\delta \quad (2)$$

132 where τ_{ds} is the interface shear strength obtained from the interface shear test, c_a is the apparent adhesion between the geogrid and the soil, and δ is the interface friction angle. Thus, the interface coefficient f_{ds} can then be calculated as:

$$f_{ds} = \frac{c_a + \sigma_n \tan\delta}{c + \sigma_n \tan\phi} = \frac{\tau_{ds}}{\tau_s} \tag{3}$$

Additionally, the pull-out resistance also has two components: (1) frictional resistance between the geogrid ribs and the soil above and below the geogrid (double shear surfaces); and (2) passive bearing resistance provided by the transverse ribs in the apertures. This mechanism can be interpreted by the following equation (Jewell 1990):

$$P_R = P_{RS} + P_{RB} = 2 f_b L_R \sigma_n \tan\phi \tag{4}$$

where P_R is the pull-out resistance per unit width, P_{RS} is the frictional component of the pull-out resistance, P_{RB} is the bearing component of the pull-out resistance, L_R is the reinforcement length in the anchorage zone, f_b is the pull-out interface coefficient. The following equations can be used to evaluate the frictional component P_{RS} and bearing component P_{RB} of the pull-out resistance:

$$P_{RS} = 2\alpha_{ds} L_R \sigma_n \tan\delta \tag{5}$$

$$P_{RB} = \left(\frac{L_R}{S}\right)\alpha_B \sigma_b B \tag{6}$$

where S is the spacing between the geogrid bearing members, L_R/S is the number of geogrid bearing members, α_B is the fraction of the total frontal area of the geogrid available for bearing resistance, B is the bearing member thickness, and σ_b is the bearing stress against the geogrid bearing members, which can be calculated using different bearing capacity theories (Peterson and Anderson 1980; Jewell et al. 1985; Matsui et al. 1996).

From the experimental results, the pull-out interface coefficient f_b can be further expressed as a ratio of the maximum shear stress mobilised at the soil-geosynthetic interface in the pull-out test to the shear strength of soil alone obtained from the direct shear test:

$$f_b = \frac{P_R}{2L_R(c + \sigma_n \tan\phi)} = \frac{\tau_p}{\tau_s} \tag{7}$$

where τ_p is the shear strength in the pull-out test, τ_s is the direct shear strength of soil alone. Therefore, the shear stress mobilised at the soil-geogrid interface in the pull-out test can be calculated using the following equation:

$$\tau_p = \frac{P_R}{2L_R} \tag{8}$$

From the experimental results of the pull-out test, the pull-out shear strength τ_p can also be interpreted by the interface shear strength parameters as in Eq. (9),

$$\tau_p = c_a + \sigma_n \tan\delta \tag{9}$$

where τ_p is the pull-out shear strength obtained from the experimental pull-out results, c_a is the apparent adhesion between soil and geogrid, δ is the interface friction angle. Herein, the interface shear strength parameters c_a and δ are also obtained from a best-fit straight line (that is, the pull-out shear strength failure envelope).

The relationship between the pull-out shear strength τ_p and interface shear strength τ_{ds} mobilised along the soil-geogrid interface can be defined as a parameter α, which is also called scale effect correction factor according to the Federal Highway Administration (FHWA) in USA (Christopher et al. 1990; Elias et al. 2001; Berg et al. 2009).

$$\alpha = \frac{P_R}{2L_R(c_a + \sigma_n \tan\delta)} = \frac{\tau_p}{\tau_{ds}} \tag{10}$$

From Eqs. (3), (7) and (10), the following relationship between the interface coefficients obtained from the interface shear and pull-out tests can be found:

$$\alpha = \frac{f_b}{f_{ds}} \tag{11}$$

In summary, the soil-geogrid interaction mechanisms interpreted above in interface shear and pull-out tests are depicted in **FIG 1**, to clearly present each component.

Multi-stage Testing Methodology

The conventional single-stage test needs to be carried out on a minimum of three identical specimens individually under three applied normal stresses, i.e., at least three specimens are required and tested separately. In order to reduce the time and expense of the laboratory testing, it is possible to use only one representative specimen to measure the shear strength, which is defined as the multi-stage testing method (Gullic 1970). The multi-stage testing procedure adopted in this study for direct/interface shear and pull-out tests comprises the following. The specimen is compressed under the first stage normal stress. After the practical completion of compression, the specimen is sheared/pulled out at a constant rate until failure or until a certain predetermined displacement is achieved. When the failure occurs, the test is stopped, and the normal stress is increased to the next predetermined level. The specimen is again allowed to compress under the new normal stress. After that, the specimen is again sheared/pulled out at the same constant rate until the second failure. This process is repeated for three or more stages (see **FIG 2**). Comparing the procedures of the single-stage and multi-stage methods, it is found that carrying out single-stage, large-scale tests are both time consuming and labour intensive, resulting in much higher costs. In general, to measure the shear strength parameters for engineering applications, the total cost of single-stage testing (three tests) will be approximately three times greater than the cost of multi-stage testing (only one test), regardless of more sampling costs that may be involved due to more specimens being required. Therefore, the multi-stage testing method introduced above was attempted in the large-scale direct/interface shear and pull-out tests in this study.

Experimental Program

Test Materials

To pursue the objectives of this study, Australian roadbase materials were collected from Pine Mountain Quarry, Brisbane, and tested at the Geomechanics Laboratory of the Geotechnical Engineering Centre at The University of Queensland (UQ). This included Australian Type 2.1 granite roadbase (designated as roadbase) and greenstone crusher dust (designated as dust). The particle size distributions of the roadbase materials are given in **FIG 3**. Also, Tensar SS40 geogrid (with a tensile strength of 40 kN/m) was used in this study to carry out the interface shear and pull-out tests, as shown in **FIG 4**. This type of biaxial geogrid, manufactured from a punched polypropylene sheet, is commonly used to reinforce the roadbase materials and to stabilise weak subgrade soils in road pavement construction in Australia. In summary, the basic properties of the test materials are shown in **TABLE 1**.

Testing Equipment

A large-scale direct shear apparatus manufactured by Wille Geotechnik of Germany (capable of performing both direct/interface shear and pull-out tests) was utilised in this study, as shown in **FIG 5**. The shear box (pull-out box) has dimensions of 300 mm by 300 mm by 200 mm and the sides of the box are 20 mm thick. The machine is moderately stiff to accommodate a load capacity of 100 kN in both horizontal and vertical directions (up to 1000 kPa). The floating upper box is designed to create a gap between the upper and lower halves of the shear box by means of two compression springs. Four linear variable displacement transducers (LVDTs) are installed on the four corners of the top loading cap to measure settlement and tilting. In the direct shear test, the upper half is fixed and the lower half is sheared, and the shear force mobilised during shearing is measured by a load cell. The geosynthetic can be clamped by grooved clamping bars on the top of the lower shear box for interface shear testing. A large number of direct and interface shear tests have been carried out using this machine (Xu et al. 2018b). Furthermore, the machine can be changed into pull-out testing mode after reassembling some parts, mainly by fixing the lower half of the shear box to the front counter-force beam, and reconnecting the pulling rod together with the load cell to a roller clamp used for clamping and pulling the geosynthetic (see **FIG 5**b). During the shearing or pulling processes, vertical displacement, horizontal displacement and shear force or pull-out force are measured and recorded at desired time intervals.

Testing Program

In order to evaluate the applicability, feasibility and reliability of multi-stage testing in the large-scale direct/interface shear and pull-out tests, both single-stage and multi-stage tests were carried out on the compacted roadbase materials and geogrid, under applied normal stresses of 15 kPa, 25 kPa, or 50 kPa, at the displacement rate of 1 mm/min. The normal stresses applied to the specimens represent the typical stress levels found in road pavements. The initial conditions controlled for the soils tested are summarised in **TABLE 2**. The internal shear stress τ_s of soil, interface shear stress τ_{ds} and pull-out shear stress τ_p between the soil and geogrid were obtained and compared in this study. Based on the shear strength results (τ_s, τ_{ds}, and τ_p) obtained, interface coefficients (f_{ds}, f_b and α) were then calculated and analysed.

Results and Discussion

Single-stage and Multi-stage Direct/Interface Shear Testing

Large-scale, single-stage and multi-stage, direct/interface shear tests were carried out on Roadbase, Dust, Roadbase-Geogrid and Dust-Geogrid. **FIG 6** compares the results of shear stress versus shear displacement plots under applied normal stresses of 15 kPa, 25 kPa or 50 kPa. In order to avoid excessive tilting of the top cap during the shearing process, a shear displacement of 30 mm (10% of total strain) was selected for the single-stage direct/interface test, while a shear displacement of 10 mm was selected for each stage of the multi-stage test, with the same total shear displacement of 30 mm after three stages. In addition, shear strength failure envelopes and inferred shear strength parameters are shown in **FIG 7** (see also **TABLE**

3 and **TABLE 4**). The failure envelopes were plotted using the shear strength (i.e., the shear stress at failure) against the applied normal stress at failure. Failure was taken as the maximum (ultimate) shear stress attained within a shear strain of 10%. It should be noted that both the measured shear stress and applied normal stress were corrected for the area reduction and then plotted to determine the failure envelopes.

From **FIG 6** and **FIG 7**, it can clearly be seen that the shear stress curves and failure envelopes match quite closely for the single-stage and multi-stage test results. In particular, for the first stage under the applied normal stress of 15 kPa, the shear stress curves are almost identical (see **FIG 6**). However, the multi-stage testing method limits the shear displacement that can be applied to each stage. Especially under a high normal stress, more shear displacement is required to reach a peak. Moreover, the earlier stages may affect the shear strength achieved in the later stages, so that the accumulated error of the ultimate shear strength for the last stage is particularly obvious, as shown in **FIG 6**. Therefore, the failure envelopes of the multi-stage results tend to be slightly lower than those of the single-stage results (see **FIG 7**). This agrees with the small-scale, multi-stage direct shear test results available in the literature (Gullic 1970; Hormdee et al. 2012). In addition, the slope of the shear stress curve for the later stages obtained from a multi-stage test tends to be steeper than that obtained from a single-stage test under the same applied normal stress. This indicates that shear stress can be mobilised more rapidly in the later stages. The soil specimen in a multi-stage test, with a pre-failure surface associated with particle reorientation, would behave in a more brittle manner than a fresh new specimen in a single-stage test. Furthermore, most of the specimens (**FIG 6** a and b) of the large-scale direct shear tests show a strain-hardening behaviour for both single-stage and multi-stage tests; that is, the stress increases with strain without a peak being reached. However, some interface shear tests on the soils and geosynthetic show a slight strain-softening in the post-peak stage if a peak was achieved within 10% of the shear strain, as shown in **FIG 6** c and d. A possible explanation for the different behaviour of the direct shear and interface shear tests might be that a peak tends to be achieved in interface shear tests due to the soil particle reorientation along the geogrid ribs and apertures. For all the multi-stage tests, because the maximum strain applied to each stage was limited to 3.3% the ultimate shear strength was not obtained. Comparison with the single stage tests without a geogrid, suggests that slight strain-hardening behaviour would be expected, whereas with a geo-grid, slight strain-softening behaviour would be expected. Despite this, the multi-stage tests gave similar shear strength parameters to the single stage tests. As a large shear box can accommodate larger displacements than a small shear box, multi-stage testing using a large shear box can provide more reliable results than those obtained using a small shear box. Also, tedious sample preparation for a large-scale, single-stage direct shear test is both very time consuming and labour intensive because a large quantity of soil specimens is involved.

Single-stage and Multi-stage Pull-out Testing

A pull-out displacement of 60 mm was selected in the single-stage test, while a pull-out displacement of 20 mm was selected for each stage in the multi-stage test, with the same total pull-out displacement of 60 mm after three stages. **FIG 8** shows the pull-out resistance versus pull-out displacement plots under applied normal stresses of 15 kPa, 25 kPa or 50 kPa for the pull-out testing of the geogrid embedded in Roadbase and Dust. The pull-out shear strength failure envelopes obtained by single-stage and multi-stage pull-out testing are compared in **FIG 9**, showing that the envelopes obtained from the multi-stage tests tend to be slightly lower than those from the single-stage tests, except for one shear strength data point obtained from the multi-stage pull-out testing of Roadbase-Geogrid under the applied normal stress of 50 kPa. The pull-out shear stress τ_p mobilised along the soil-geogrid interface in the pull-out tests was calculated by Eq. 8. As also shown in **FIG 8**, it is noteworthy that the single-stage pull-out test results tend to show an elastic-plastic behaviour with a yield point, while the multi-stage pull-out test results basically show a nonlinear-elastic behaviour. Because the multi-stage pull-out tests were limited to a maximum strain of 3.3% for each stage, it is found that the friction resistance increases with pull-out displacement throughout the pulling process, without a peak being reached. Therefore, similar limitations of the multi-stage testing method in pull-out tests can be listed as: 1) multi-stage pull-out test would limit the pull-out displacement that can be applied to each stage, which may not be sufficient to achieve a peak. This is most noticeable for the final stage under the highest normal stress, which tends to require more pull-out displacement, and 2) the earlier stages may affect the maximum (ultimate) pull-out resistance achieved in the later stages. However, the maximum pull-out resistance obtained in this study still matched quite closely despite these limitations, as shown in **FIG 8** and **FIG 9**. All the pull-out results for Roadbase-Geogrid and Dust-Geogrid are further summarised in **TABLE 5** for convenience.

