Proceedings of the 9th World Congress on Civil, Structural, and Environmental Engineering (CSEE 2024)
London, United Kingdom – April 14-16, 2024
Paper No. ICGRE 159
DOI: 10.11159/icgre24.159

Plane Strain Sand Properties from Numerical Modelling of Direct Shear Test

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Abstract **-** Direct shear test is the simplest, inexpensive and the oldest among shear tests in soil laboratories. Although such test is commonly used in research and practice, analysis for many long geotechnical structures such as earth pressure and slope stability problems require measurement of plane strain soil properties. Plane strain soil properties are complex and need special skills and equipment to measure in the lab. Therefore, engineers usually rely on empirical relations to predict the plane strain soil properties from direct shear or triaxial test. In this study, a two-dimensional, plane strain finite difference model is employed in the software FLAC to simulate the mechanical behaviour of sandy soil tested in direct shear box. The study showed that the results of the finite element analysis complied with those obtained from laboratory tests conducted with the help of a direct shear box. The plane strain properties of the sandy soil can be back calculated from numerical simulations of direct shear tests with reasonable accuracy. Moreover, the numerical model was able to capture the trend in the experimental results and in most cases gave reasonable estimate of the shear strength and volume change of sandy soil.

Keywords**:** Direct shear, Numerical modelling, Sandy soil, Plane strain conditions, FLAC.

1. Introduction

The Direct Shear Box Test method has been widely used by researchers and practitioners to determine engineering properties of sand soils under shearing stresses due to its rapid and ease of operation [1, 2, 3]. Despite the disadvantages and limitations of the direct shear apparatus, mostly because of the nonuniform distribution of stresses and strains and for progressive failure within the sample during shearing, it is still the most widely used method. Typical laboratory setup for direct shear test is shown in Fig 1. Constant normal load applied at top of the specimen produces a uniform normal stress over the soil sample. A uniform displacement is applied to the lower half of the box to shear the material inside from the predetermined horizontal plane between the two halves. Thus, a thin, well-defined failure surface is provided in that plane, where the failure in shear is to be measured. The change in height of the material is also measured from the top of loading cap in order to determine volume changes and dilatancy of sandy soil.

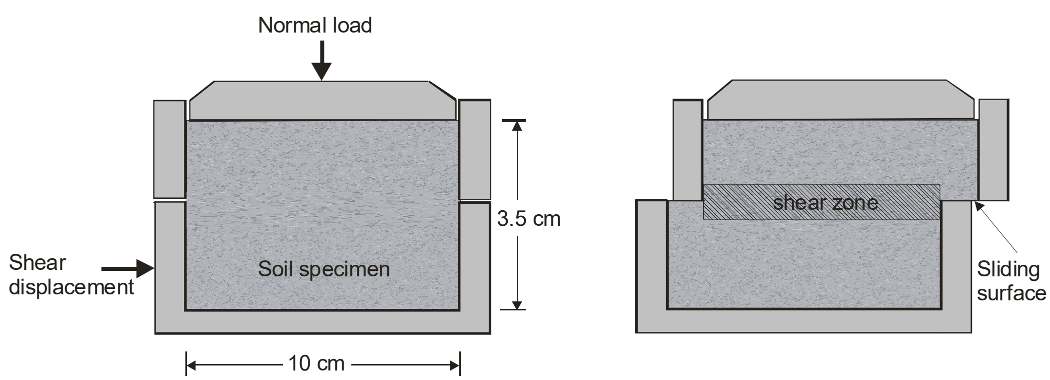


Fig. 1: Direct shear test scheme and specimen deformation.

In practice, plane strain condition is normally assumed for simplifying stress conditions as many of geotechnical engineering problems can be solved using plane strain assumption such as earth pressure and slope stability problems. Thus, any problem satisfying plane strain conditions can be simplified into two-dimensional form which is easier to analyze. Therefore, the plane strain friction angle is required to accurately model this type of problems. Row [4] derived a theoretical relationship between the peak friction angle ϕ_{Peak} measured in direct shear for sandy soil and the plane strain friction angle ϕ_{ps}. To verify this relationship, Row compared direct shear test results, measured in a previous study [5], and results obtained by Wightman [6] in plane strain compression test over the same order of mean pressure range. The comparison indicated that the plane strain friction angle ϕ_{ps} is larger than the direct shear friction angle ϕ_{Peak} by 4° to 9°, depending on the type of sand. Row [7] concluded that, the implementation of the direct shear friction angle ϕ_{Peak} is conservative, and still attractive to be used in practice.

