REVIEW OF THE VIBRATORY LABORATORY COMPACTION TEST

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ABSTRACT

In New Zealand, road pavements are typically constructed of flexible pavements, with thin bituminous surfacings over unbound aggregate layers. These pavements derive their main structural capacity from the unbound granular base and subbase layers. The design and construction control of an unbound granular basecourse in the field is commonly based on the results of laboratory compaction tests. There are however other non–vibratory compaction methods. The test for vibratory compaction is specified in the New Zealand Standard (NZS) Vibrating Hammer Compaction Test (NZS 4402: Test 4.1.3.).

The test method is widely used and is renowned for being economical, simple and versatile. However, recently the applicability of the laboratory test has been questioned by industry due to the variability in laboratory test results and, consequently, its insufficient reflection of field conditions. There are a number of test variables that affect the test outcomes and therefore the reliability for designing and controlling the field construction of an unbound granular (UG) basecourse.

In this paper, the potential reasons for laboratory compaction test variability (NZS 4402: Test 4.1.3) are explored and reviewed and the principle framework of a new test method is to address most of the major shortfalls described.

The key finding is that the NZS test does not induce significant multi-directional cyclic shear strain; the parameter which is dominant for realising the densest packing state of the particles of an UG material, irrespective of the particle size distribution (PSD). Thus, the development of a new laboratory compaction method is an imperative for reducing laboratory variability and the gap between field and laboratory compaction.

INTRODUCTION

During the phase of road construction, a significant influence on life-time pavement performance is pavement compaction (Austroads, 2004; Huerne, 2004; NZS, 2010; T. Youd, 1973). In the field, rolling compaction is the means by which a pavement final structure, of specified geometry and performance, is produced (Zealand, 2005). The design and construction control of pavements with thin bituminous surfacings, in New Zealand, is very dependent on the results of the Vibrating Hammer Compaction Test (NZS 4402: Test 4.1.3.)(NZS, 1986; Zealand, **2000**). This laboratory compaction test is conducted under a constant set of parameters. These laboratory-based compaction parameters do not simulate those parameters available in the field (Bartley, 2007; Karan, Larkin, & Wilson, 2017a). Consequently, physical and mechanical properties of final products of the laboratory and field compaction are often different. To make matters more complex, the test can result in significant variability in terms of repeatability and reproducibility (Karan, Larkin, & Wilson, 2017b; Karan, Wilson, & Larkin, 2014; McLachlan & Bagshaw, 2017; Shahin, 2010).Thus, implementing this NZS laboratory compaction test can lead to premature pavement distress, revealing defects in pavement design and/or construction control (Bartley, 2007; JE Patrick, Alabaster, & Dongol, 1998; J. Patrick & Werkmeister, 2010).

The NZS Compaction test is evidently not always adequate for tightly controlling the construction of an unbound granular basecourse designed for a thin-surfaced bituminous pavement. The realisation of the target field density specified in TNZ B/02 (Zealand, 2005) as a deduced percentage of the Maximum Dry Density (MDD) of the laboratory test is a controversial issue (Bartley, 2007; Karan et al., 2017a; McLachlan & Bagshaw, 2017). While some contractors report that the laboratory test-deduced field target density could not be realized in the field, others report the opposite (McLachlan & Bagshaw, 2017). The TNZ B/02 document confirms this controversy (Zealand, 2005). The NZ standard (NZS 4402) justifies implementing the MDD of a plateau density test as a criterion for controlling the construction of an UG base layer, instead of that resulting from the NZS laboratory test when the laboratory derived target field density is impossible to achieve (Zealand, 2005). This difficulty in achieving the target MDD in the field was cited as being caused by particle degradation in the NZS vibratory test, rather than change in the structure and fabric of the particle arrangement (Karan et al., 2017a). A key variable in the compaction process is the ratio of the maximum particle size to the diameter of the mould used to confine the specimen. Thus, field over-compaction, resulting in particle crushing, can occur since the necessary ratio of maximum particle size to mould size is not utilised (Karan et al., 2017a). This effect of using an under-sized mould is worse when a thick basecourse layer is considered (J. Patrick & Werkmeister, 2010). Relatively rapid development of high profile rutting and a general decrease in pavement density by the onset of trafficking can result (JE Patrick et al., 1998; J. Patrick & Werkmeister, 2010).