It should be noted that the high strength geogrids (such as the Tensar SS series) with strong ribs and thick joints have excellent tensile performance, so the extension of the geogrid embedded in roadbase materials was found to be negligible under the road service load (within 50 kPa) in the pull-out tests. The maximum pull-out resistance achieved for the Tensar SS40 geogrid under applied normal stress of 50 kPa ranged from 24 kPa to 28 kPa in this study, which was still within the ultimate tensile strength 40 kN/m of SS40 (see also **FIG 8**). It should also be noted that higher applied normal stresses of 75 kPa and 100 kPa were also attempted in our study; however, sudden rupture failure of the SS40 geogrid at the clamping area was found to occur frequently, instead of the pull-out failure. This is because the pull-out resistance achieved was close to its tensile strength 40 kN/m, and the clamper was not capable of gripping the geogrid sufficiently tightly. **FIG 10** presents two photos of Tensar SS40 geogrid embedded in Roadbase and Dust following the pull-out testing under the applied normal stress of 50 kPa (after removal of the soil on the top of the geogrid). As shown in **FIG 10**, the free end of the geogrid moved together with the front clamping bar during the pulling process, and all the nodes of the geogrid had the same horizontal pull-out displacement. Overall, there was no obvious extension or distortion observed for the geogrid. This observation is different from some previously published pull-out studies on different geosynthetics (Alfaro et al. 1995; Alobaidi et al. 1997; Perkins and Cuelho 1999; Moraci and Gioffre; 2006; Moraci and Recalcati 2006; Hsieh et al. 2011; Ferreira et al. 2015). These different findings could be due to three reasons: 1) the poor mechanical properties of geosynthetics tested; 2) relatively higher normal stress applied in their research, which caused significantly non-uniform deformation of geosynthetics during the pulling processes; and 3) the occurrence of rupture failures of the geosynthetics rather than the expected pull-out failures. The deformation of geosythetics in the large-scale pull-out tests is deserved further study using some advanced measurement techniques, such as fiber bragg grating sensors or optical fiber sensors (Pei et al. 2013; Wang et al. 2015).

Comparisons of Shear Strength Parameters Obtained from Single-stage and Multi-stage Tests

Shear strength parameters (c, ϕ) and interface parameters (c_a, δ) were calculated based on the failure envelopes obtained from the single-stage and multi-stage direct/interface shear and pull-out tests. It was found that the apparent cohesions obtained from the multi-stage tests are slightly lower than those from the single-stage tests (see **FIG 11**a). However, the friction angles obtained from the multi-stage tests are not always lower, as shown in **FIG 11**b. In general, they are still very close to the single-stage test results. The errors of the apparent cohesions (either c or c_a) and friction angles (either ϕ or δ) ranged from -2.7 kPa to 0.3 kPa, and -1.8° to 2.4° for all the multi-stage and single-stage tests in this study (see **FIG 11**c and **TABLE 6**). The errors were calculated by the multi-stage test results minus the single-stage test results, as shown in

Table 6. Therefore, the multi-stage testing method can produce relatively reliable shear strength parameters for the large-scale direct/interface shear and pull-out tests.

Relationship Between Direct Shear Stress, Interface Shear Stress and Pull-out Shear Stress

The relationship between direct shear stress, interface shear stress and pull-out shear stress is still not quite clear due to the different shear mechanisms for a wide range of soils and geosynthetics. It was therefore decided to compare the shear stresses obtained from the direct/interface shear and pull-out tests to seek any potential relationship. **FIG 12** shows the shear stress curves obtained from direct/interface shear and pull-out tests using single-stage and multi-stage testing methods, under applied normal stresses of 15 kPa, 25 kPa or 50 kPa. It can be observed that the shear stress curves of the soil-geogrid interface are quite close to those of soils alone for both the single-stage and multi-stage direct/interface shear testing. However, the shear stress curves obtained from the pull-out tests tend to flatten out with more horizontal displacement required to reach the failure, indicating that the mobilisation of shear stress along the soil-geogrid interface is much slower in the pull-out tests than in the interface shear tests. The horizontal displacement required for the pull-out tests was doubled (60 mm for the single-stage tests and 20 mm for each stage of the multi-stage tests) compared to the direct shear tests (30 mm for the single-stage tests and 10 mm for each stage of the multi-stage tests), to ensure that the pull-out resistance could be sufficiently developed. It can be clearly observed that the pull-out shear stress mobilised along the soil-geogrid interface is relatively lower than the corresponding interface shear stress within a horizontal displacement of 30 mm under each normal stress. This is most noticeable for the single-stage tests under the highest normal stress of 50 kPa. However, the maximum interface shear stress mobilised is still comparable when the pull-out displacement reached a horizontal displacement of 60 mm (see **FIG 12**a-b). Also, from the multi-stage test results (see **FIG 12**c-d), the same conclusion can readily be drawn. In addition, it is recommended that the required horizontal displacement be increased with increasing applied normal stress (higher confinement) in order to sufficiently develop the shear stress (see also **FIG 12**).

FIG 13 compares the failure envelopes of the soil-geogrid interface obtained from the interface shear and pull-out tests. In general, the failure envelopes obtained from the pull-out tests are slightly lower than those obtained from the interface shear tests. It should be noted that area correction for both normal stress and shear stress is necessary since a significant reduction in the contact area would cause an increase in both normal stress and shear stress in large-scale direct/interface shear and pull-out tests. For example, when a normal stress of 50 kPa was subjected to a specimen, the actual applied normal stress at failure was higher than 50 kPa, as shown in **FIG 13**. Therefore, even though some shear strengths obtained from the pull-out tests were found to be higher than those from the interface shear tests, the failure envelopes were, however, generally slightly lower. This is because the horizontal displacement was doubled (60 mm) for the pull-out tests, so that the actual normal stress at failure increased after applying the area correction. Therefore, the obtained failure envelopes were flattened.

FIG 14 compares the direct shear strength of soils τ_s, interface shear strength τ_{ds} and pull-out shear strength τ_p of soil-geogrid interfaces, and their empirical relationships. In general, quite good linear relationships were found in **FIG 14** for both the single-stage and multi-stage results. The interface shear strengths τ_{ds} and pull-out shear strengths τ_p are quite close to the direct shear strengths τ_s of the soils. In addition, interface parameters f_{ds}, f_b, and α calculated by Eqs. (3), (7) and (10) are presented in **FIG 15** and **TABLE 7**. It can be found that the average values of these three parameters (1.043, 0.984 and 0.946) were similar to the linear regression results of all data (1.028, 0.995 and 0.969), which are all quite close to 1. Therefore, based on the interface parameters obtained, these three shear strengths can be correlated with each other.

Finally, the relationship between the single-stage and multi-stage test results was constructed through linear regression of all the experimental shear strength data obtained, as shown in **FIG 16**. It can be found that a good linear relationship exists, although the shear strengths obtained from the multi-stage tests were slightly lower. **FIG 16** has shown the reliability of the multi-stage testing method applied to both large-scale direct/interface shear and pull-out testing of compacted soils and a geogrid.

Conclusion

In this paper, a multi-stage testing method was attempted for both large-scale direct/interface shear and pull-out tests. The obtained multi-stage test results were analysed and compared with the obtained conventional single-stage test results. In summary, the main conclusions of this paper are:

(1) The multi-stage testing method was successfully applied to large-scale direct/interface shear and pull-out testing of compacted soils and a geogrid, resulting in slightly lower shear strengths and reasonably accurate shear strength and interface parameters for compacted soils and a geogrid.

(2) The measured direct shear strengths of soils τ_s, interface shear strengths τ_{ds}, and pull-out shear strengths τ_p of compacted soil-geogrid interfaces are found to be very close in this study, resulting in the interface parameters f_{ds}, f_b, and α close to 1.

(3) The mobilisation of the interface shear stress between the soil and geosynthetic in pull-out tests is much slower than that in the interface shear tests, so that more horizontal displacement is required for pull-out tests.

(4) The main limitation of multi-stage tests is that it limits the shear/pull-out displacement that can be applied to each stage, which may not be sufficient. Therefore, a suitable

displacement for each stage should be chosen with particular caution, considering the properties and the initial conditions of specimens.

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Caption List of Figures

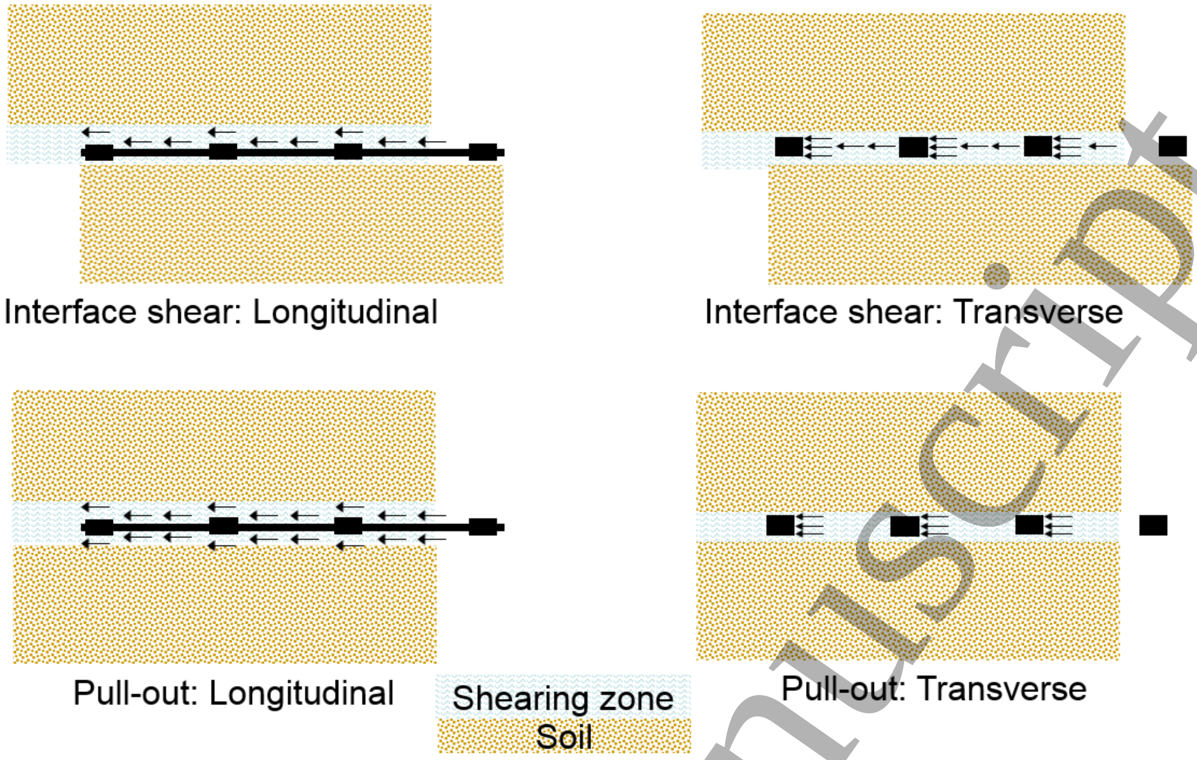


FIG 1 Soil-geogrid interaction mechanisms for interface shear and pull-out testing.

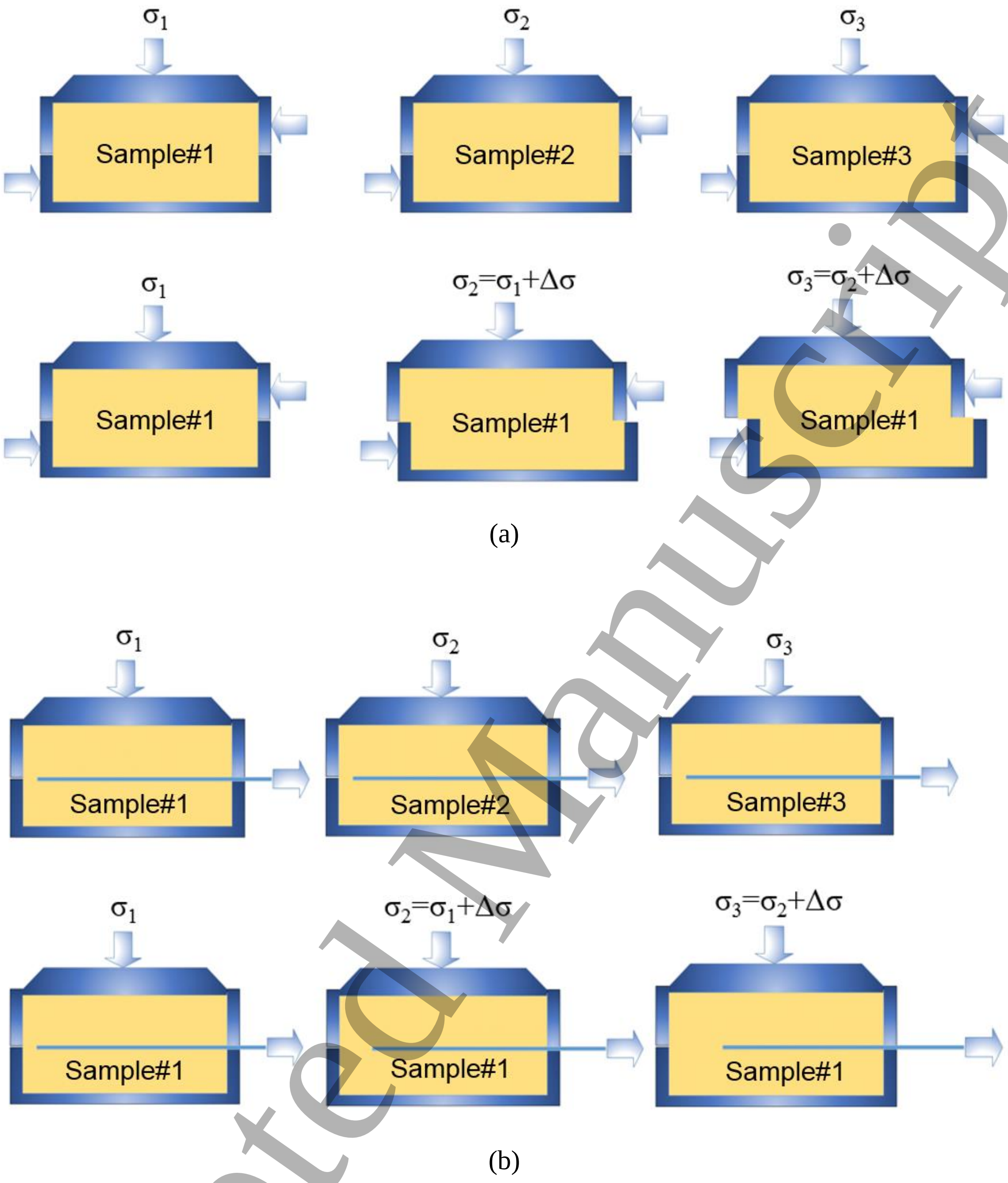


FIG 2 Single-stage and multi-stage testing in: (a) direct/interface shear test and (b) pull-out test.