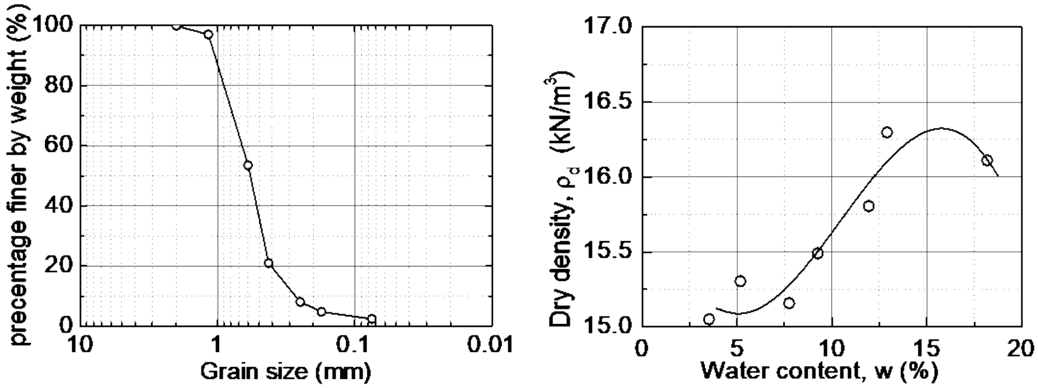
In this paper, a finite difference numerical simulation of direct shear test on sandy soil is presented. The laboratory tests have been conducted on selected uniformly graded sand using a 10 cm by 10 cm shear box. The sandy soil was modelled as a cohesionless material with elastic-plastic response and Mohr-Coulomb (M-C) failure criterion available in the FLAC^{2D} software [8]. FLAC^{2D} is a two-dimensional, finite difference-based software with analysis capabilities that covers a wide range of problems. The plastic response of the soil was simulated with a strain softening model and a dilation angle. The numerical calibration exercise was carried out by adjusting the soil shear modulus, G, bulk modulus, K and peak friction angle, ϕ_{Peak} until the curves representing the variation of stress ratio, τ/σ_N and vertical displacement of the soil specimen with shear strain showed a satisfactory match with the measured curves. During this calibration procedure, the soil unit weight, γ, dilation angle, ψ, and residual friction angle, ϕ_{Res} were kept constant.

With regard to previous studies on the subject, Jacobson et al. [9] offered insight into the standard test method for direct shear with regard to specimen size and boundary conditions through discrete element simulations carried out with numerical soil specimen. Particle translation data demonstrated that in the tested formation, localized shear regions sited far from the specimen borders develop only when the specimen size has length-to-depth ratio greater than 58. Wang et al. [10] studied the direct shear test through a discrete-continuum methodology. Findings from the discrete simulations showed that development of shear bands springs from the side boundaries toward the central region with both primary and secondary bands formed. Simulation data using flow rule and experiments using a conventional flow rule converge; thus, indicating that the effect of non-coaxiality is negligible at peak state. Ziaie Moayed et al. [11] used the finite element method to model the direct shear test on sandy clay after calibration against experimental results. They found out that the shear strength is enhanced by the friction angle at normal stresses above 100 kPa, the magnitude of shear strength was increased with higher cohesion, and an increment in Young's modulus leads to increase the stiffness of the soil. Dirgėlienė et al. [12] studied the direct shear of soils using experimental and numerical approaches. They concluded if the real distribution of stress and strain in the soil sample is known, it is likely to establish the soil shear strength, deformation parameters, and the influence of different factors on soil properties. They also determined that not all applied vertical load on top of the soil sample is transmitted to the shear plane. Adolphe et al. [13] employed numerical modelling to predict the behaviour of the Mohr-Coulomb type of soil with geosynthetics. The results from the finite element approach on silty sand reinforced by a geosynthetic layer showed that increasing the stiffness and the friction angle of geosynthetic layer changes the soil behaviour, leading to equivalent geosynthetics bending failure instead of shear failure.

