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A review on the effect of rubber membrane in triaxial tests

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Abstract This paper presents a review on the effect of rubber membranes on the measured stress and volume change data during the triaxial tests. In many instants, the error associated due to membrane penetration is measured to be close to the total sample volumetric strains. Hence, in addition to precise measurements, adopting an appropriate correction to the measured data is pivotal. This paper provides a detailed review on the methods used to estimate and reduce the influence of rubber membrane on the measured triaxial test results. The discussion therefore clearly highlights the stiffness, thickness, and diameter of the membrane used, to have significant influence on the measured deviatoric stress and the volume change data. The mean grain size of sample has an equally significant influence on the volume change. The methods in general are limited to test conditions, and therefore, it is practically uncertain to have a generalized correction procedure. Effectively, the outcome from this review work enhances the understanding of the reader towards the effect, methods, and corrections to be considered in triaxial testing due to rubber membrane and membrane penetration effects.

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List of symbols

A_c	Post-consolidation average cross sectional area of the sample
A_m	Area of contact between the membrane and the sample
A_s	Soil surface area covered by the membrane
α	Angle of the failure plane
D_c	Post-consolidation diameter of the sample
d_{50}	Mean grain size
d	Sample diameter
d_g	Equivalent diameter when converted to spherical shape
d_m	Membrane diameter
V_0	Sample volume prior to change in stress
ΔV_T	Total volume change
ΔV_m	Volume change caused by membrane penetration
ΔV_{Soil}	Volume change caused by soil deformation
ΔV_T	Total volume change
Δv_m	Membrane effect unit area ($\Delta v_m = \Delta V_m / A_m$)
E_m	Stiffness of the rubber membrane
ε_a	Axial strain
ε_m	Unit membrane penetration or membrane penetration per unit membrane surface area
ε_v	Total volumetric strains
ε_{vm}	Volumetric strains due to membrane penetration
q_m	Membrane resistance
σ_1	Major principle stress
σ_2	Intermediate principle stress
σ_3	Minor principle stress
σ_{3m}	Minor principle stress due to membrane restraint
σ_c'	Effective confining pressure
σ_r	Resultant force
σ_m	Membrane restraint force

t_{m} Thickness of the membrane
u Pore water pressure

Introduction

Since early 1950s, triaxial compression tests were conducted on saturated soil samples to measure their shear strength characteristics (example, De Beer 1950; Fleming 1952; Bishop and Henkel 1962). In typical triaxial testing practice, the soil sample is enclosed in a rubber membrane to isolate it from the cell media (de-aired water in most of the tests), which is used to apply the confining pressure. The rubber membrane so used in the triaxial tests has a significant effect with apparent increase in the measured strength (Henkel and Gilbert 1952) and erroneous volume change data due to membrane penetration (Newland and Allely 1959). Certainly, the influence of rubber membrane on the measured strength along with suitable procedure for membrane correction has been well documented in the standards for both consolidated undrained and drained test conditions. The effect of membrane penetration on the measured volume change of the sample plays a pivotal role in assessing either compressive or dilative behaviors of the sample. Previous literatures present various methods to estimate the penetration of rubber membrane under varied effective confining pressures, while none of the methods are proved to be unique, but are shown dependent on test condition and type of the test materials (Vaid and Negussey 1984).

   The main objective of this review paper is to highlight various methods used to estimate the error associated in the measured volume change data due to membrane penetration from the previous literatures. Understanding the influence of the rubber membrane on apparent increase in the measured deviatoric stress is also essential. Because methods used to reduce the effect of membrane penetration, for example increased membrane stiffness (Molenkamp and Luger 1981), use of double membrane (Evans 1992) contrarily contribute towards additional error in the measured deviatoric stress. The comparison on different methods to estimate the membrane penetration highlighted the dependence on the type of membrane and soil particles (Vaid and Negussey 1984; Baldi and Nova 1984; Al-Karni 2011; Choobbasti et al. 2009; Raghunandan et al. 2012), however limited to works prior to mid-1980s. The review work presented in this paper includes discussion on various parameters related to membrane stiffness (effect of membrane stiffness on the stress-state, membrane resistance) and membrane penetration (concept of membrane penetration, error in measured volumetric strains, unit membrane penetration). Effectively, the outcome from this review work enhances the understanding of the reader on the

effect, methods, and corrections to be considered in triaxial testing due to rubber membrane.

Effect of rubber membrane on the measured deviatoric stress

The rubber membrane used to enclose the soil sample in undrained triaxial compression test results in apparent increase in the measured strength, depending up on the stiffness, thickness, and diameter of the membrane (ASTM D 4767-11). The effect is similar in drained triaxial compression tests; moreover, it is more significant when the tests are conducted at small effective stresses (Henkel and Gilbert 1952). The membrane stiffness (E_{m}) plays a pivotal role in the additional increase in the deviatoric stress measured. E_{m} in turn depends on the material type, thickness, and dimension of the membrane used, and hence to be determined prior to the correction to the strength is calculated. E_{m} commonly is the average secant modulus value determined from the extension test results. Previous literatures show different methods to determine E_{m} including uniaxial tensile strength (Henkel and Gilbert 1952) and the stiffness using air-inflated membrane (LaRochelle et al. 1988). *ASTM D 4767-11* clearly specifies the use of uniaxial tensile (extension) test and also suggests the calculation (using Eq. 1) to determine the increase in deviatoric stress due to membrane, defined as membrane resistance, q_{m}, in this paper.