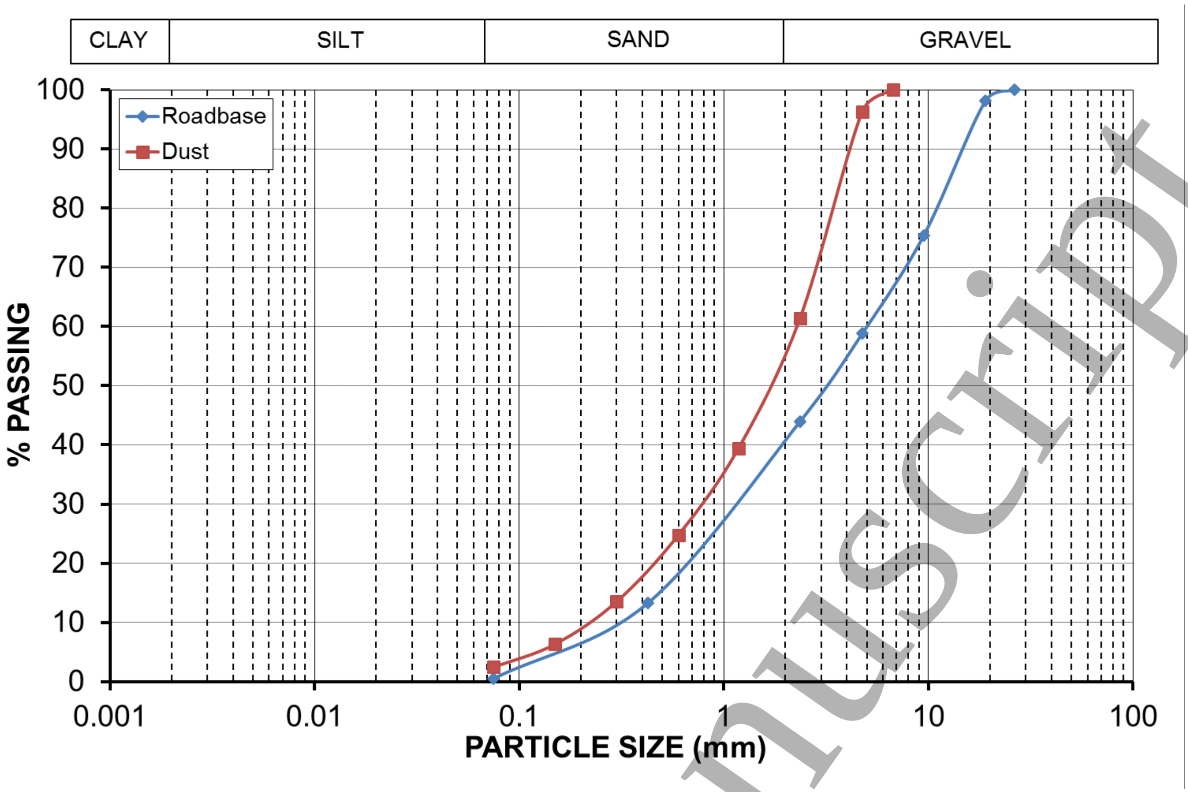


FIG 3 Particle-size distribution curves of tested soils.

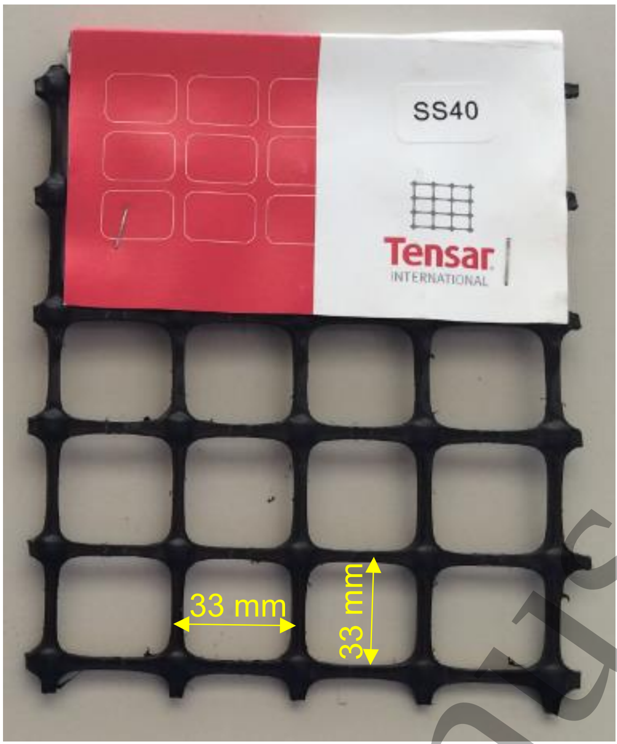
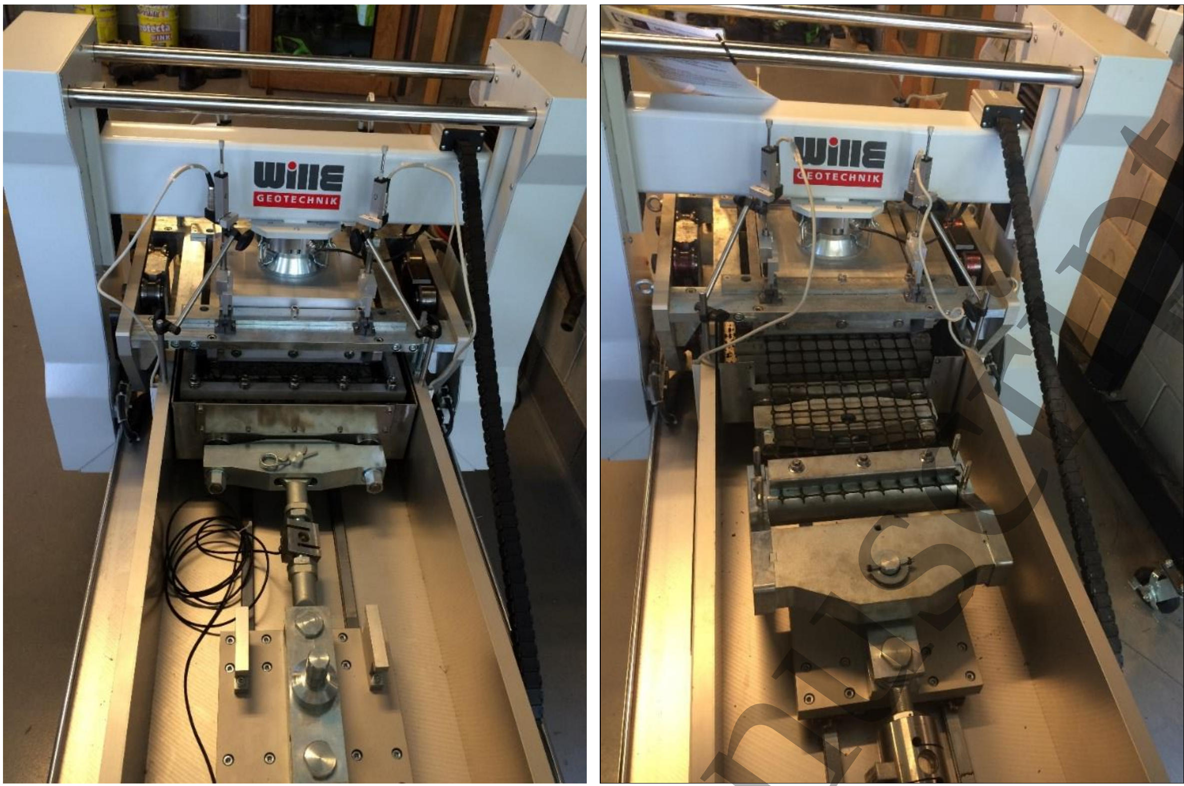
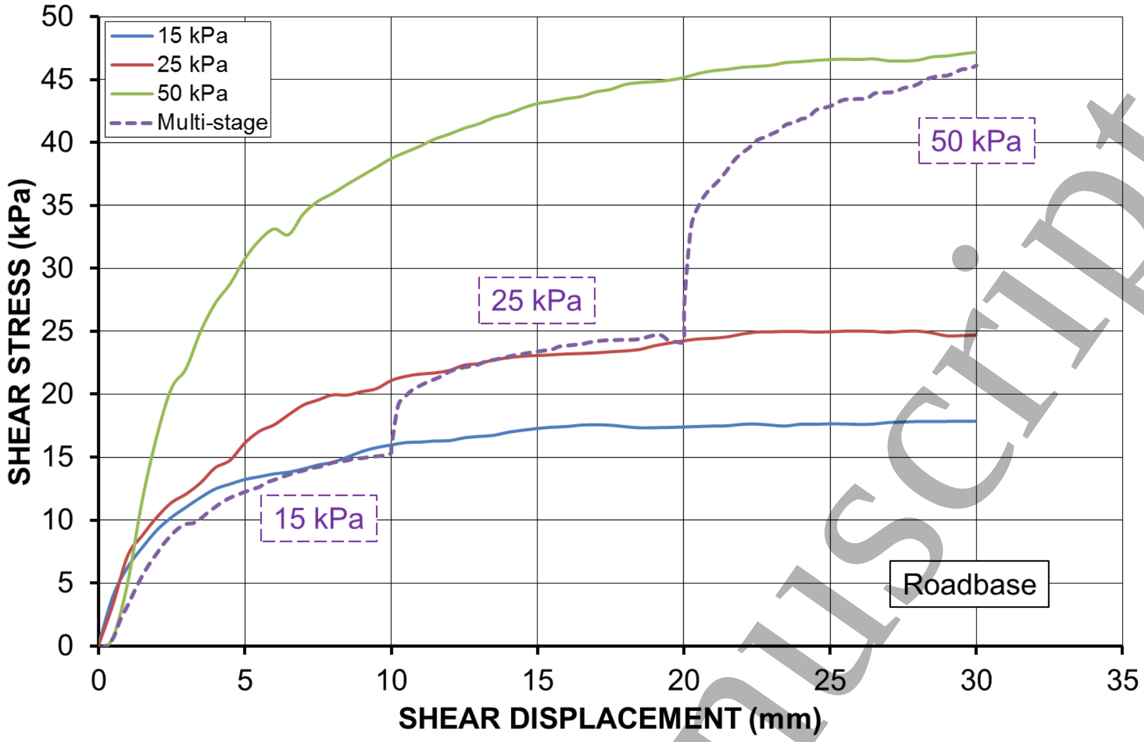


FIG 4 Tensar SS40 geogrid.



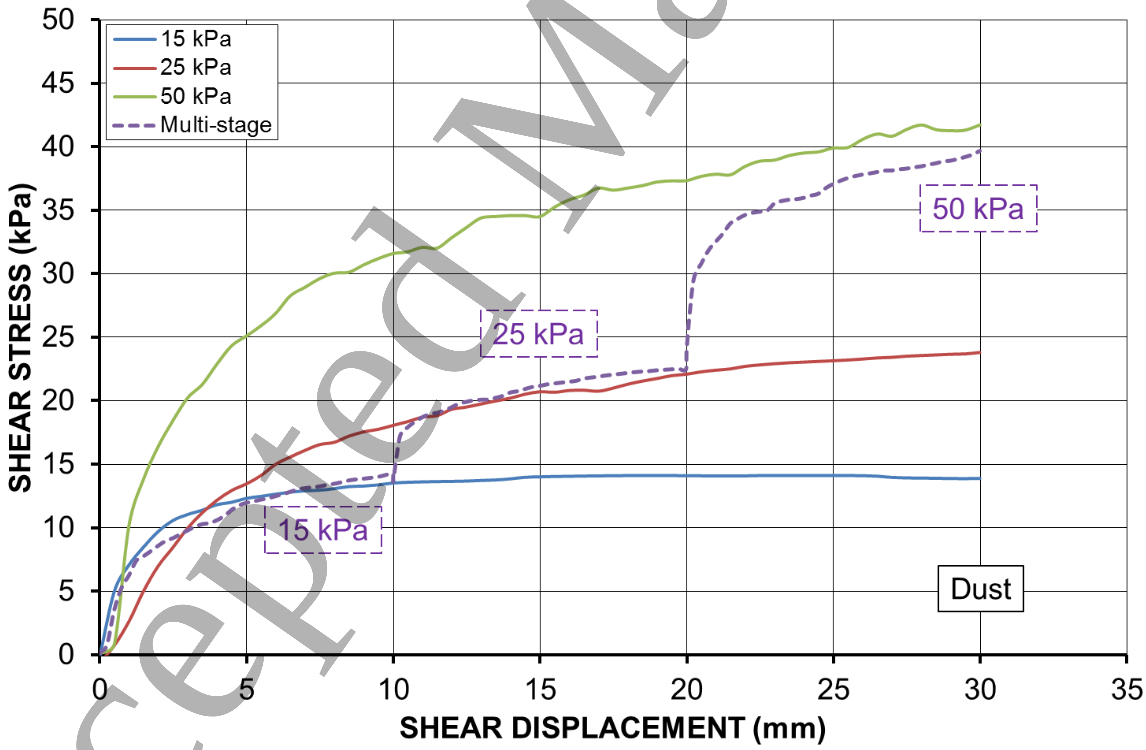
(a) (b)

FIG 5 Testing equipment: (a) direct/interface shear testing mode and (b) pull-out testing mode.