Confidence in the use of the laboratory test MDD to control field construction is misplaced for several reasons and the use of the NZS test MDD was recommended to cease and be replaced by a specification of Total Air Voids (TAV) for higher reliability, simplicity and precision (Bartley, 2007). Relying on the NZS test conditions being valid to simulate those applicable when densifying an UG material in the field is substantially incorrect (Aviles, 2008; Bartley, 2007; Hanna & Yulek, 2014; Karan et al., 2017a; Roudgari, 2012). The conditions controlling the laboratory test are not replicated in any element of basecourse in an UG layer during compaction in the field (Aviles, 2008; Hanna & Yulek, 2014; Karan et al., 2017a; Roudgari, 2012). Compacting an UG material in a laboratory mould prevents its global lateral deformation, which is almost representative of a K_0 condition and is thus substantially different from the lateral boundary conditions in the field (Aviles, 2008; Hanna & Yulek, 2014; Karan et al., 2017a; Roudgari, 2012). When trying to induce compaction of a UG material, allowing the freedom for lateral deformation is a critical factor for rearrangement of the material particles into a densely packed state, the result of which is significant interlocking manifested as a substantially higher shear modulus (Chen & Fang, 2008; Huerne, 2004; Peploe, 1991; T. Youd, 1973; T. L. Youd, 1972). Overall the result is a UG layer which is resistant to plastic shear strain through-out the life of the pavement.

The variability in laboratory test results of the NZS Vibrating Hammer Compaction test, is generally considered to have low reliability for furnishing parameters for design of unbound granular (UG) basecourse pavements. This vibratory method is used to prepare the specimens of other characterising and strength indicating tests such as repeat load triaxial and CBR tests (Karan et al., 2017b; NZS, 1986). Intuitively, the variability of the results of these characterising tests depends, at least in part, on the variability of the results of the NZS compaction test (Karan et al., 2017b). Accordingly, designing a pavement cross section of the same materials for a constant traffic load and environmental conditions can lead to an increased probability of failure. This variability is due to generic factors in the laboratory testing and specific reasons for the inconsistent results of this NZS test have been described by (McLachlan & Bagshaw, 2017) and relate mainly to the equipment design and the testing method (McLachlan & Bagshaw, 2017; Shahin, 2010). The net effect of these inconsistencies result in a variation in compactive effort, which was demonstrated by obtaining significantly variable densities, although constant conditions of testing were faithfully reproduced (McLachlan & Bagshaw, 2017). Thus variation in compactive effort lies at the heart of the issue. However, increasing the mould size in relation to the maximum particle size was shown to largely mitigate the influence of variation in compactive energy (Karan et al., 2017a).

In addition, the NZS test does not set-out to create any realistic simulation of a field roller compactor. (Bartley, 2007). A realistic simulation should imply either a small-scale emulation of the essential aspect of a field roller compactor or its induced compaction mechanism (Partl et al., 2012) and vibration is the only aspect of similarity to field vibratory rollers. However, fundamentally the laboratory test vibration-inducing mechanism and method of application are different from that of a field vibratory rolling compactor.

In this paper, the fundamentals that lie at the heart of the reasons for the variability of laboratory compaction test result variability (the NZS 4402: Test 4.1.3) are explored and reviewed and the broad outline of the development of a new test method are described that address most of the major shortfalls.

COMPACTION ENERGY AND CYCLIC SHEAR STRAIN

The compaction duration prescribed for conducting the NZS compaction test is 180 seconds for each layer of material (NZS, 1986). The observations of the authors however, in the case of an M/4 AP40 basecourse material, reveal that specimens undergo almost no height reduction in the last 150 seconds of "compaction". The remaining 150 seconds of the test duration has been shown to result in particle size degradation when the NZS sized mould (150 mm diameter) is used (Karan et al., 2017b). Clearly, the test conditions obstruct the optimum transfer of energy within the test specimen. Realisation of the optimum energy transfer depends on the amplitude and configuration of normal vertical stress as well as the amplitude, directionality and number of cycles of shear strain with stress reversal (Peploe, 1991; T. L. Youd, 1972).