$$\delta(\sigma_{\mathrm{d}})_{\mathrm{m}} = \frac{4E_{\mathrm{m}}t_{\mathrm{m}}\varepsilon}{D_{\mathrm{c}}} \tag{1}$$

where t_{m} is the thickness of the membrane, ε_{a} is the axial strain, D_{c} is the post-consolidation diameter of the sample ($D_{\mathrm{c}} = \sqrt{4A_{\mathrm{c}}\pi}$), and A_{c} is the post-consolidation average cross-sectional area of the sample. Equation 1 is obtained when the rubber membrane is modeled as a hollow cylinder, and the E_{m} is assumed to be constant along the length (Greeuw et al. 2001). The measured deviatoric stress is corrected at each ε_{a} value; however, the correction is neglected if the error in the deviatoric stress is <5 % (ASTM D 4767-11).
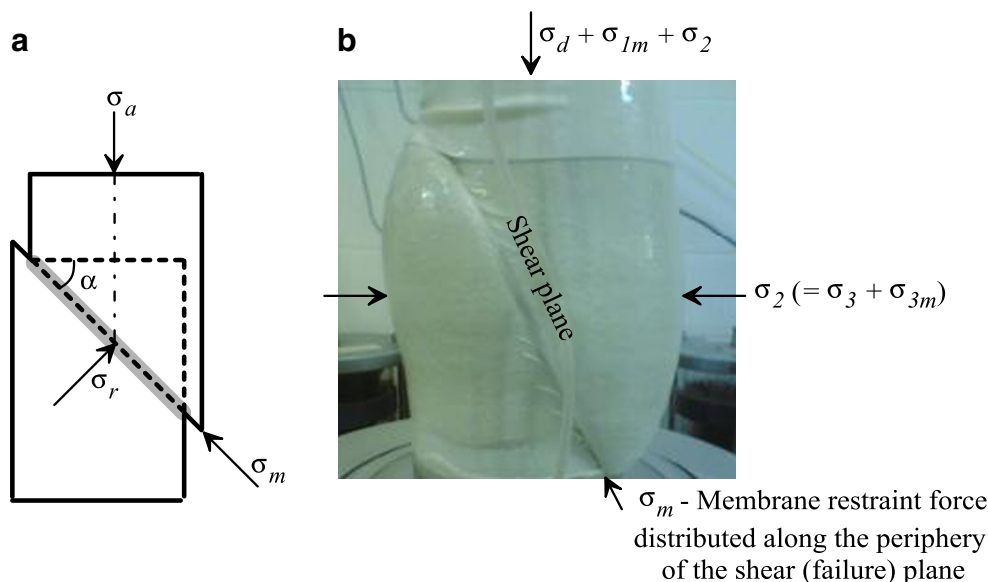
   Figure 1a and b presents a schematic diagram to highlight the ideal stress-state condition expected during compression tests including condition under both rubber only and triaxial loading on cylindrical samples. The *rubber only* condition refers to the sample encompassed with rubber membrane tested in the absence of confinement (σ_3=0). Understanding the stress-state condition prior to the shear stage (post consolidation stage) and during shear, which includes conditions before and after the development of failure, is pivotal. This has been well explained using the three principle stresses: major (σ_1), intermediate (σ_2), and minor (σ_3) principle stresses

acting on an idealized soil element subjected to triaxial loading (Pachakis 1976). Figure 1a indicates the development of a failure plane at an angle 'α' measured from the minor principle plane. The figure also highlights the contact zone shown as the hypotenuse of an idealized right angled triangle (highlighted in the figure) at any stage during shearing (Pachakis 1976). Hence, in evaluating the effect of rubber membrane, the significance of contact zone is to value the forces resisting the shear process including the resultant force, σ_r and the membrane restraint force, σ_m. The magnitude of σ_r depends up on the principle stresses, for example σ_1 and σ_{3m} in rubber only, while σ_1, σ_2, and σ_3 in triaxial loading as explained by the Cauchy's stress theorem (Irgens 2008).

Nonetheless, the direction of σ_r depends up on the type of failure and other material properties. Hence, the type of failure has significant effect on the direction of the membrane restraint force acting on the sample. For example, the laboratory behavior of localized deformation resulting in a bulging-type failure mode in soft clays (Sabatini and Finnob 1996) very closely is in agreement with the explanation of prestressing caused due to firm membrane around the sample presented by LaRochelle et al. (1988). The shear plane developed in stiff materials as one shown in Fig. 1b is of less significance in regard to membrane effect at high effective stresses because the membrane restraint force is expected to be much less than the strength (error within 5 %) and hence be neglected (Henkel and Gilbert 1952). At rubber-only (or low effective stress) condition, the correction is set to be considered. The membrane restraint force, σ_m, is thus considered to act along the periphery of the failure plane as demonstrated in Fig. 1a and the photograph presented in Fig. 1b.

The discussion presented above demonstrates the significance of E_m on the measured σ_m. E_m in turn depends up on two properties of the membrane, the membrane thickness, t_m, and the membrane diameter, d_m. This has been well documented in the earlier literatures (for example Henkel and Gilbert 1952; Bishop and Henkel 1962; Frydman et al. 1973; LaRochelle et al. 1988; Head 1998; Greeuw et al. 2001; Raghunandan 2012; Della et al. 2013). Figure 2 shows the comparison of the two extreme conditions, considering both t_m and d_m in the same plot. The figure shows data on t_m with using three membranes of different thicknesses (presented by Henkel and Gilbert 1952) and d_m using membranes of 59 and 66 mm diameter (presented by Greeuw et al. 2001). Table 1 tabulates the properties of the different types of membranes used to compare in the figure. The experimental results (q_m) were calculated as the difference between the compression strengths measured by unconfined compression tests with that measured using rubber-only and triaxial tests. The triaxial test data showed close comparison with the predictions using compression shell theory at $\varepsilon_a = 15$ %, with the data for thin membrane being more ideal. However, considering the results obtained using rubber-only tests, the experimental data suggest the compression shell theory to overestimate the q_m value, while the Hoop stress theory to underestimate q_m irrespective of the membrane type. On other hand, super imposing the influence of d_m on q_m with results for membrane thickness suggest the effect of d_m to be less significant considering the error associated with the measured deviatoric stress in laboratory strength tests. This is because the experimental data at 15 % strain was scattered