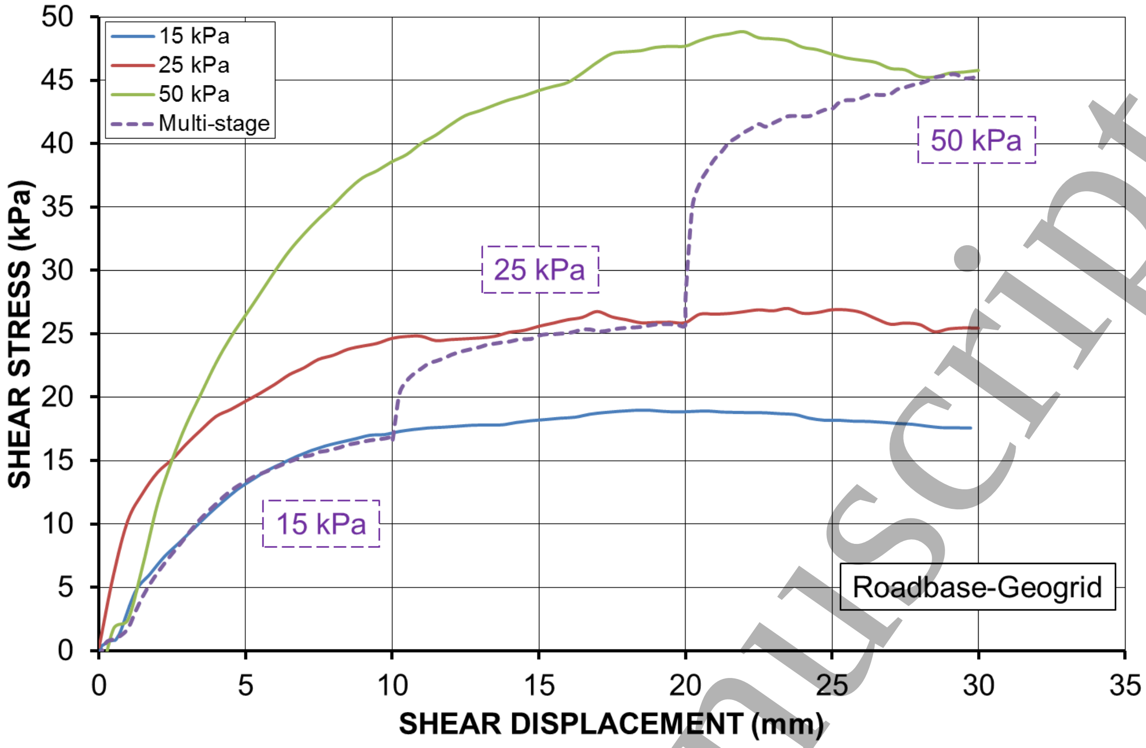
15 kPa
25 kPa
50 kPa
Multi-stage
50 kPa
25 kPa
15 kPa
Roadbase
SHEAR STRESS (kPa)
SHEAR DISPLACEMENT (mm)
0
5
10
15
20
25
30
35
40
45
50

(a)

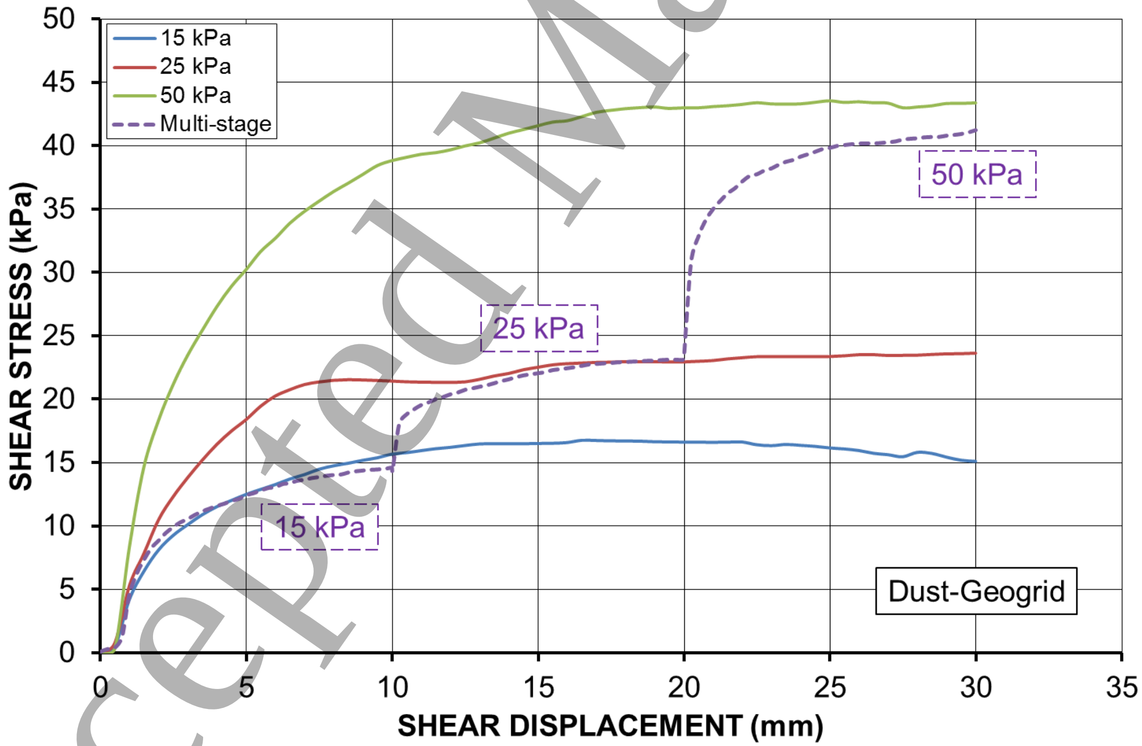


15 kPa
25 kPa
50 kPa
Multi-stage
50 kPa
25 kPa
15 kPa
Dust
SHEAR STRESS (kPa)
SHEAR DISPLACEMENT (mm)
0
5
10
15
20
25
30
35
40
45
50

(b)

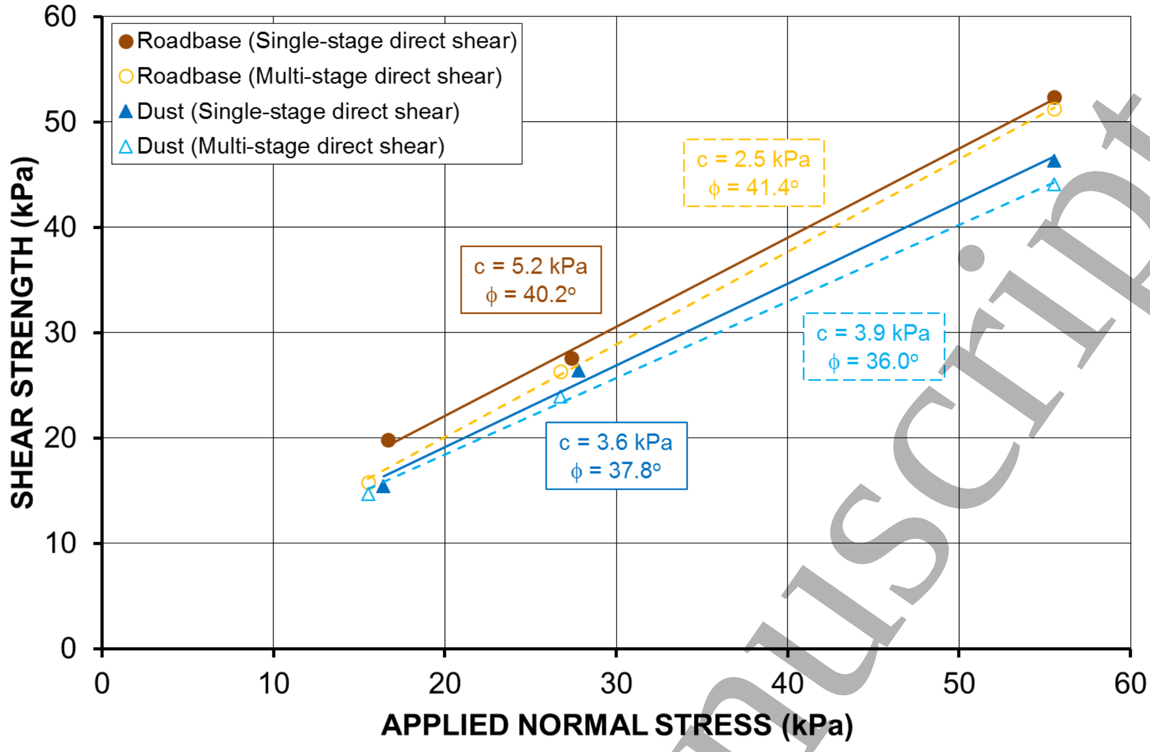


(c)

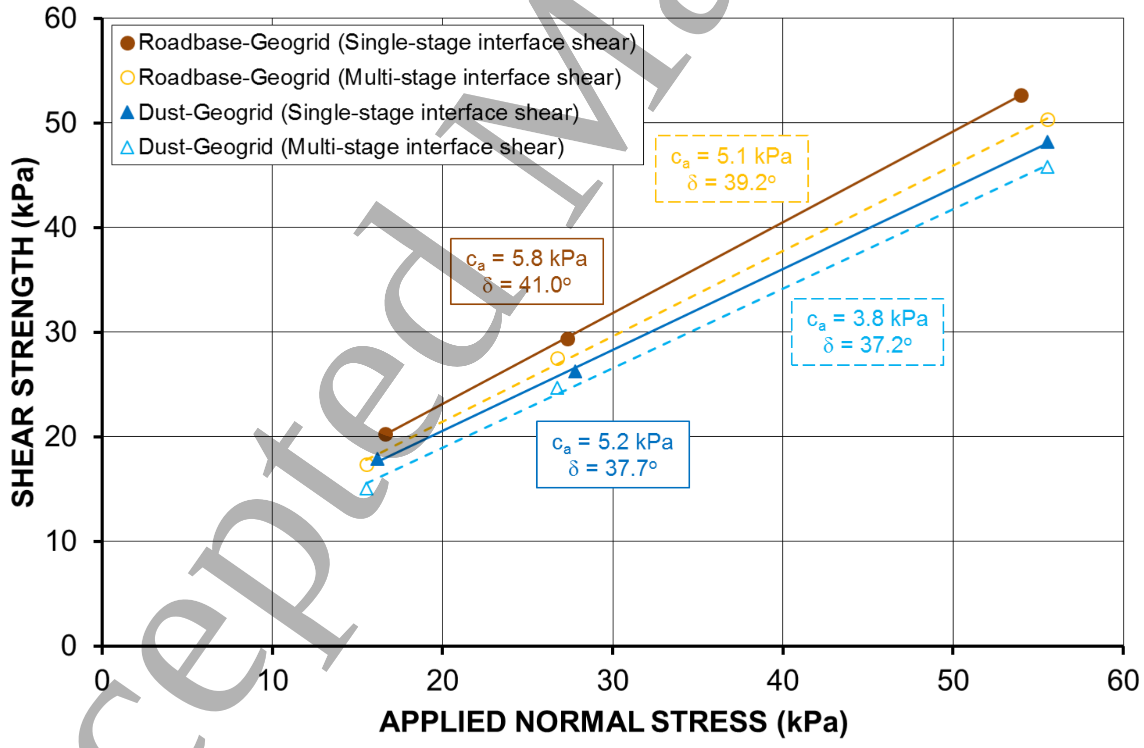


(d)

FIG 6 Single-stage and multi-stage direct/interface shear test results: (a) Roadbase, (b) Dust, (c) Roadbase-Geogrid, and (d) Dust-Geogrid.

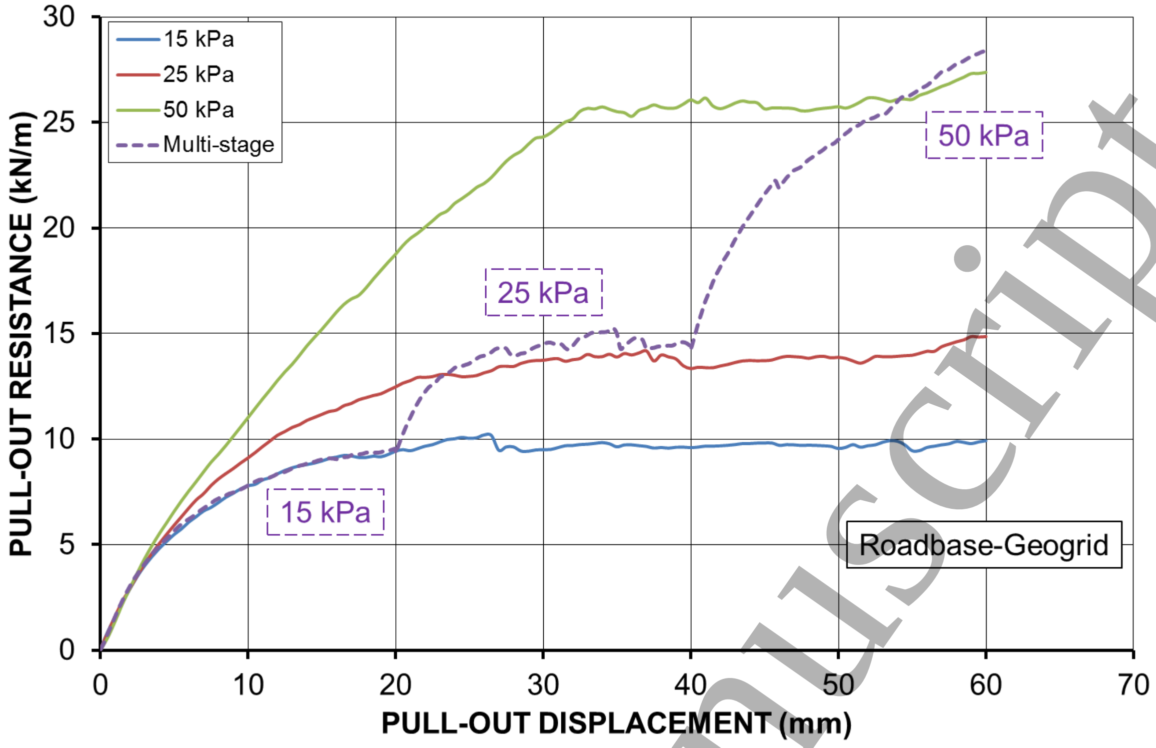


(a)