2. Experimental Program

2.1. Soil Properties

The granular soil used in this investigation was clean uniformly graded sand. This sand was chosen because it can be easily compacted with uniform mechanical properties which ensure repeatable sand placement conditions for all tests. The particle size distribution curve and standard proctor test results for the sand is shown in Fig. 2. The soil is uniformly graded sand (SP) with about 2.5% fines according to the Unified Soil Classification System. The value of the coefficient of curvature (C_c) is about 1.27 and the value of uniformity coefficient (C_u) is 2.5. The modified Proctor test results which conducted in accordance with ASTM D698-91 (Fig. 2.b) [14] indicated that, the maximum dry density of the sand is 16.27 kN/m^3 at optimum moisture content value of 15%. The minimum dry density which accompanied with large strain and loose conditions is 12.9 kN/m^3 and specific gravity (G_s) equal to 2.88. Results in Fig. 2b shows a typical compaction curve for poorly graded sand which shows relatively high moisture content and low dry density compared to well graded sand [15].



a) Particle size distribution b) Standard Proctor test results

Figure 2: Particle size distribution and Standard Proctor test results for sand.

2.2. Experimental Direct Shear Test

In order to obtain strength parameters for the sand, a series of direct shear tests was performed in accordance using direct shear apparatus at soil laboratory. The normal stresses used in the tests varied between 5 and 20 kN/m^2. All the specimens had nominal dimension of 10 cm by 10 cm in area and 3.5 cm height and loaded in shear at constant strain rate equal to 0.4 mm/min. Each sample was compacted to a density equal to about 15.7 kN/m^3, which represent 86% relative density (D_r). There were differences of 0.2 kN/m^3 for the densities of the different samples; however, according to Bolton [16] it is believed that this is insignificant source of error in the final shear strength parameters.

Figure 3 shows the shear stress and vertical deformation versus horizontal shear strain for a series of samples tested in direct shear test at different normal stresses, σ_N. The soil is clearly typical dense sand with a peak and residual shear strength as well as a dilation angle. The maximum stress ratio for the sand is about 1.2 to 1.3 for the range of normal stresses used in the tests. It is also clear from Fig. 3b that the volumetric deformation of the sand is independent of the applied normal stresses.

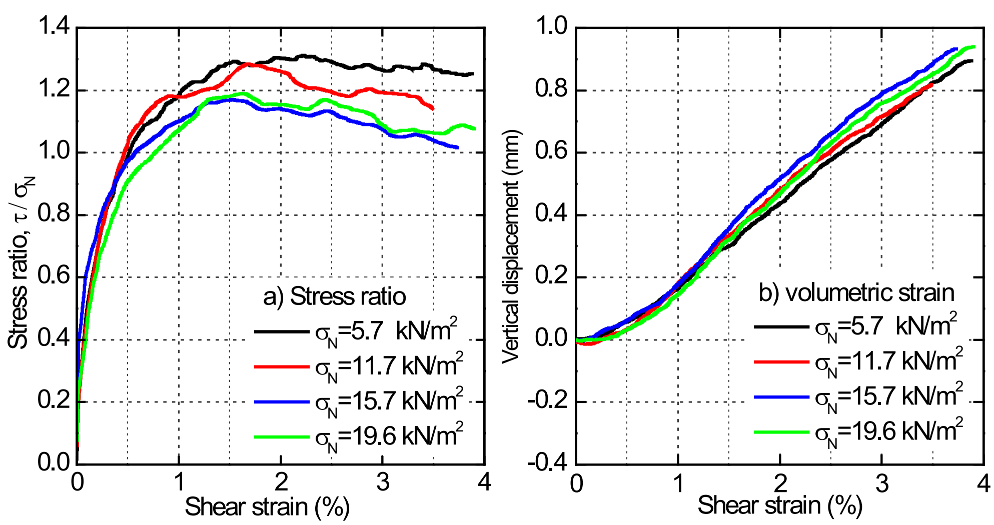
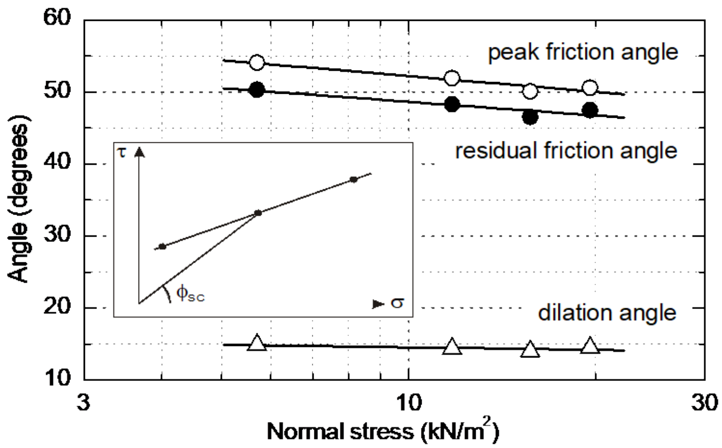