During the compaction of an UG material, it is well known that particles will only rearrange themselves into a more dense state if the compaction-induced stresses exceed a particular threshold level (Briaud & Seo, 2003; Peploe, 1991; T. L. Youd, 1972). For a dense state to occur the material must transition through several stages of distortion (T. L. Youd, 1972), resulting in relative displacement between the particles and a new fabric developing. These stages of distortion imply the occurrence of combinations of plastic volumetric and shear strains (T. L. Youd, 1972). The levels and number of cycles of plastic strain are such that on removal of the stress field the fabric of the medium is such that the volume changes are irreversible. Shear strain with reversal is found to be the decisive parameter governing the state of compaction of an UG material (Peploe, 1991; T. L. Youd, 1972). Figure (1) shows the experimental evidence of the effect of applying cycles of shear strain with reversal on the compaction of an UG material.

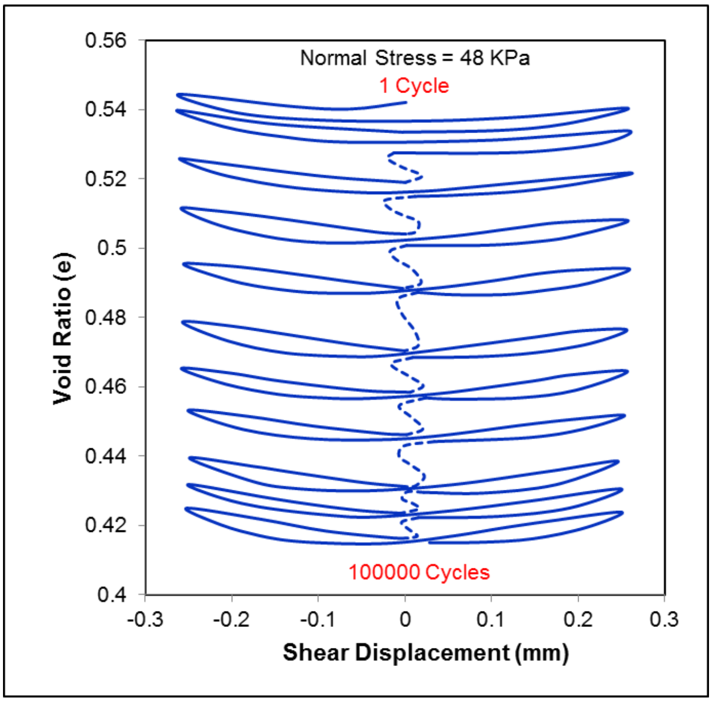


Figure (1): compaction versus shear strain history of a specimen of UG material at (48 KN/m^2) vertical stress (Adapted from (T. L. Youd, 1972))

A review of published work strongly suggests that when particles are brought into contact, the realisation that any further compaction will not occur unless local (inter-particle) and global shear strains are induced (T. L. Youd, 1972). There is an interplay between the state of vertical effective stress, the induced shear stress reversals, and the resulting plastic volumetric strain. Studies have shown that both in the field and in laboratory, the highest densification of an UG material, under compaction load, is achieved at a particular depth, rather than at the surface of the medium (Chen & Fang, 2008; T. L. Youd, 1972). At that particular depth, the highest shear strain develop and, consequently, the largest relative lateral displacement of particles occurs (Chen & Fang, 2008; T. L. Youd, 1972). If the applied shear stresses are inadequate to overcome the mobilised inter-particle friction degradation can occur, with little or no further compaction (Peploe, 1991; T. L. Youd, 1972). These authors consider that this is likely to be the reason why implementing a relatively small mould in the NZS compaction test results in particle degradation in some cases, as stated in (Karan et al., 2017b).