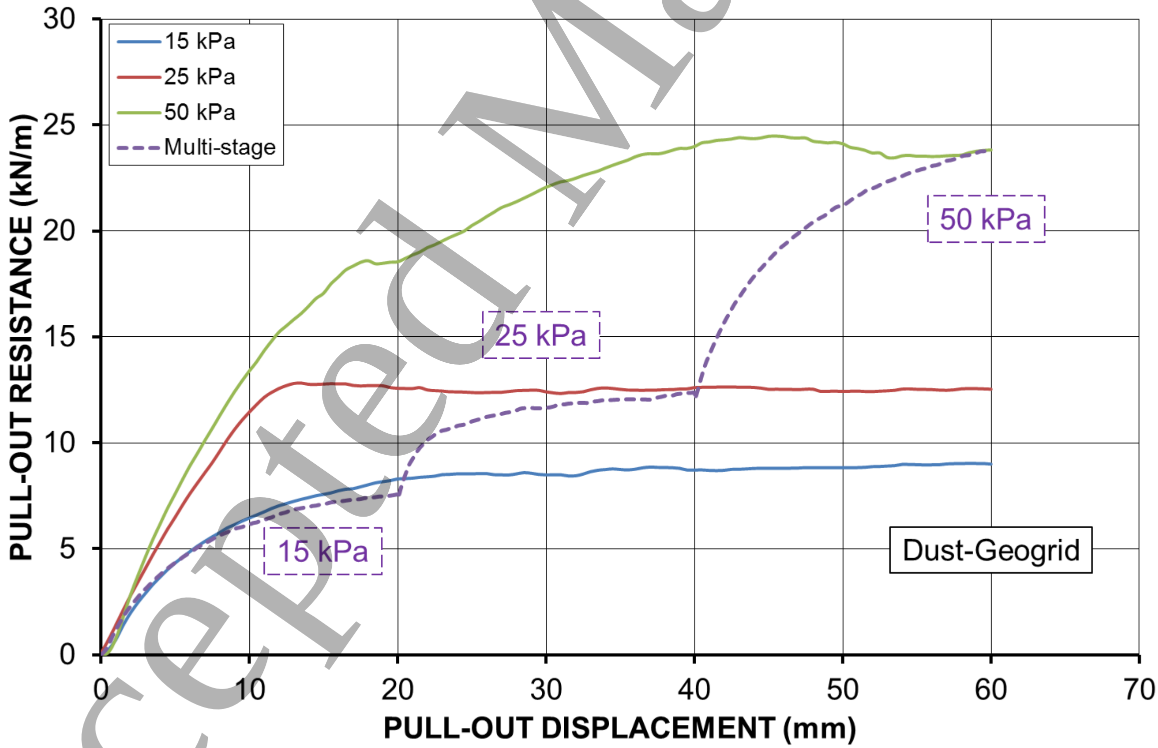


(b)

FIG 7 Comparisons of failure envelopes for single-stage and multi-stage tests: (a) direct shear and (b) interface shear.



(a)



(b)

FIG 8 Single-stage and multi-stage pull-out test results: (a) Roadbase-Geogrid and (b) Dust-Geogrid.

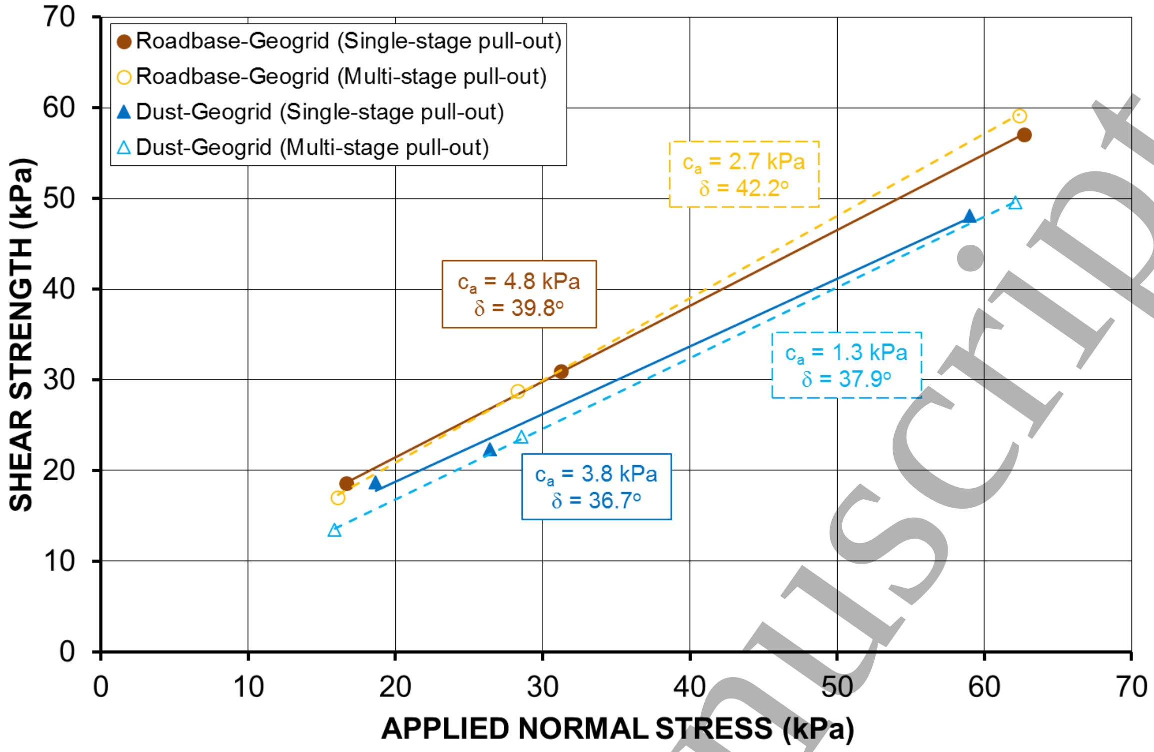
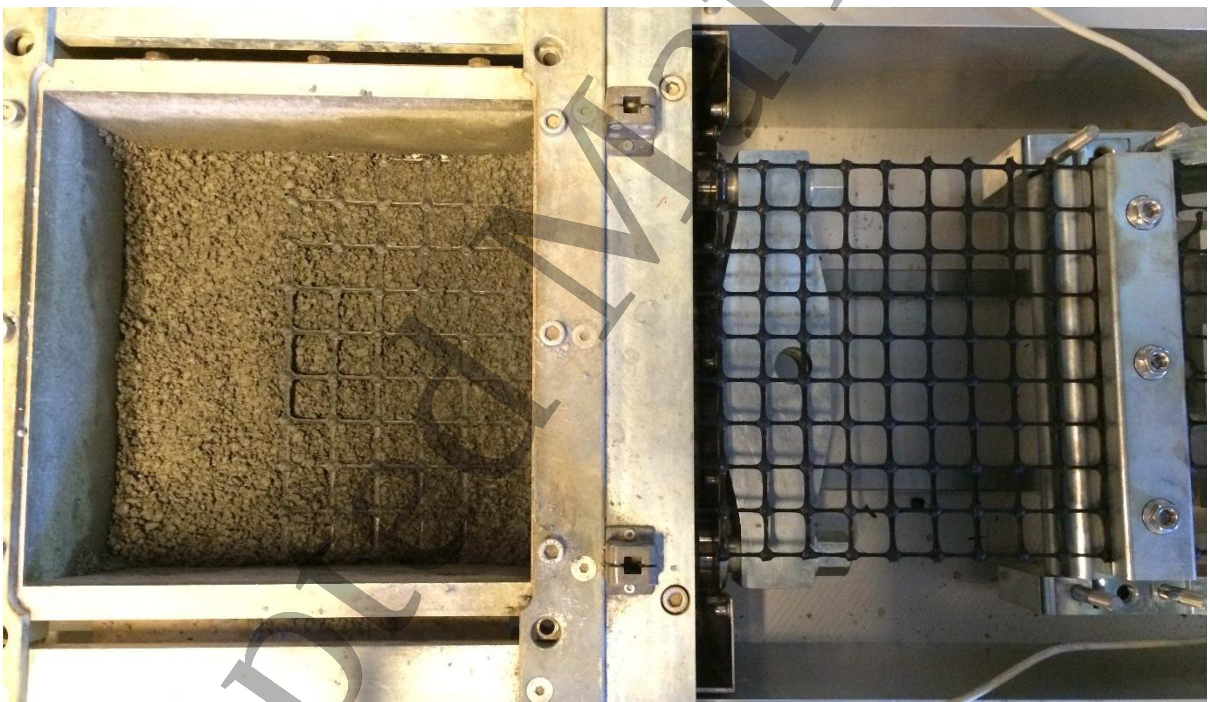


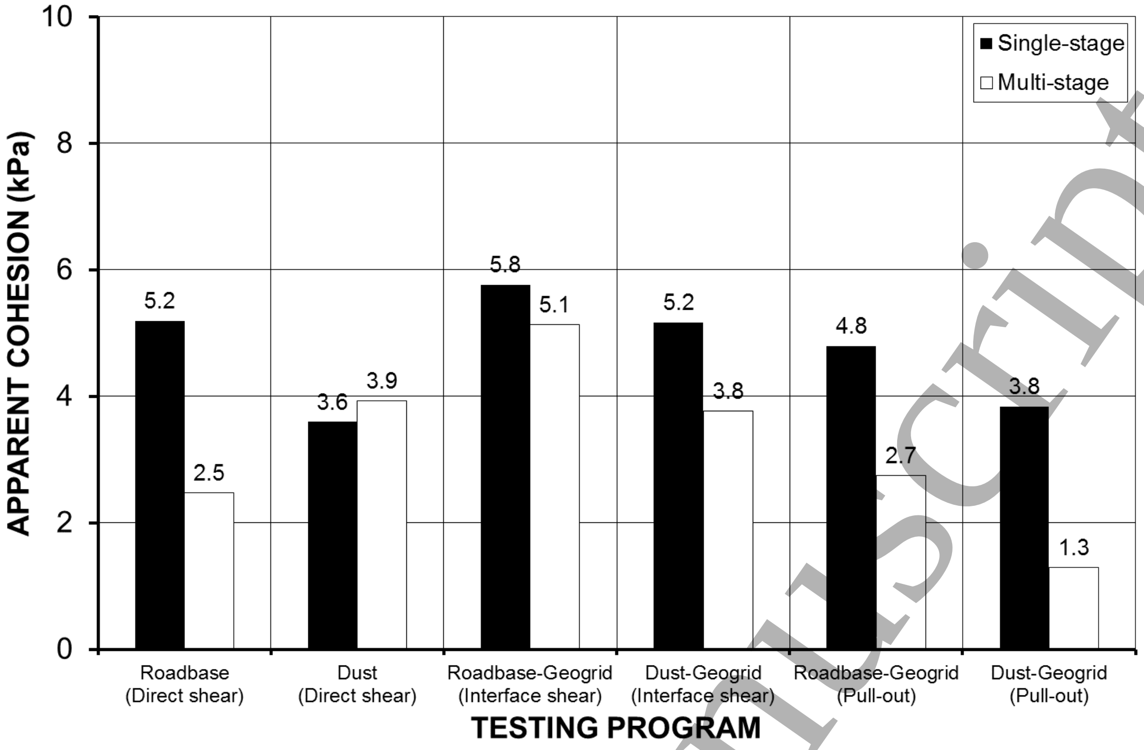
FIG 9 Comparisons of failure envelops for single-stage and multi-stage pull-out tests.

(a)

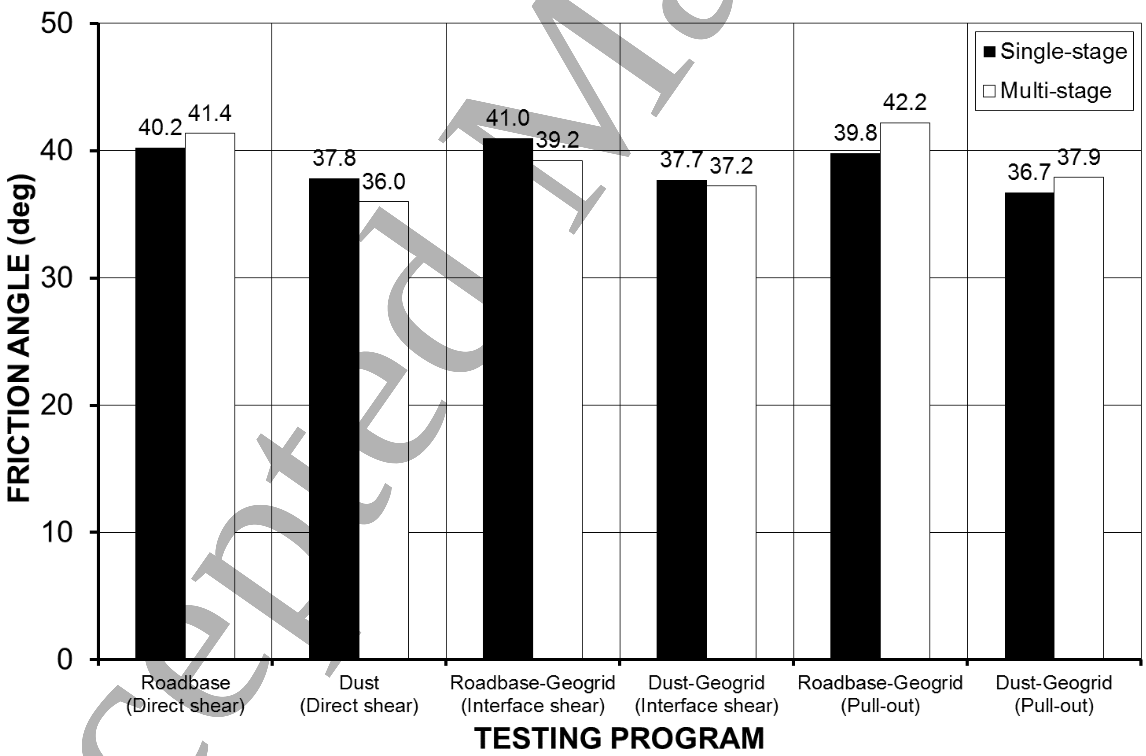


(b)