Figure 3: Shear stress and volumetric deformation versus shear strain for sand from direct shear tests.



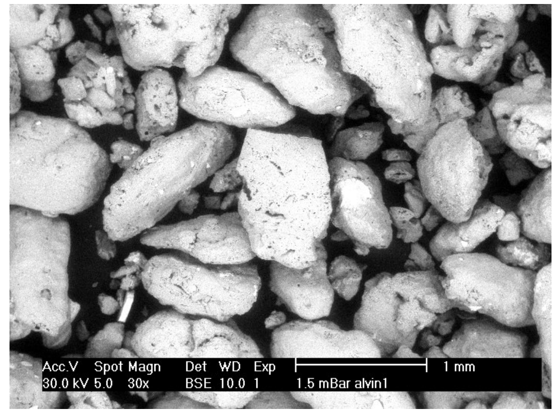


Figure 4: Direct shear test results expressed as secant peak and residual friction angles and dilation angle versus normal stress.

Figure 4 shows the variation of peak secant friction angle, ϕ_{peak}, residual secant friction angle, ϕ_R, and dilation angle, ψ, with normal stress. The plot shows that the soil internal friction angle is a stress dependant parameter. This emphasizes the importance of proper choice of the granular soil friction angle for design and analysis of earth structures and foundation [17]. For the average normal stress used in the current series of tests the value of the peak internal friction angle, ϕ_{Peak}, is predicted to be about 51° and the residual friction angle, ϕ_R is about 46°. In contrast to the friction angle which is stress-dependant parameter, the dilation angle, ψ, is independent of the normal stress and equal to 14.5°. The high peak friction angle is attributed to the angular to subangular surface of soil particles as shown in Figure 4.

3. Numerical Modelling, Mesh setup, and Boundary Conditions

The direct shear box test has been modelled using FLAC^{2D}, a two-dimensional explicit, time-marching, finite difference computer code for simulating soil–structure interaction, which undergoes plastic deformation behaviour when the respective yield limits are reached. The response to the applied forces followed a linear or nonlinear stress–strain behaviour. In the case of high stresses that cause the material to yield and flow, however, the grid elements deform and move with the material represented by the grids.

FLAC^{2D} has the advantage of being able to simulate the exact test procedures and finite boundary conditions used in physical laboratory direct shear test. The materials applied in the modelling of laboratory tests were the soil material and the solid cap at the top. Both soil and solid top cap materials are generated by the FLAC^{2D} rectangular elements (i.e. four points and four sides). The dimensions of the soil material are 0.1 m (W) × 0.1 m (L) × 0.035 m (H). The bottom of the numerical model was fixed in both x and y directions. However, both sides were fixed in only x direction to allow the specimen to consolidate vertically, but not laterally, which is consistent with the mechanism of the real lab test. The normal stress was selected to be similar to those used in the experimental program. Fig. 5 shows the numerical model Direct Shear Box and the boundary conditions used in FLAC^{2D}.

The sand backfill was modelled as a cohesionless material with elastic-plastic response and Mohr-Coulomb (M-C) failure criterion. The plastic response of the soil was simulated with a strain softening model and a dilation angle. The M-C failure criterion has been shown to be a satisfactory model for granular soil materials. Vermeer and deBorst [18] have reported experimental triaxial test results on sand specimens that showed satisfactory agreement using the Mohr-Coulomb failure criterion. According to this model the mechanical response of a given soil can be divided into elastic and plastic phases, based on the magnitude of shear strain in the element. The elastic phase of the soil model is normally characterised by the soil shear modulus G, and bulk modulus K. The strain softening phase of soil response and Mohr-Coulomb failure criterion are characterised by peak friction angle, ϕ_{Peak}, cohesion intercept, c, residual friction angle, ϕ_R, and dilation angle, ψ. Based on the results of the direct shear tests, the cohesion intercept of the granular backfill soil in this study was taken as zero.