Fig. 1 a Schematic diagram showing the stress-state condition of a triaxial sample encompassed in the rubber membrane and b photograph of post-test triaxial sample (after Raghunandan 2011) visualizing the membrane restraint force
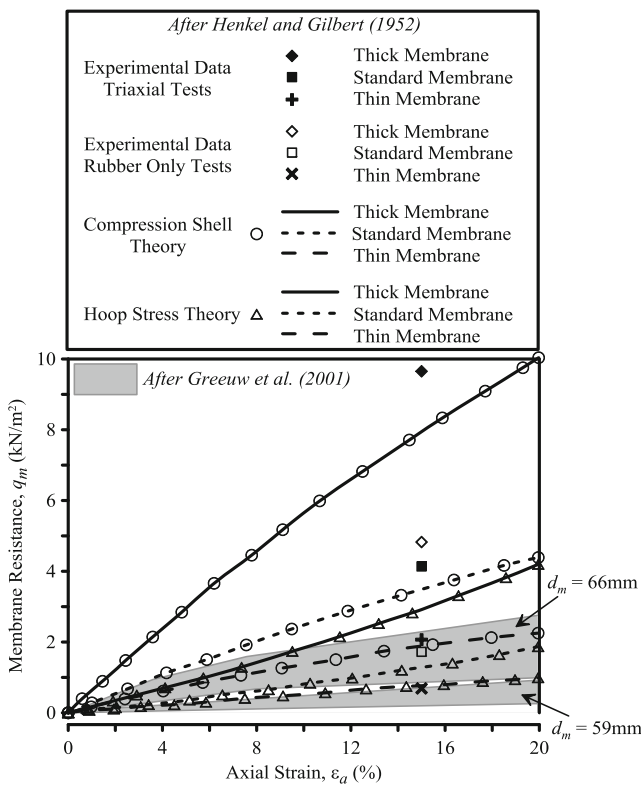
a

σ_a

α

σ_r

σ_m

b

$\sigma_d + \sigma_{1m} + \sigma_2$

Shear plane

$\sigma_2 (= \sigma_3 + \sigma_{3m})$

σ_m - Membrane restraint force distributed along the periphery of the shear (failure) plane

Fig. 2 Effect of membrane thickness and diameter on the membrane resistance with increasing axial strains

within and away from the boundary suggested by Greeuw et al. (2001). Henceforth, the discussion highlights the membrane stiffness (physically measured as t_m) as the factor influencing the additional deviatoric stress measured in the laboratory triaxial tests.

Effect of rubber membrane on the measured volume change

The volume change measured in consolidated drained triaxial tests on granular materials is associated with erroneous volume change measurements due to the penetration of rubber membrane into the soil voids. The effect of membrane penetration is significant when the effective confining pressure is

not constant at any stage of the test (Newland and Allely 1959). For example, the membrane penetration during the consolidation and drained shear stages in triaxial test needs proper supervision and hence suitable corrections. While in the saturation stage, variation in effective confining pressure (σ_c') is associated with subsequent variation in the sample pore water pressure (u) depending up on the Skempton's B factor (Skempton 1954). This in turn limits the possible penetration of the rubber membrane into the soil voids; hence, the influence of membrane penetration is considered to be less in saturation stage (Raghunandan 2011). Newland and Allely (1959) explained the total volume change under drained conditions as the sum of volumetric compression of soil skeleton and due to membrane penetration at any applied ambient stress-state conditions, theoretically expressed as

$$\Delta V_T = \Delta V_{Soil} + \Delta V_m \tag{2}$$

where ΔV_T is the total volume change, ΔV_m is the volume change caused by membrane penetration, and ΔV_{Soil} is the volume change caused by soil deformation. This further suggests the total volume change depends up on the soil structure and the sample volume (V_0) prior to change in stress, and the physical properties of the rubber membrane expressed as the membrane penetration per unit membrane surface area (ε_m). Hence, Eq. (2) is reformed by Vaid and Negussey (1984) as

$$\Delta V_T = (\varepsilon_v \times V_0) + (\varepsilon_m \times A_s) \tag{3}$$

where A_s is the soil surface area covered by the membrane, and ε_v is the total volumetric strains.

Comparison of available methods to estimate membrane penetration

Precise estimation of the volumetric strains due to membrane penetration (ε_{vm}) from the total volumetric strains (ε_v) measured during a triaxial test plays pivotal role to arrive at an appropriate adjustment to the data. In previous studies, this

Table 1 Properties of the rubber membrane used in the literatures compared in Fig. 2

Reference	Henkel and Gilbert (1952)			Greeuw et al. (2001)
Membrane type	Thick	Standard	Thin	
Thickness, t_m (mm)	0.5	0.2	0.1	0.35
Diameter, d_m (mm)	38	38	38	63
Modulus in extension (kN/m^2)	2,380[a]	1,050[a]	560[a]	1,750

[a] Calculated considering the length/diameter ratio of the membrane as 4

adjustment has been proposed in both as correction to the measured data and/or an experimental procedure to limit or eliminate membrane penetration during the test procedure. Table 2 presents the significant methods proposed and used by various researchers to estimate the influence of membrane penetration. Various terminologies have been used previously to assess the error due to membrane penetration, which include ε_{vm} (volumetric strains due to membrane penetration) and ε_m (membrane penetration per unit membrane surface area or unit membrane penetration) to name few. However, in this manuscript, volumetric strains due to membrane penetration, ε_{vm} will be extensively used to refer the error due to membrane penetration, if otherwise specified.