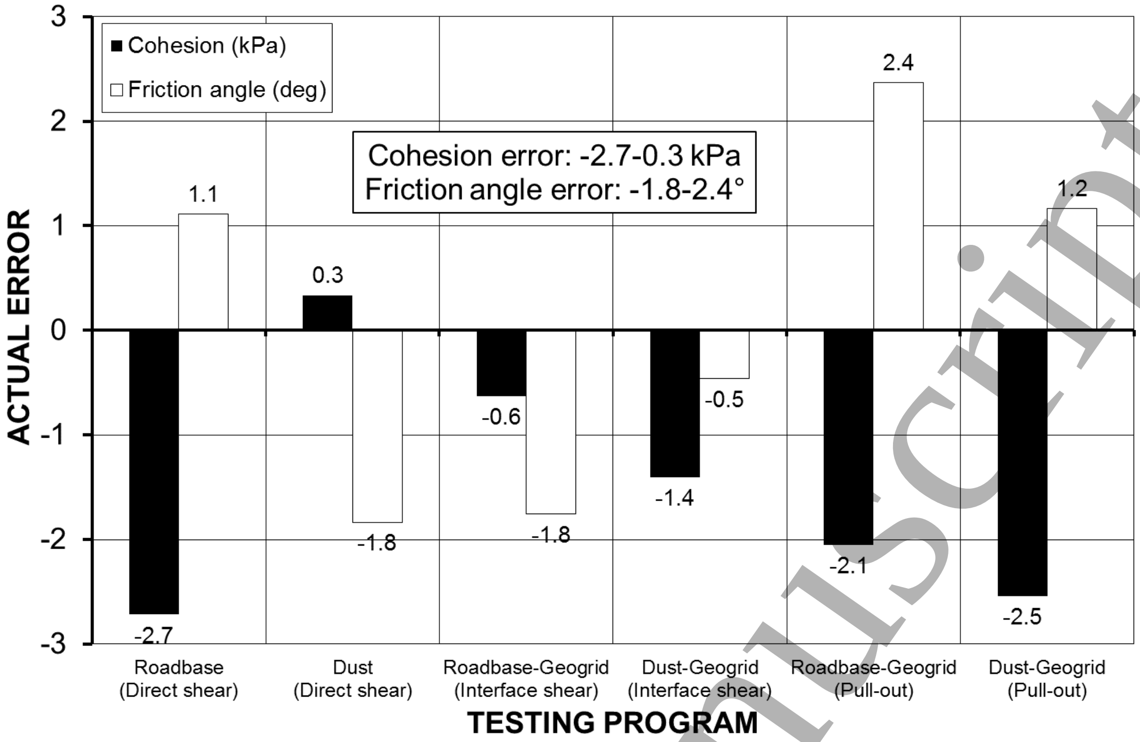
FIG 10 Two photos of Tensar SS40 geogrid embedded in soils after pull-out testing under applied normal stress of 50 kPa: (a) embedded in Roadbase and (b) embedded in Dust.


APPARENT COHESION (kPa)
Single-stage
Multi-stage
5.2
2.5
3.6
3.9
5.8
5.1
5.2
3.8
4.8
2.7
3.8
1.3
Roadbase (Direct shear)
Dust (Direct shear)
Roadbase-Geogrid (Interface shear)
Dust-Geogrid (Interface shear)
Roadbase-Geogrid (Pull-out)
Dust-Geogrid (Pull-out)
TESTING PROGRAM

(a)

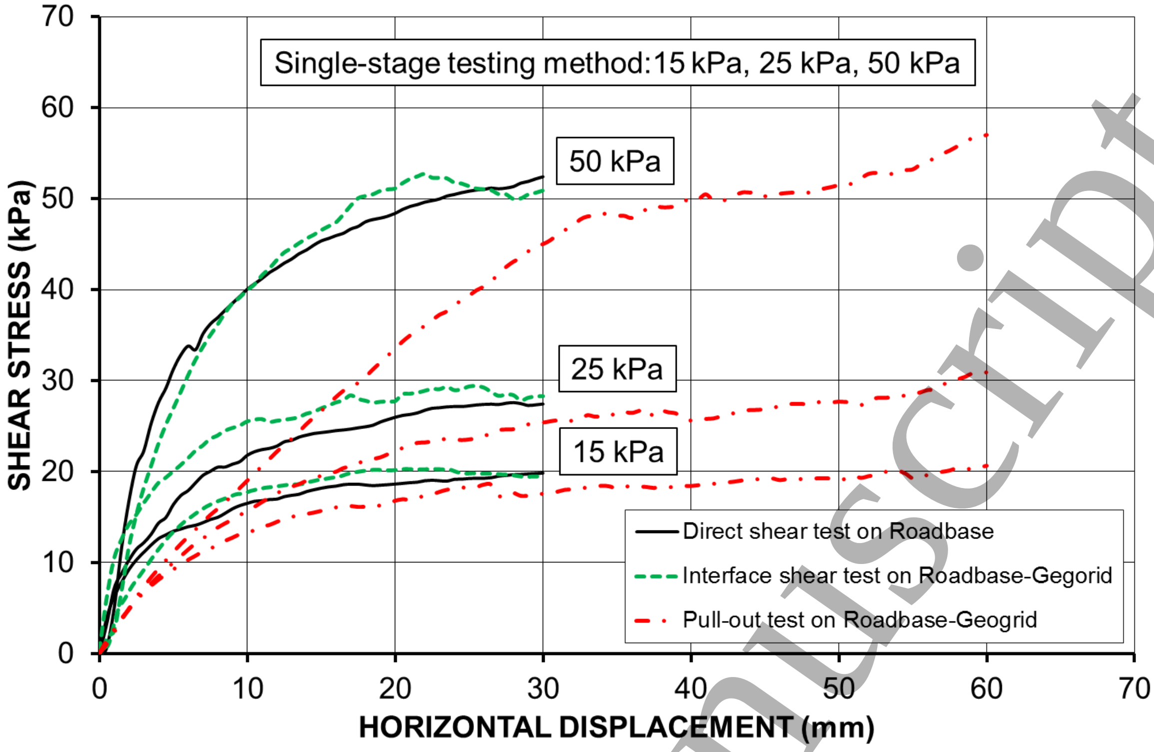

FRICTION ANGLE (deg)
Single-stage
Multi-stage
40.2
41.4
37.8
36.0
41.0
39.2
37.7
37.2
39.8
42.2
36.7
37.9
Roadbase (Direct shear)
Dust (Direct shear)
Roadbase-Geogrid (Interface shear)
Dust-Geogrid (Interface shear)
Roadbase-Geogrid (Pull-out)
Dust-Geogrid (Pull-out)
TESTING PROGRAM

(b)

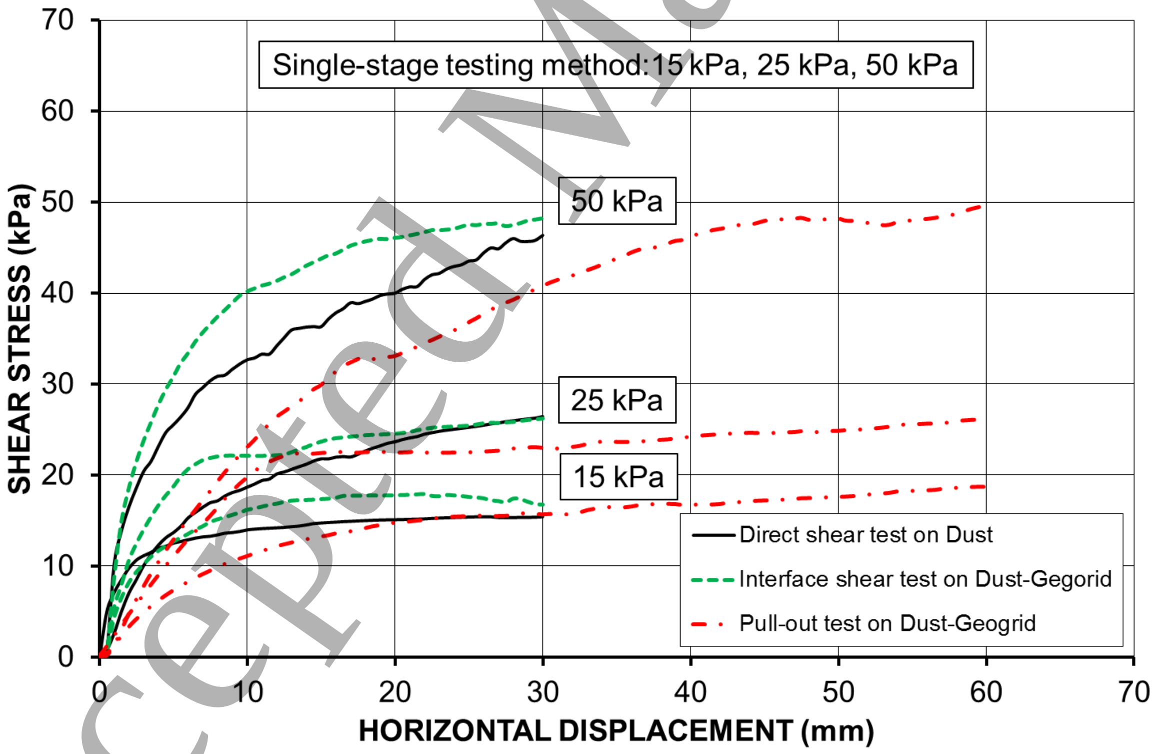


(c)

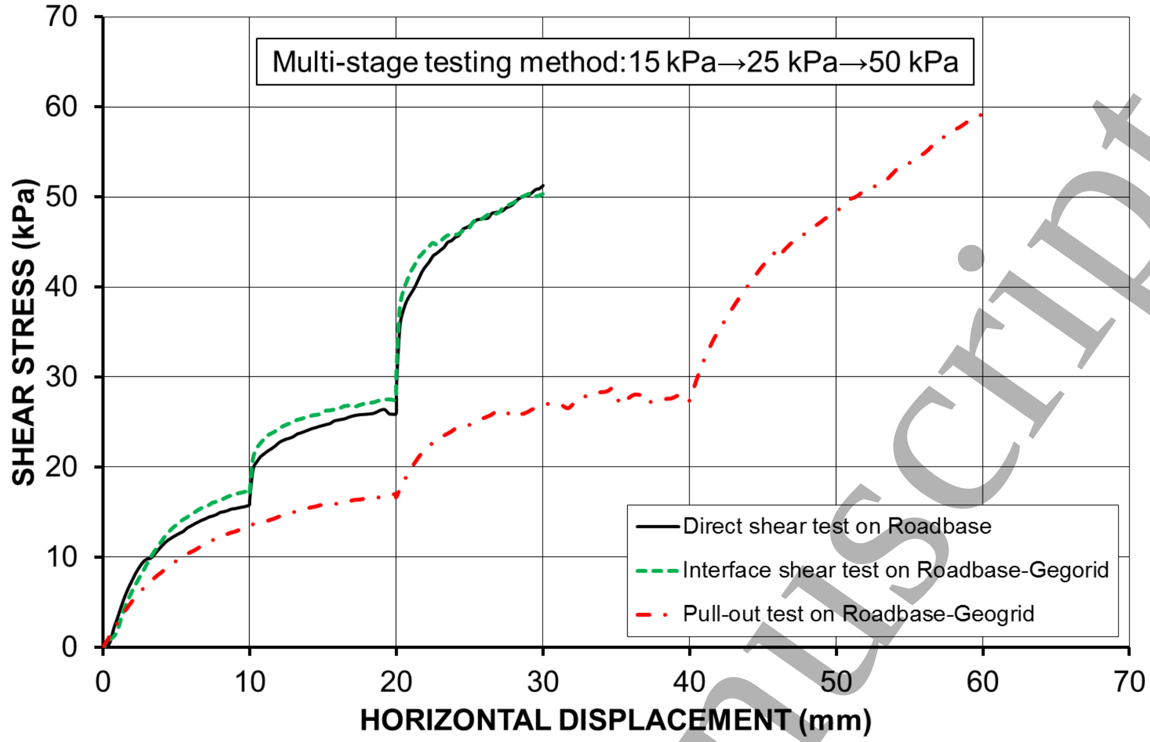
FIG 11 Comparisons of shear strength parameters obtained from single-stage and multi-stage tests: (a) cohesion, (b) friction angle, and (c) error between two testing methods.


Single-stage testing method:15 kPa, 25 kPa, 50 kPa
50 kPa
25 kPa
15 kPa
Direct shear test on Roadbase
Interface shear test on Roadbase-Gegorid
Pull-out test on Roadbase-Geogrid
SHEAR STRESS (kPa)
HORIZONTAL DISPLACEMENT (mm)
0
10
20
30
40
50
60
70

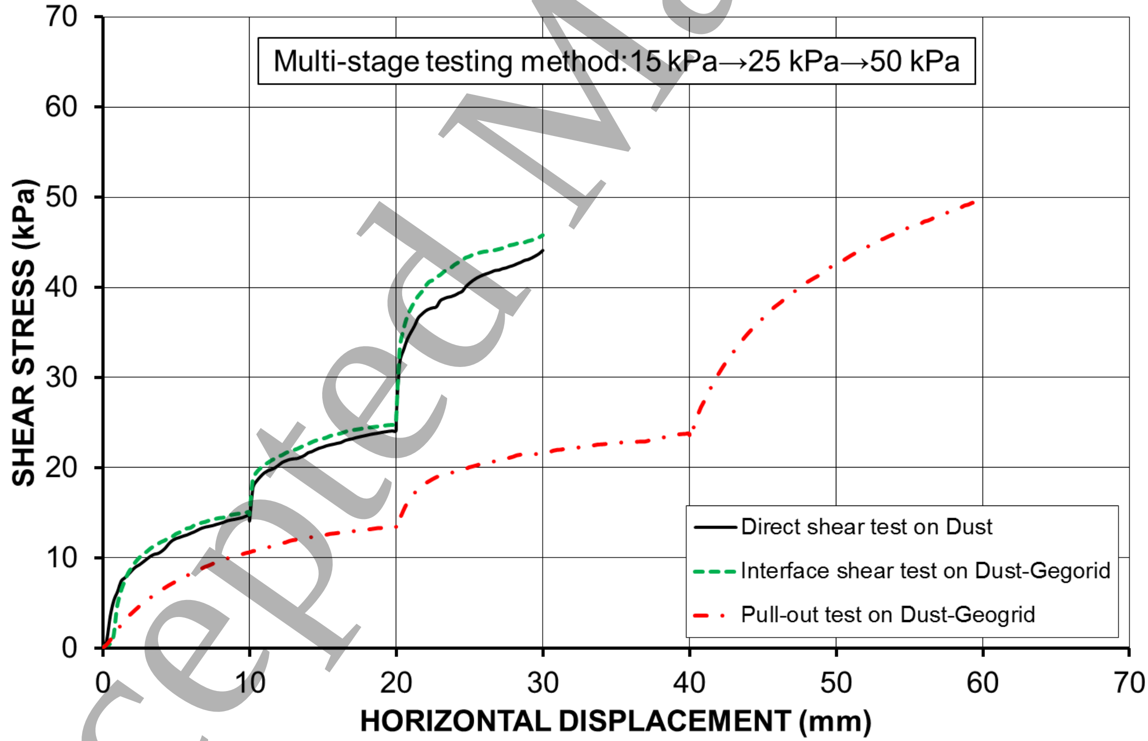
(a)