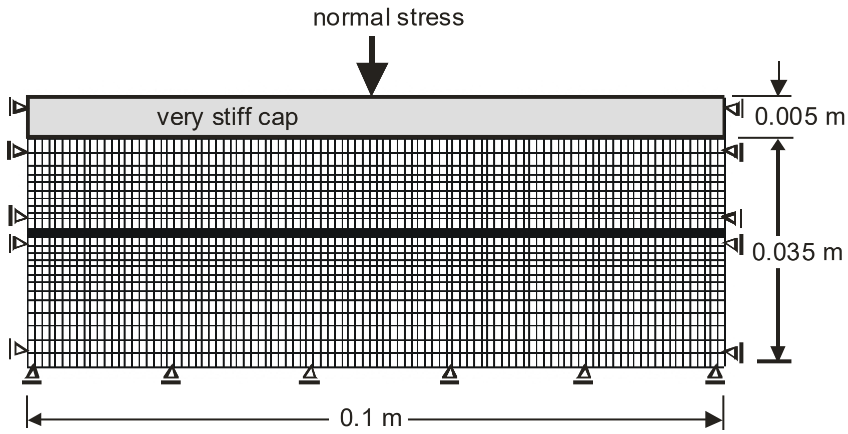


Figure 5: 0.1m x 0.1 m Direct Shear Box numerical mesh used in FLAC^{2D}.

3. Results and Discussion

The values of peak friction angle, ϕ_{Peak}, residual friction angle, ϕ_R, and dilation angle ψ were measured in the laboratory using direct shear tests. The numerical calibration exercise was carried out by adjusting the soil shear modulus, G, bulk modulus, K and peak friction angle, ϕ_{Peak} until the curves representing the variation of stress ratio, τ/σ_N and vertical displacement of the soil specimen with shear strain showed a satisfactory agreement with the measured curves (Fig. 6). During this calibration procedure, the soil unit weight, γ, dilation angle, ψ, and residual friction angle, ϕ_R were kept constant, and equal to the measured values.

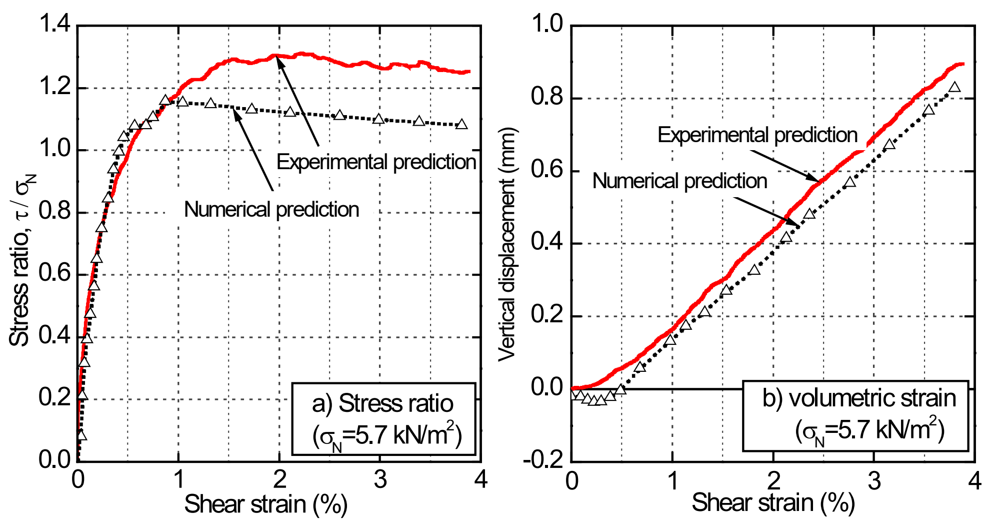


Figure 6: Measured and simulated direct shear test results for sand.