Newland and Allely (1959) recognized the occurrence of ε_{vm} during triaxial test on a granular material and furthermore suggested correction to the measured ε_v. ε_{vm} was then calculated as difference between the total volumetric strains measured and the calculated volumetric strains. The procedure to calculate ε_v assumed the samples to behave isotropically under hydrostatic loading, and hence, the volumetric strains were calculated as three times the axial strains. This procedure set an error overestimating ε_{vm} as explained by Vaid and Negussey (1984). Vaid and Negussey (1984) favored the procedure suggested by Newland and Allely (1959), but used a different approach to evaluate the relation between ε_{vm} and the effective confining pressures. The procedure initially aimed to attain a relation between the ratio of $\Delta V_T / A_s$ (A_s is the cross-sectional area of the sample) and the sample diameter (d) because ε_{vm} shall remain constant when tested at the same density but at different sample diameters for any value of σ_c' (Vaid and Negussey 1984). This, in the laboratory, was achieved by testing samples with identical densities and different diameters and confining stresses. Further linear relationship between $\Delta V_T / A_s$ and d was used to calculate ΔV_T, followed by a linear relationship between the so calculated ΔV_T and σ_c' was used to estimate ε_{vm}. Lin and Selig (1987) suggest that the use of linear relation between ΔV_T and σ_c' underestimates the influence of membrane penetration at low values of σ_3'. The second method suggested by Vaid and Negussey (1984) recommends the use of hydrostatic unloading in simple shear apparatus for the sample, which in turn to be used to determine ε_{vm}. Nonetheless, this procedure assumes the sample to behave isotropically elastic during hydrostatic unloading, which is seldom true in the laboratory. Lin and Selig (1987) further contribute to the same procedure with a suggestion on the use of hyperbolic relationship for the test results on samples of different diameter but same density and confining pressures, hence replacing the linear relationship used by Vaid and Negussey (1984). Bohac and Feda (1992) also used the procedure with logarithmic and hyperbolic approximations; however, in conclusion, this highlights the accuracy of the analytical methods to be small and limited. Sivathayalan and Vaid (1998) further suggested the use of

hollow cylinder test, in which the membrane penetration was measured using ε_v and the state of stress and strain in the inner cavity of the sample. The calculation assumed that the sample is subjected to hydrostatic loading, hence gives equal radial and tangential stresses, which therefore results in a condition of identical tangential strains across the wall of the sample.

Roscoe et al. (1963) proposed an experimental procedure to determine the relationship between ε_v and ε_{vm}. Cylindrical brass rods of different diameters, but the same heights were used in the test procedure. The brass rod was placed coaxially with the sand sample during testing to measure ΔV_T in each test. This procedure was repeated using different diameters of the brass rods; hence, the volume of soil was varied in each trial, but the ε_{vm} remained constant because the contact area between the membrane and the sample was unchanged. This was then used to establish a relation between the diameter of the brass rod and ε_{vm}. In addition, the procedure assumes that the volume change due to soil skeleton at any applied confining stress is a function of the initial volume of soil, and hence, a linear relationship between ΔV_T and V_0 was considered to determine the volumetric strains and the membrane penetration (Raju and Sadasivan 1974; Vaid and Negussey 1984). Likewise, Raju and Sadasivan (1974) adopted similar procedure with an improvement by replacing the conventional rigid top platen by an annular flexible and lubricated top platen to ensure the soil sample is subjected to a hydrostatic compression; otherwise, the vertical stress acting on the sample is less than the applied hydrostatic pressure. However, the improvement addresses less considering the assumption of sample to behave isotropically.

Frydman et al. (1973) proposed an experimental procedure to establish a relation between the ε_{vm} and σ_c' using a series of hollow cylinder tests on glass microspheres with three different diameters (d_{50}=0.18, 0.3, and 1.85 mm). Membrane effect unit area ($\Delta v_m = \Delta V_m / A_m$), the ratio of total volume change measured due to membrane penetration (ΔV_m) to the area of contact between the membrane and the sample (A_m) and the ε_v was measured at different σ_c'. Furthermore, ε_v plot against Δv_m at any value of σ_c' showed a linear variation, which was then used to calculate the ε_{vm} at any particular value of σ_c'. While the procedure does not address the influence of incremental σ_c' on the A_m because this requires thorough monitoring of the contact established between the penetrating membrane and the adjacent soil grains.

Kramer and Sivaneswaran (1989) used two identical membranes to transmit the confining pressure to the soil sample. The space between the inner and the outer membranes was initially filled with water. The confining pressure was slowly increased, while the net pressure acting on the outer membrane was maintained close to zero. When the desired confining pressure was reached, the inner membrane should have penetrated into the soil voids, after which the water between the two membranes was drained. The volume of water drained was the

Table 2 Tabulation of methods used to estimate membrane penetration and its limitations from the previous literatures