Single-stage testing method:15 kPa, 25 kPa, 50 kPa
50 kPa
25 kPa
15 kPa
Direct shear test on Dust
Interface shear test on Dust-Gegorid
Pull-out test on Dust-Geogrid
SHEAR STRESS (kPa)
HORIZONTAL DISPLACEMENT (mm)
0
10
20
30
40
50
60
70

(b)

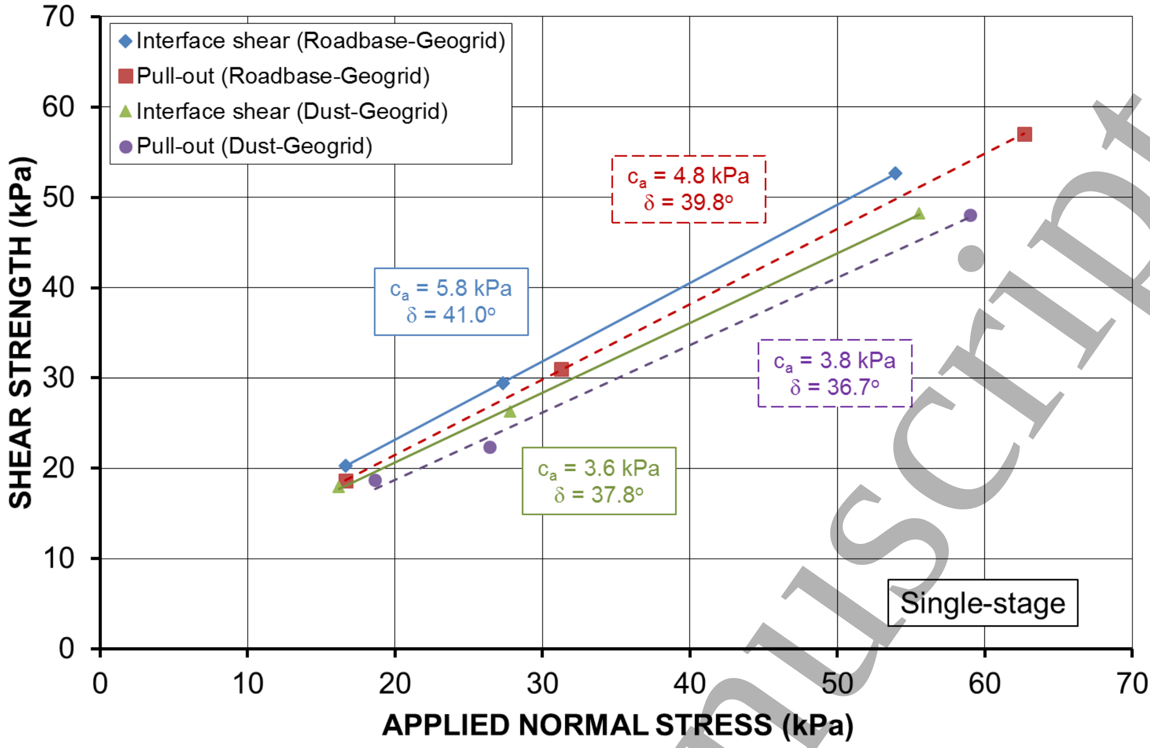


(c)

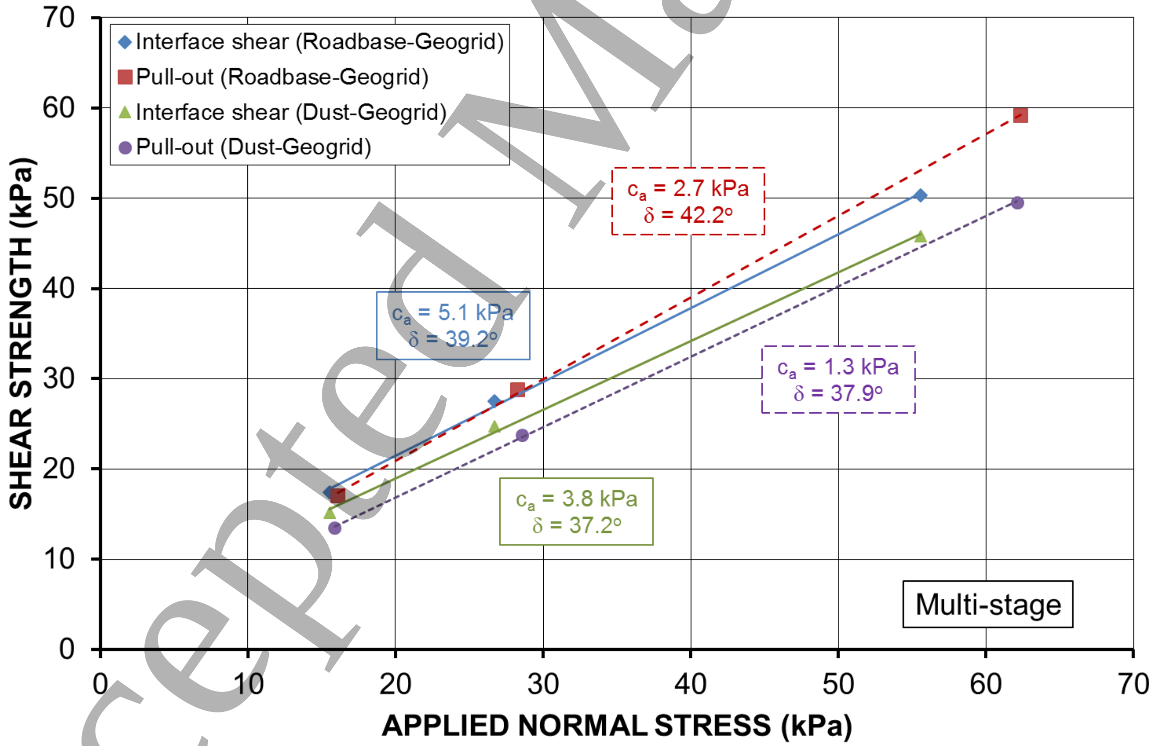


(d)

FIG 12 Comparisons of shear stress curves obtained from direct/interface shear and pull-out tests: (a) single-stage test on Roadbase, (b) single-stage test on Dust, (c) multi-stage test on Roadbase, and (d) multi-stage test on Dust.

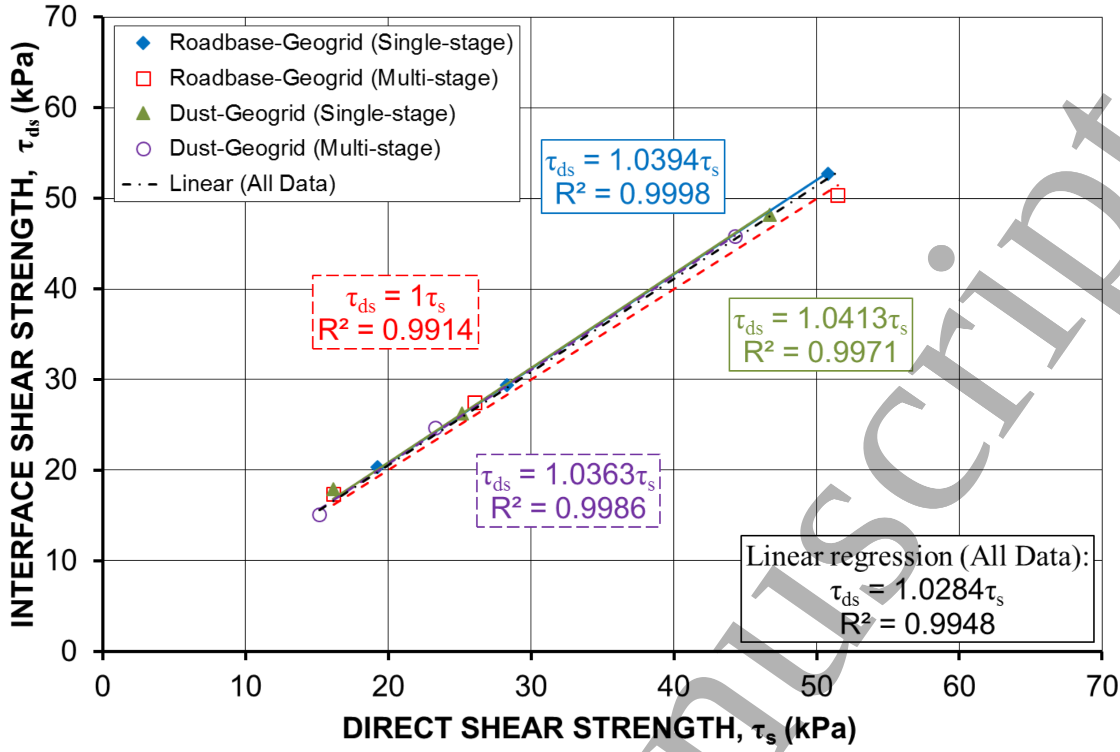


(a)

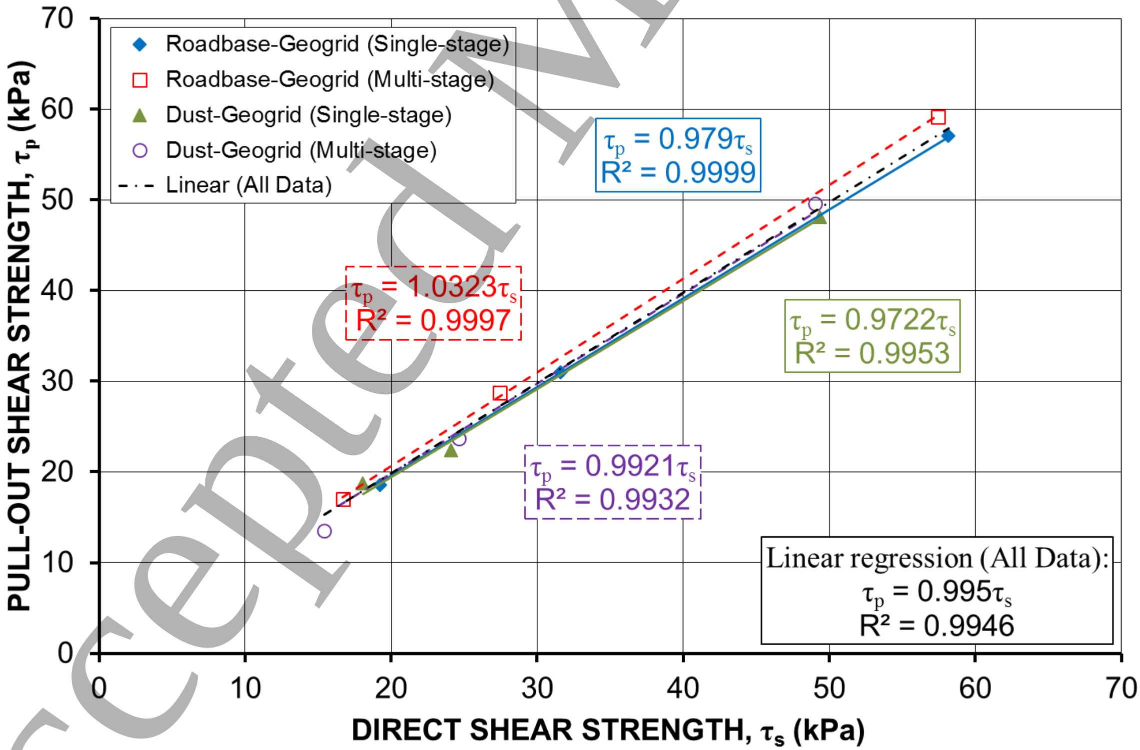


(b)

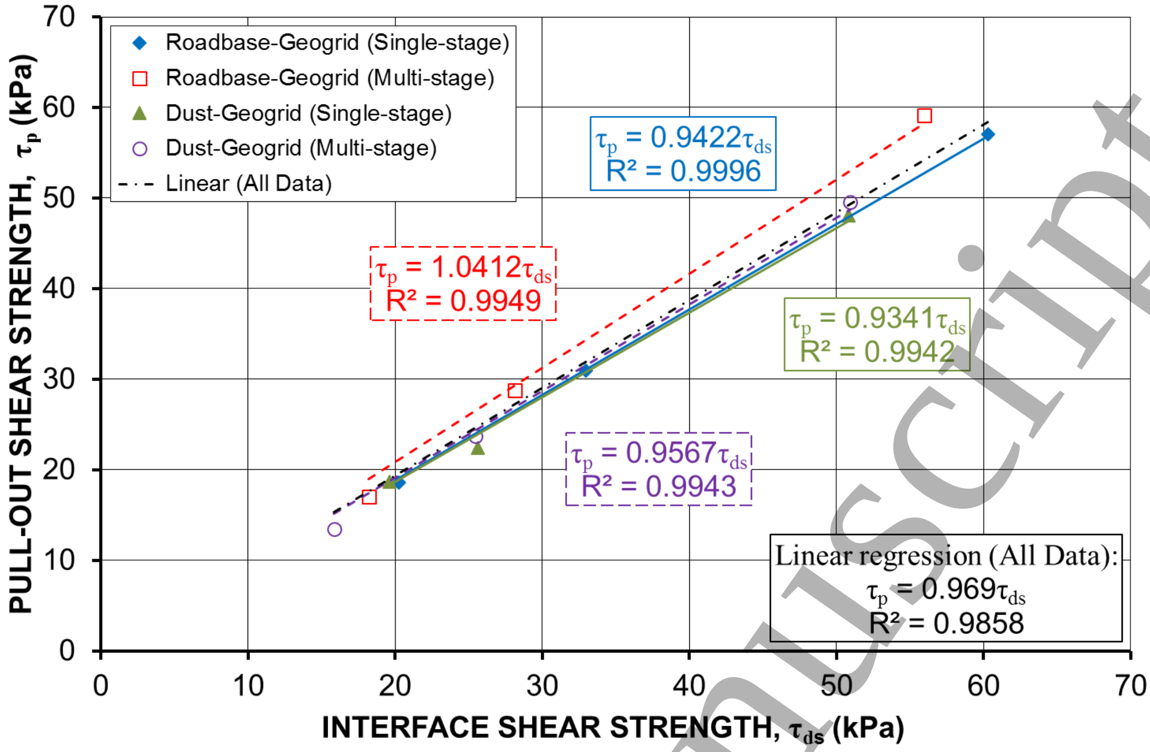
FIG 13 Comparisons of failure envelops obtained from interface shear and pull-out tests: (a) single-stage and (b) multi-stage.