Figure 6 compares both measured and predicted stress ratio-strain and vertical displacement-strain relationships. There is close agreement between the direct shear test and numerical simulation results. During the initial loading, the plane strain numerical model shows the same soil stiffness response as direct shear. However, the measured maximum shear strength is under predicted by 11% using numerical simulation. Pottes et al. [19] reported a 4.5% difference in maximum stress ratio and a 10-20% in the soil initial stiffness when using finite element model to simulate direct shear test. They attributed this reduction to the freedom of the top cap for rotation, and to the initial isotropic stress applied in the numerical model, K_o. In the current study it is strongly believed that the main reason for under prediction of the maximum stress ratio in numerical model was the smaller value of the normal stress applied at the shear surface compared to the value applied at the top cap. Figure 7a showed that the normal stress σ_N at the shear surface location is about 4.0 kN/m^2, while the stress applied at the top cap is about 5.7 kN/m^2. The reasons for the reduction of the normal stress at the shear surface are not clear and needs more investigation.

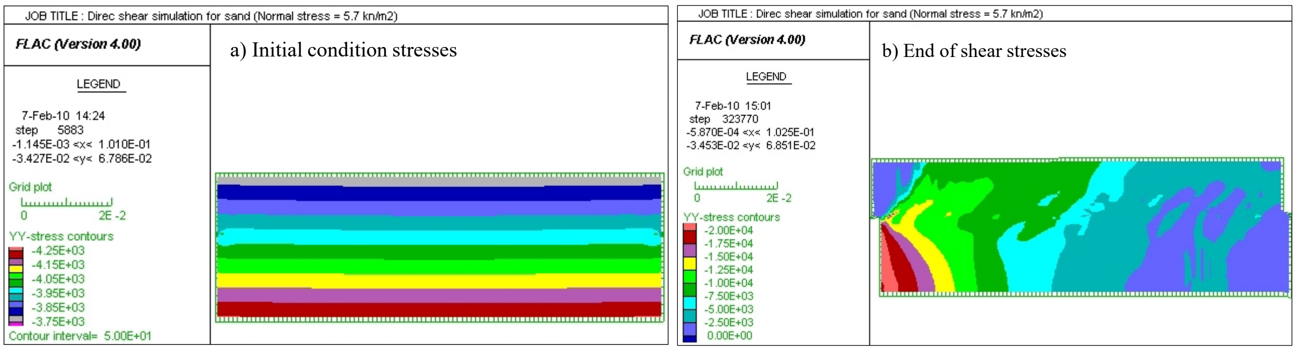


Figure 7: Normal stress distribution at the shear surface before and at the end of shearing process (σ_N = 5.7 kPa).

Despite the good agreement between the stress ratio and vertical displacement-strain relationships shown in Fig. 6, the numerical analysis confirms that the stress state and strain within the direct shear box are far from uniform. Fig. 7b indicated that the normal stress at failure surface is changed to non-uniform stresses during shearing process and at the end of shearing. It is clear that the normal stress is re-distributed towards the left halve of the box and reduced at the right halve. Despite the uniformly distributed 4.0 kN/m^2 before shearing process (Fig. 7a), the normal stress is increase to about 12.0 kN/m^2 in the left-hand side and decreased to less than 3.0 kN/m^2 in the right-hand side. This is also accompanied by a counterclockwise rotation of the top cap. As a result of this normal stress non-uniformity, the shear stress is also showed non-uniform distribution at the failure surface, during shearing process and at the end of shearing (Fig. 8). The distribution of the shear stress showed in Figure 8 indicated that the right half of the box mobilized shear stress value of 20.0 kN/m^2 which is double the value of shear stress mobilized in the right half of the box. There is also a shear stress concentration at the right side of the shear surface, which is resulted from the normal stress concentration indicated in Fig 7b. Pottes et al. [19] stated that the stress non-uniformity in the shear box might be expected to cause progressive failure, especially if it is accompanied by strain softening in soil.