Reference	Material	Estimation method	Limitations
Newland and Allely (1959)	Granular	The ε_{vm} was determined as the difference between the measured and calculated ε_v	Assumes the granular material to behave isotropically under hydrostatic loading ($\varepsilon_v = 3\varepsilon_a$)
Roscoe et al. (1963)	Sand	Experiments using cylindrical brass rods of varied diameters were coaxially placed with saturated sand. Relationship between the measured ε_v and the rod diameter was established and then extrapolated to the diameter value same as the sample diameter. The value of ε_v obtained at diameter equal to sample diameter was considered as ε_{vm}	Assumes the volume change due to soil skeleton at any applied confining stress is a function of the initial volume of the soil, and hence, a linear relationship between ΔV_T and V_0 was considered to determine the volumetric strains and the membrane penetration (Raju and Sadasivan 1974; Vaid and Negussey 1984)
Frydman et al. (1973)	Glass spheres	Experiments using conventional triaxial and hollow cylinder tests on glass microspheres of diameters 0.18, 0.3, and 1.85 mm. Linear relation between the measured volumetric strains and a ratio of $\Delta V_m/A_m$ was used to calculate ΔV_m	It is practically difficult to determine A_m with change in the effective confining pressure applied during testing
Raju and Sadasivan (1974)	Sand	Experimental procedure similar to that suggested by Roscoe et al. (1963) was used, with an improvement by replacing the rigid top platen by an annular and flexible top platen.	The procedure, however still assumes a linear relationship between ΔV_T and V_0
Vaid and Negussey (1984)	Ottawa sand	Method 1: linear interpretation using test results conducted on samples of different diameter but same density and effective confining pressures Method 2: to determine ε_{vm} during hydrostatic unloading in simple shear apparatus and use method similar to Newland and Allely (1959)	The linear relationship between σ_3' and ΔV_m underestimates the effects of membrane penetration at low values of σ_3' (after Lin and Selig 1987) Assumes the sand sample to behave isotropically elastic during hydrostatic unloading
Lin and Selig (1987)	Medium to coarse sand	Interpretation using hyperbolic relationship of test results on samples of different diameter but same density and confining pressures	Volume change caused by membrane penetration during unloading and loading are same at similar stress states
Kramer and Sivaneswaran (1989)	Coarse sand	Experiments with two identical membranes; inner and outer membranes to transmit pressure and provide drainage respectively	Use of double membrane method increases the membrane resistance and hence an addition to the measured deviatoric stress
Bohac and Feda (1992)	Zbraslav sand	Experiments with correction to initial sample porosity using K_O stress path Analytical methods with logarithmic and hyperbolic approximations	Depends up on the material and initial test conditions Authors suggest the accuracy of analytical methods to be small
Sivathayalan and Vaid (1998)	Coarse and fine sand	Experiments using hydrostatically loaded hollow cylinder test samples, membrane penetration was measured using the total volumetric strain and stress–strain states in the inner cavity	Sample subjected to hydrostatic loading gives equal radial and tangential stresses, and hence, the tangential strains are identical across the wall of the sample
Raghunandan (2011)	Fine sand	Experimental model sample with central concrete core was used to prevent water movement at the core and force water through the void space between the peripheral sand particles and the rubber membrane. A glue of adhesive and fine sand grains ($d_{50} = 0.31$ mm) was prepared in the laboratory and painted on the surface of the concrete core. This enabled the measurement of ε_{vm} only under applied effective confining pressure	Experimental model simulate the condition only in the consolidation stage; however, one should relay on the methods previously proposed to estimate the correction during shear
Noor et al. (2012)	Sand with uniform grain size (0.3, 0.6, 1.18, and 2 mm)	Similar experimental procedure as used in Raghunandan (2011) was used, with a central core consisting of cylindrical steel tube filled with compacted material. The sand sample was then prepared around the core by compacting it to required packing	The test procedure and results are limited to isotropic consolidation stage

indicator for the volume of membrane penetration. However, the method is limited to consolidation stage because the use of double membrane method increases the membrane resistance and hence an addition to the measured deviatoric stress.

Recently, Raghunandan (2011) conducted an experimental study to measure ε_{vm} using an experimental model in the triaxial tests. The model was prepared using a 100-mm diameter cylindrical concrete block, painted on the surface with a paste prepared using fine sand sample (d_{50}= 0.31 mm) and an adhesive. The central concrete core was used to prevent any drainage of water from that region. The volume change thus measured is solely due to the penetration of the rubber membrane. The experiment successfully simulates and is limited to isotropic consolidation stage at any applied σ_c' in the triaxial test setup. Noor et al. (2012) presented a similar experimental method, in which the central core was a cylindrical steel tube filled with compacted material, and the sand sample was then prepared around the core by compacting it to required density.

Comparison of available methods to reduce/control membrane penetration

Applying suitable corrections to the measured ε_v using any of the methods listed in Table 2 is one way to deal with the error associated with the use of rubber membranes in triaxial tests. However, another way likely to reduce or control the membrane penetration is to modify the material or procedure during the tests. Table 3 tabulates different methods previously used to reduce or control membrane penetration effect and their limitations.

Kiekbusch and Schuppener (1977) proposed an experimental procedure in which the inner surface of the membrane was coated with a layer of liquid rubber prior to encase the triaxial sample. This modification, in turn offers more resistance to the penetration of the membrane into the soil voids, resulting in about one sixth (85 %) reduction in penetration of that compared with the untreated membrane as pointed out by Kramer and Sivaneswaran (1989). Raju and Venkataramana (1980) also favored the procedure, with replacing the liquid rubber with a thin layer of viscous liquid polyurethane. The authors reported about 85 % reduction in ε_{vm}. Contrarily, Lo et al. (1989) used the procedure proposed by Raju and Venkataramana (1980) to evaluate the influence of increase in the membrane rigidity on the sample diameter. The results presented by Lo et al. (1989) clearly showed the influence of coating in rubber membranes to be is more for samples with smaller diameter and decrease with increase in the sample diameter. Secondly, increasing the rigidity of the rubber membrane contribute more to the error associated with the measured deviatoric stress, and also due to rubber coating, less uniformity in applied cell pressure is expected since the

stiffened membrane tend to strain radially during shear. Evans (1992) worked on the same concept, but the membrane rigidity was increased by increasing the number of layers of rubber membranes used in the test.