Roadbase-Geogrid (Single-stage)
Roadbase-Geogrid (Multi-stage)
Dust-Geogrid (Single-stage)
Dust-Geogrid (Multi-stage)
Linear (All Data)
τ_{ds} = 1.0394τ_s
R² = 0.9998
τ_{ds} = 1τ_s
R² = 0.9914
τ_{ds} = 1.0413τ_s
R² = 0.9971
τ_{ds} = 1.0363τ_s
R² = 0.9986
Linear regression (All Data):
τ_{ds} = 1.0284τ_s
R² = 0.9948
INTERFACE SHEAR STRENGTH, τ_{ds} (kPa)
DIRECT SHEAR STRENGTH, τ_s (kPa)

(a)

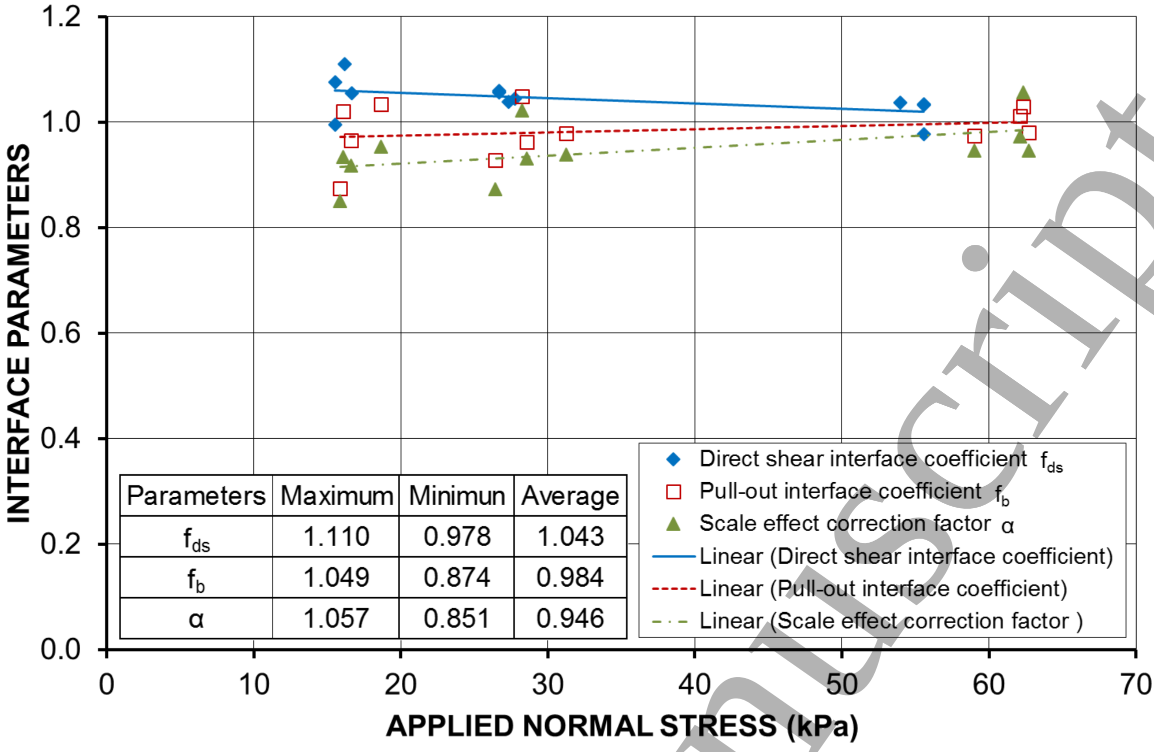

Roadbase-Geogrid (Single-stage)
Roadbase-Geogrid (Multi-stage)
Dust-Geogrid (Single-stage)
Dust-Geogrid (Multi-stage)
Linear (All Data)
τ_p = 0.979τ_s
R² = 0.9999
τ_p = 1.0323τ_s
R² = 0.9997
τ_p = 0.9722τ_s
R² = 0.9953
τ_p = 0.9921τ_s
R² = 0.9932
Linear regression (All Data):
τ_p = 0.995τ_s
R² = 0.9946
PULL-OUT SHEAR STRENGTH, τ_p (kPa)
DIRECT SHEAR STRENGTH, τ_s (kPa)

(b)



(c)

FIG 14 Comparisons of shear strengths obtained from direct/interface shear and pull-out tests: (a) τ_{ds} versus τ_s, (b) τ_p versus τ_s, and (c) τ_p versus τ_{ds}.



Parameters	Maximum	Minimun	Average
f_{ds}	1.110	0.978	1.043
f_b	1.049	0.874	0.984
α	1.057	0.851	0.946

FIG 15 Calculated value of interface parameters.

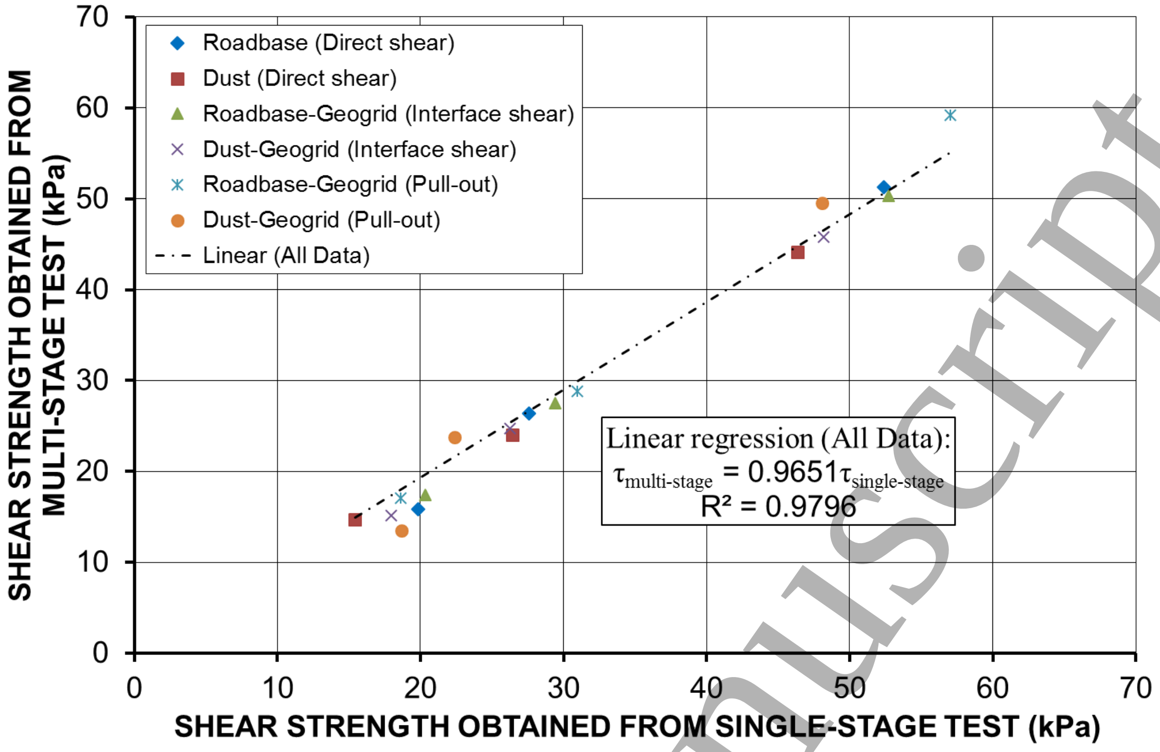


FIG 16 Linear regression of shear strengths for single-stage and multi-stage tests.

Caption List of Tables:

TABLE 1 Basic properties of tested materials.

Soil	D_{50} (mm)	C_u	C_c	G_s	OMC (%)	ρ_{dmax} (t/m^3)	USCS
Roadbase	3.1	15.45	1.34	2.706	6.1	2.275	GW
Dust	1.8	9.58	1.16	2.725	8.8	2.158	SW
Geogrid	**Polymer**	**Aperture Shape**	**Tensile Strength (kN/m)**	**Aperture size (mm)**	**Nodal thickness (mm)**	**Nominal rib thickness (mm)**	**Percentage of opening area (%)**
Tensar SS40	Polypropylene	Square	40	33×33	5.8	2.5	77.4

TABLE 2 Initial conditions controlled for tested soils.

Soils	Moisture content (%)	Specimen mass (kg)	Bulk density ρ (t/m^3)	Dry density ρ_d (t/m^3)	Void ratio
Roadbase	4.80	22	1.95	1.86	0.46
Dust	5.03	21	1.85	1.76	0.55

TABLE 3 Direct shear test results for Roadbase and Dust.

Roadbase				Dust			
Single stage		Multi-stage		Single stage		Multi-stage	
σ_n (kPa)	τ_s (kPa)	σ_n (kPa)	τ_s (kPa)	σ_n (kPa)	τ_s (kPa)	σ_n (kPa)	τ_s (kPa)
16.7	19.8	15.5	15.8	16.4	15.4	15.5	14.7
27.4	27.6	26.7	26.4	27.8	26.4	26.7	24.0
55.6	52.4	55.6	51.3	55.6	46.4	55.6	44.1
c (kPa)	φ (°)	c (kPa)	φ (°)	c (kPa)	φ (°)	c (kPa)	φ (°)
5.2	40.2	2.5	41.4	3.6	37.8	3.9	36.0

TABLE 4 Interface shear test results for Roadbase-Geogrid and Dust-Geogrid.

Roadbase-Geogrid				Dust-Geogrid			
Single stage		Multi-stage		Single stage		Multi-stage	
σ_n (kPa)	τ_{ds} (kPa)	σ_n (kPa)	τ_{ds} (kPa)	σ_n (kPa)	τ_{ds} (kPa)	σ_n (kPa)	τ_{ds} (kPa)
16.6	20.3	15.5	17.4	16.2	17.9	15.5	15.1
27.3	29.4	26.7	27.5	27.8	26.3	26.7	24.7
54.0	52.7	55.6	50.4	55.6	48.2	55.6	45.8
c_a (kPa)	δ (°)	c_a (kPa)	δ (°)	c_a (kPa)	δ (°)	c_a (kPa)	δ (°)
5.8	41.0	5.1	39.2	5.2	37.7	3.8	37.2

TABLE 5 Pull-out test results for Roadbase-Geogrid and Dust-Geogrid.

Roadbase-Geogrid				Dust-Geogrid			
Single stage		Multi-stage		Single stage		Multi-stage	
σ_n (kPa)	τ_p (kPa)	σ_n (kPa)	τ_p (kPa)	σ_n (kPa)	τ_p (kPa)	σ_n (kPa)	τ_p (kPa)
16.6	18.6	16.1	17.0	18.6	18.7	15.9	13.5
31.3	31.0	28.3	28.8	26.4	22.4	28.6	23.7
62.7	57.0	62.3	59.2	59.0	48.1	62.1	49.6
c_a (kPa)	δ (°)	c_a (kPa)	δ (°)	c_a (kPa)	δ (°)	c_a (kPa)	δ (°)
4.8	39.8	2.7	42.2	3.8	36.7	1.3	37.9

TABLE 6 Shear strength parameters obtained from direct/interface shear and pull-out tests.

Specimen	Test	Single-stage		Multi-stage		Errors	
		c (kPa)	*φ* (°)	*c* (kPa)	*φ* (°)	*c* (kPa)	*φ* (°)
Roadbase	Direct shear	5.2	40.2	2.5	41.4	-2.7	1.1
Dust	Direct shear	3.6	37.8	3.9	36.0	0.3	-1.8
Roadbase-Geogrid	Interface shear	5.8	41.0	5.1	39.2	-0.6	-1.8
Dust-Geogrid	Interface shear	5.2	37.7	3.8	37.2	-1.4	-0.5
Roadbase-Geogrid	Pull-out	4.8	39.8	2.7	42.2	-2.1	2.4
Dust-Geogrid	Pull-out	3.8	36.7	1.3	37.9	-2.5	1.2

Note: For interface shear and pull-out tests, c, φ also stand for the apparent adhesion c_a and interface friction angle δ herein for simplicity.

TABLE 7 Interface parameters obtained from interface shear and pull-out tests.

Specimen	Test	Direct shear		Pull-out test		
		σ_n (kPa)	f_{ds}	σ_n (kPa)	f_b	α
Roadbase-Geogrid	Single-stage	16.6	1.054	16.6	0.966	0.918
		27.3	1.039	31.3	0.979	0.939
		54.0	1.037	62.7	0.980	0.946
	Multi-stage	15.5	1.076	16.1	1.021	0.935
		26.7	1.056	28.3	1.049	1.022
		55.6	0.978	62.3	1.029	1.057
Dust-Geogrid	Single-stage	16.2	1.110	18.6	1.035	0.953
		27.8	1.044	26.4	0.929	0.873
		55.6	1.032	59.0	0.974	0.947
	Multi-stage	15.5	0.995	15.9	0.874	0.851
		26.7	1.059	28.6	0.963	0.931
		55.6	1.035	62.1	1.011	0.973
Average			1.043		0.984	0.946