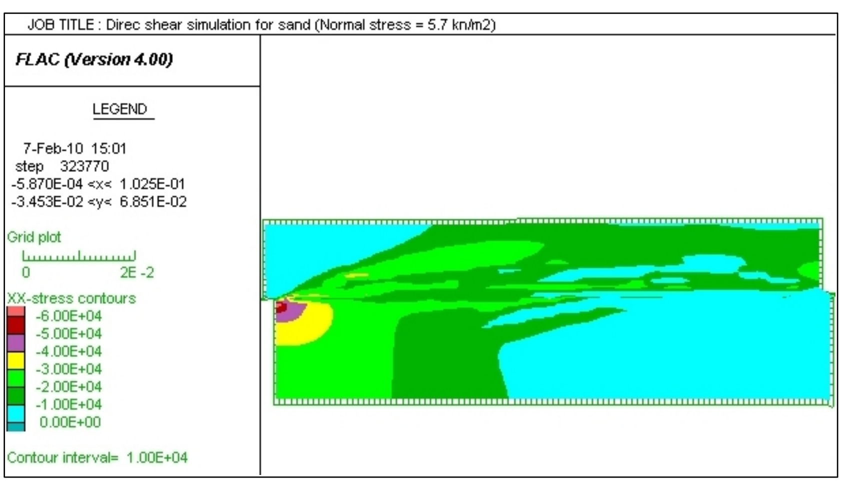


Figure 8: Shear stress distribution at shear surface at the end of shearing process.

Figure 9 shows the deformed shape of the direct shear numerical modelled in FLAC^{2D}. The measured backfill soil properties and the corresponding values for the plane strain model inferred from numerical model are summarised in Table Table 1. While there is about 13% difference in the peak friction angle, the results of the numerical analysis are identical to to those obtained from the direct shear test results.

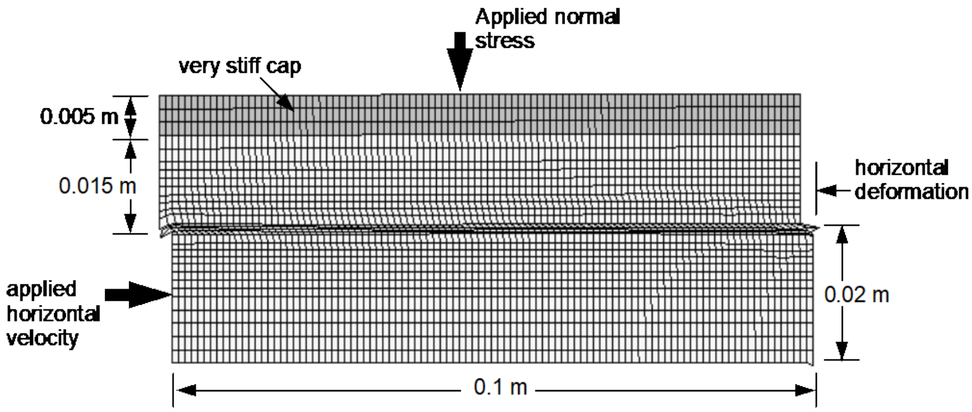


Figure 9: Two-dimensional deformed numerical model of direct shear test simulation.

Table 1: Tested and simulated material properties of the backfill soil.

Material property	Direct Shear Test	FLAC^{2D} Simulation Results
Peak friction angle, ϕ_{Peak}	51^o	58^o
Residual friction angle, ϕ_{Res}	46^o	46^o
Dilation angle, ψ	14.5^o	14.5^o
Cohesion, c	0	0
Shear Modulus, G	-	7 MPa
Bulk Modulus, K	-	6 MPa
Unit weight (dense state), γ	15.7 kN/m^3	15.7 kN/m^3

4. Conclusion

Numerical simulations of direct shear tests have been developed using the FLAC^{2D}. The results, in terms of the stress-strain-dilation response, are qualitatively similar to the experimentally observed behaviour of sandy soil. Taking advantage of the numerical simulation technique, the stress distribution inside the shear band has been examined. Although the stress distribution within the specimen is non-uniform, as indicated by the normal and shear stress, it has been shown that the predicted stress ratio (τ/σ) is similar to that inferred from laboratory shear test. It has also been shown that the dilation in the numerical model is in close agreement with the experimental results. On average, the numerical model under predicted the stress ratio (τ/σ) by about 11%. The plane strain friction angle is larger compared to the direct shear friction angle. Finally, the numerical model developed in this study can be used to predict the soil shear and bulk modules.

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