Alternatively, Lade and Hernandez (1977) proposed an experimental procedure to use thin brass plates of dimension 25.4×25.4 mm between the sample and the membrane with slight overlapping to allow axial compression during shear. The test results presented by the author showed about 65 % reduction in the membrane penetration when compared with the test results without brass plates. Raju and Venkataramana (1980) also presented similar experimental study with thin polyurethane strips replacing the brass plates. Results showed 65 % reduction in membrane penetration as similar to Lade and Hernandez (1977). The overlapped portion of the materials introduced between the sample and membrane is expected to be compressed by the applied σ_c', hence applying more resistance to the axial stress. Lade and Hernandez (1977) also concluded the resistance to be significant; however, a procedure for accurate prediction of the correction to the measured axial/deviatoric stresses is absent.

Raju and Venkataramana (1980) presented a compensation method in the undrained tests. The procedure involved the compensation of addition volume change due to membrane penetration by injecting water into the sample suitably. The volume of water to inject was determined based on the volume change due to membrane penetration using the analytical relation between the ε_{vm} and σ_c'. The author's observed the test procedure to be more unwilling because of the continued manual correction required during the procedure to maintain the injection process. Seed et al. (1989) and Nicholson et al. (1993) used the same procedure to compensate volume change due to membrane penetration. In addition, Nicholson et al. (1993) improved the procedure with the use of a closed-loop computer-controlled system to monitor accurate water injection process. The procedure is still unreliable since the relation between the ε_{vm} and σ_c' used to calculate the volume of water to inject itself has limitations as discussed in the previous section. To eliminate this limitation, Sivathayalan and Vaid (1998) calculated the ε_{vm} using the measured volumetric and axial strains along with the total volume change of the sample and inner cavity caused under the hydrostatic loading. However, the procedure yet assumes an axisymmetrical deformation of the hollow cylinder to calculate the radial and tangential strains, which can be rarely expected in the laboratory.

Evans (1992) used the method of sluicing the gravel sample with sand along the periphery of the cylindrical sample. This process of sluicing eventually filled the voids formed between the gravels with sand which was conventionally occupied by water. This process resulted in the reduction of void space available for membrane

Table 3 Tabulation of methods used to reduce/control membrane penetration effect and its limitations

Reference	Methods used	Limitations
Kiekbusch and Schuppener (1977)	The samples were initially prepared, and the surface of the membrane penetrating into the sample voids under confining pressure was coated with liquid rubber. The membrane coated with rubber offered more resistance to penetration, resulting in about 85 % reduction in penetration	The membrane coated with rubber applied more resistance to the applied axial stress, hence making it more difficult to determine the correction to the measured deviatoric stress during shear. Secondly, due to rubber coating less uniformity in applied cell pressure is expected since the stiffened membrane strain radially during shear
Lade and Hernandez (1977)	Thin brass plates of dimension 25.4 mm× 25.4 mm were placed between the sample and the membrane with slight overlapping of the strips to allow axial compression during shear. The membrane penetration was reduced by about 65 % compared with test results without brass plates	The overlapped portion of the brass plates was compressed by the effective compressive pressure, hence applying more resistance to the axial stress. The authors concluded the resistance to be significant and procedure for accurate prediction of the correction to the measured axial/deviatoric stresses is absent. Hence, the accuracy in measuring the soil and membrane response in such tests is uncertain
Raju and Venkataramana (1980)	Method 1: Similar procedure suggested by Kiekbusch and Schuppener (1977) was used, except that the membranes were coated with thin layers of viscous liquid polyurethane. The result showed about 85 % reduction in the penetration Method 2: Similar procedure suggested by Lade and Hernandez (1977) was also examined with thin polyurethane strips replacing the brass plates. The results specified about 65 % decrease in the membrane penetration Method 3: Compensation method in undrained tests was used in which the member penetration volume change was compensated by injecting addition water into the sample. The membrane penetration volume change was predetermined using the relation between the membrane penetration and the effective confining pressure	Similar limitations as observed in Kiekbusch and Schuppener (1977) apply Similar limitations listed for Lade and Hernandez (1977) apply The author observed the test procedure to be more unwilling because of the continued manual correction required during the procedure to maintain the injection process. The procedure is unreliable because the relation between the membrane penetration and effective confining pressure used to calculate the volume of water to inject itself has limitations
Lo et al. (1989)	Test procedure similar to Kiekbusch and Schuppener (1977) was conducted on samples with different diameters. The results showed the influence of membrane rigidity due to coating to be comparatively less in 100 mm diameter samples	Similar limitations as observed in Kiekbusch and Schuppener (1977) apply
Seed et al. (1989)	Tests procedure similar to the method 3 presented by Raju and Venkataramana (1980) was used	Similar limitations listed for Raju and Venkataramana (1980) apply
Evans (1992)	Methods 1: The gravel were sluiced with sand (treated to fill the voids) at the periphery of the cylindrical sample, such that the void filled with water in the conventional methods is now replaced by sand and hence making the peripheral surface more smooth. This procedure showed reduced membrane penetration in the gravel Methods 2: Multiple layers (2 and 4 layers) of rubber membranes were used basically to reduce permanent membrane deformation observed in tests using single layer rubber membrane. This as well contributes towards reducing membrane penetration due to increase in the membrane stiffness	The procedure is limited to remolded samples, because sluicing of sand in undisturbed samples is impossible However, increase in number of membrane increase the membrane stiffness, which adds on to the deviatoric stress measured during shearing
Nicholson et al. (1993)	Tests procedure similar to the method 3 presented by Raju and Venkataramana (1980) was used, with an	The procedure eliminates the limitation of manually controlling the injection process. However the accuracy of the relation

Table 3 (continued)

Reference	Methods used	Limitations
	exception that the injection process was now controlled using a closed-loop computer-controlled system	between the membrane penetration and the effective confining pressure is yet to be addressed
Sivathayalan and Vaid (1998)	Compensation method by injecting additional water into the sample was used in the hollow cylinder tests. Unlike in the procedures presented by Raju and Venkataramana (1980) and Nicholson et al. (1993), the membrane penetration correction was obtained using the measured volumetric and axial strains, and the volume changes of the specimen and inner cavity caused under the hydrostatic loading	The procedure to estimate the membrane volume change assumes an axi-symmetrical deformation of the hollow cylinder to calculate the radial and tangential strains which can be rarely expected in practice

penetration and in turn reduced ε_{vm}. The procedure could be effective in reducing ε_{vm}; however, it is limited to remolded samples because sluicing of sand in undisturbed samples changes the field conditions.

Factors influencing membrane penetration

The literatures show various studies and methods to estimate ε_{vm}. This in turn dictates the need to list the factors influencing membrane penetration. Methods to estimate and/or control the membrane penetration presented in the previous sections clearly illustrates the key role of the effective confining pressure (σ_c'). Figure 3 shows the variation of ε_{vm} with σ_c' for samples with different grain sizes (d_{50}). The experimental results in the figure were selected such that the sample density for all the curves is similar (relative density, $D_r \approx 50$ %). Previous researchers suggest that the membrane penetration is strongly governed by the stress-state conditions with more emphasis on σ_c' acting on the sample (Frydman et al. 1973; Baldi and Nova 1984). Figure 3 addresses two main observations; firstly, σ_c' has a major effect on the membrane penetration; likewise, the mean grain size of the sample also has similar influence on membrane penetration. This is very clear from the figure that ε_{vm} increase by about three times when d_{50} for the sample was increased from 0.3 to 2 mm as presented by Noor et al. (2012). Secondly, from the stress–strain curves presented in the figure, the membrane shows an elastic deformation at lower values of σ_c', as observed from the experimental results presented by Baldi and Nova (1984). This behavior clearly suggests the rubber membrane to undergo permanent deformation during penetration in to the sample voids. The permanent deformation in the rubber membrane was also noticed by Evans (1992) in the laboratory triaxial tests. The deformation was considerably high in single membrane tests and eventually decreased with increase in the number of membranes used. This hence precludes the reuse of rubber membranes in the laboratory.

Figure 4 shows the variation of membrane penetration for samples with different mean grain sizes. It should be noted that the data presented in the figure are from the experimental results published by the previous studies. Hence, details on the experimental procedure, equipment used, properties of rubber membrane, sample type, and sample shape are very well expected to vary. Previous studies clearly suggest that the influence of sample density, particle shape, and particle type on the membrane penetration is comparatively small (Frydman et al. 1973; Baldi and Nova 1984), and hence, the influence of these variation is omitted in the figure. The effect of membrane penetration, ε_{vm} is further normalized to consider the variation of σ_c' using the following expression proposed in Baldi and Nova (1984).
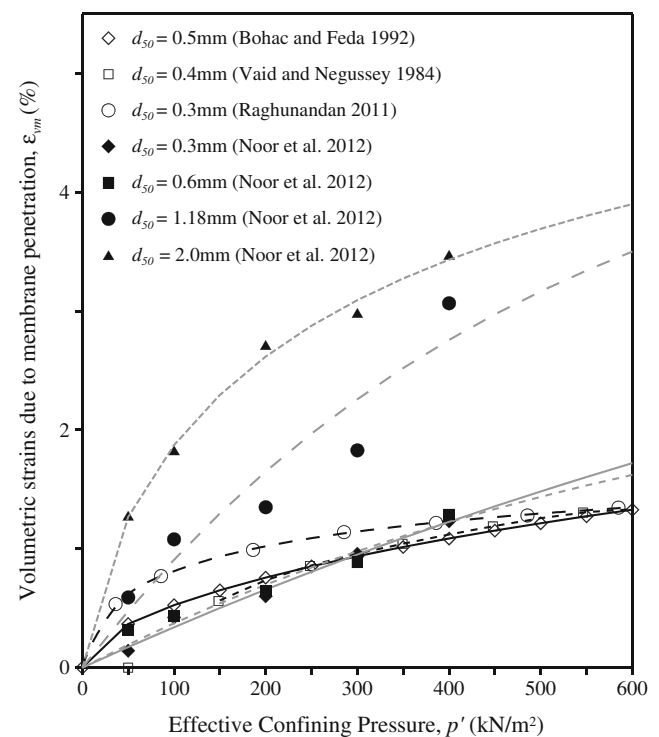

Fig. 3 Influence of applied effective confining pressure on the membrane penetration effect
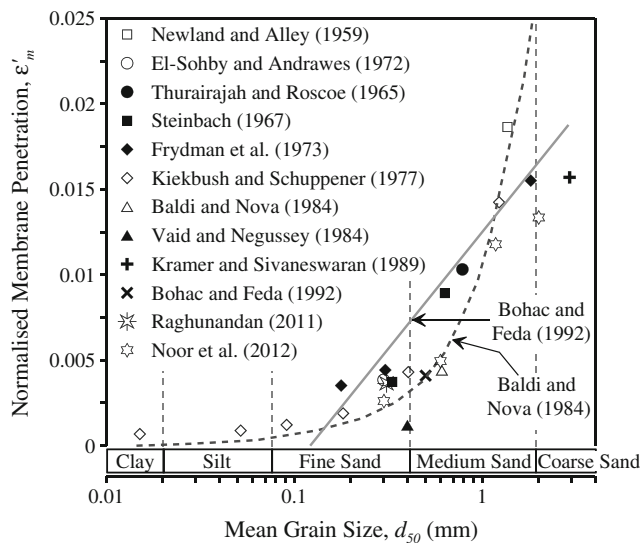
Fig. 4 Influence of grains size on the membrane penetration effect

Fig. 5 Influence of confining pressure on the membrane penetration effect (after Sivathayalan and Vaid 1998)

$$\varepsilon'_{vm} = \frac{\Delta \varepsilon_{vm}}{\Delta \log \sigma'_c} \tag{4}$$

where ε'_{vm} is the normalized membrane penetration. Observations from the figure shows the data points scattered with different values of ε'_{vm} over a wide range of particle size from clay sized particles, $d_{50}=0.015$ mm (Kiekbusch and Schuppener 1977) to coarse sands, $d_{50}=2.92$ mm (Kramer and Sivaneswaran 1989). Attempts to express both terms (ε_{vm}' and d_{50}) in an equation have been made by Baldi and Nova (1984) and Bohac and Feda (1992), which is presented as lines in the figure. Baldi and Nova (1984) derived an expression assuming the grains to be in spherical shape with an equivalent diameter, d_g, which is further in contact with the membrane layer. The expression proposed was as follows.

$$\varepsilon_{vm} = \frac{1}{8} d_g \left(\frac{\sigma'_c d_g}{E_m t_m} \right)^{1/3} \tag{5}$$

In addition, Bohac and Feda (1992) considered a linear correlation between ε'_{vm} and d_{50}. Both lines in the figure fail to have a good agreement with the data points. Hence, a precise relationship between ε'_{vm} and d_{50} is yet not clear. Therefore, further research to address this analytical issue shall give a better tool the estimation of ε_{vm} during triaxial testing. The overall remarks from the discussion, however, is limited to the grains size of the sample to have a considerable influence on the ε_{vm} and in turn on the measured ε_v. Figure 5 address the influence of the applied σ'_c on the membrane penetration. The figure is modified from the experimental data presented by Sivathayalan and Vaid (1998) using laboratory hollow cylinder tests on different materials of varied d_{50}. The figure is used
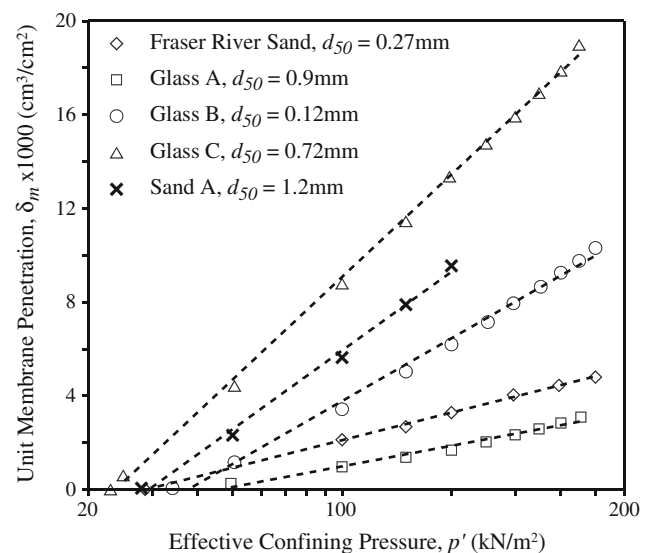
in this manuscript to give the reader a clear understanding on the influence of both effective confining pressure (σ'_c) and the mean grain size (d_{50}) on the membrane penetration. The authors use the term unit membrane penetration (δ_m) in the literature to explain the effect of membrane penetration. δ_m is derived as a function of the measured volume changes in the sample and inner cavity, external and internal radii of the sample, and the surface areas of the sample covered by the inner and outer membranes to be brief. Coming to the behavior of membrane penetration the figure clearly shows a linear variation of δ_m with σ'_c on a semi-log sheet. This result forms a bright side to establish a relationship between the membrane penetration and the applied confining pressure, which in turn can be used to apply corrections to the measured ε_v in laboratory tests. In any case, this procedure is again limited to a hollow cylinder test setup. Hence, further research is a must to evaluate either for a precise correction to the measured ε_{vm} or to make a modification in the use of conventional rubber membrane.

Concluding remarks

This paper presents a review on the influence of rubber membrane used to encompass soil samples in the laboratory tests. In general, the rubber membrane used in the tests has a significant influence on both measured deviatoric stress and the volume change data. Hence, these measured test data need to be suitably corrected or the test procedure be modified to eliminate or reduce the membrane penetration effect. Literatures on the correction procedure to estimate the membrane resistance showed the importance of membrane stiffness E_m,

which in turn depends up on the material type, membrane thickness t_m, and the membrane diameter, d_m (Henkel and Gilbert 1952; Bishop and Henkel 1962; Frydman et al. 1973; LaRochelle et al. 1988; Head 1998; Greeuw et al. 2001). The discussion and comparison with the experimental data suggest the compression shell theory to overestimate the q_m value and the Hoop stress theory to underestimate q_m irrespective of the type of membrane used. Hence, the correction calculated using the membrane stiffness (Eq. 1) is a more reliable method to calculate the precise deviatoric stress values from the measured data.

The discussion on influence of rubber membrane on the measured volume change data presented various methods to estimate the value of ε_{vm}, which is then used to calculate the corrected ε_v. Most of the procedures showed limitations with theoretical assumptions and/or specific to certain test conditions. Experimental methods to reduce the effect of membrane penetration also showed limitations and experimental complications as discussed in this paper. The important outcomes from the detailed discussion presented in this paper highlight the key role of σ_c' and d_{50} of the sample in controlling the extent of ε_{vm} that can be accepted. The influence of sample density, particle shape, and particle type is comparative small. Also from the review of previous literatures, it is therefore highly recommended to evaluate the permanent deformation in the rubber membrane while reused, and it is more appropriate to avoid reuse of the rubber membranes during testing. The procedure proposed by Sivathayalan and Vaid (1998) forms bright side to express relation between the ε_{vm} and σ_c', which is again limited to the hollow cylinder test setup. Hence, based on the reviews and discussions presented in this paper, it is clear that a general precise correction or a modification in the use of conventional rubber membrane is required to address the influence of rubber membrane on measured data in the triaxial tests.

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