The magnitude of an applied vertical surface stress on an UG material can bring about a premature end to compaction before the material has reached the limit of possible change in volume (Huerne, 2004; Peploe, 1991). Vertical normal stress compresses the particles of the primary skeleton of an UG material and brings them into increasing contact (Huerne, 2004; Peploe, 1991). An increase in the magnitude of vertical normal stress increases the potential for compaction by compressing the primary skeleton (Peploe, 1991; T. L. Youd, 1972). This compression induces the development of inter-particle friction which, depending on the angle of internal friction, can result in inter-particle slip (relative displacement) with associated volumetric strain and change in structure of the primary skeleton. However, neglecting the change in volume of the solid particles, no change in volume will occur without inter-particle slip which results from the shear stress being of sufficient magnitude to exceed the inter-particle shear strength. Thus the relationship between vertical stress and shear stress is of critical importance. (Huerne, 2004; Peploe, 1991; T. L. Youd, 1972). Theoretically, during the compaction of an UG material, the case of an isotropic confinement, which implies a confining normal stress equal in all directions, cannot induce any shear (Huerne, 2004). Thus, the development of this isotropic condition during the NZ compaction test may be the reason for no further reduction in specimen height after 1/6 of the specified duration of vibration has been completed. Figure (2) shows the effect of applying a cyclic shear strain with 4 levels of amplitude on the compaction of an UG material compared to that of applying a vertical surface stress with 4 levels of amplitude.

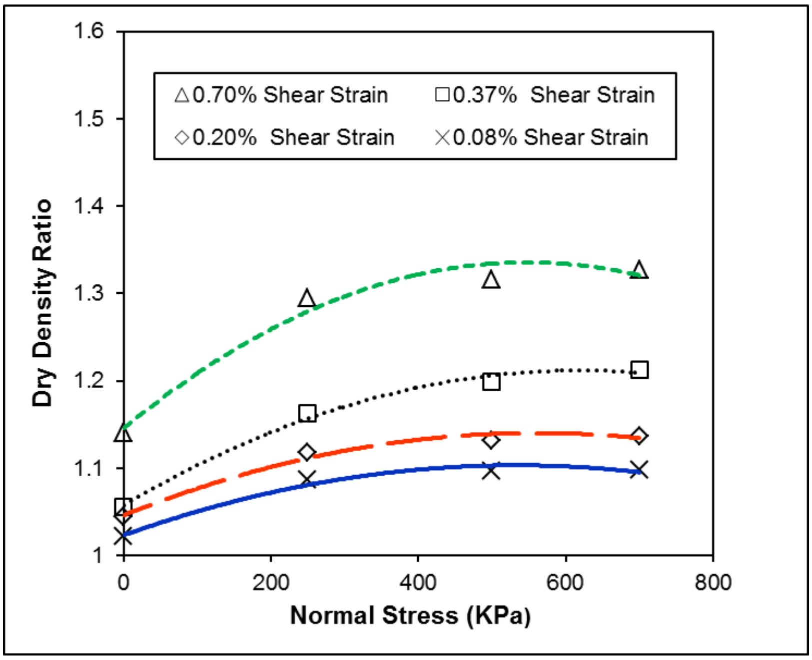


Figure (2): Plot of dry density ratio (after 20,000 shear strain cycles) versus normal stress magnitude (Adapted from(Peploe, 1991))

In the NZ compaction test, the amplitude of the applied vertical surface stress and the mould diameter control the magnitude of the stress ratio, σ_v / τ, i.e. the vertical effective stress upon the shear stress (Huerne, 2004). Comparatively, under a constant amplitude of vertical stress, using a mould of small diameter can halt the compaction of an UG material in a shorter time than a mould with a bigger diameter and thus the use of a small diameter mould results in a lower degree of compaction compared to the use of a larger diameter mould (Huerne, 2004). The lower effective vibration duration and compaction of the material when a mould of small diameter size used is due to the faster erection of barriers against the relative displacement of particles compared to that when a mould of larger diameter is used (Peploe, 1991). The erection of these barriers is caused by mobilising the inter-particle friction (Peploe, 1991; T. L. Youd, 1972). For further compaction to occur, the material needs to be subjected to a different stress field that can induce shear strains higher than were induced by the previous stress field (Peploe, 1991). This is essential to overcome the mobilised inter-particle friction from the previous stress field (Peploe, 1991; T. L. Youd, 1972). Thus, in the laboratory and the field, the efficient realisation of the highest compaction level of an UG material dictates maintaining an adequate shear stress/mean normal stress ratios in the course of compaction (Huerne, 2004; Peploe, 1991; T. L. Youd, 1972).

In the field, the overlapping zone of a rolling compaction pattern often reveals the highest compaction level across a compacted layer of a road foundation (IMRAN, 2016; Masad, Koneru, Scarpas, Kassem, & Rajagopal, 2010). Obviously, this is due to the influence of the unique induced cyclic shear strains of alternating direction in this zone (Peploe, 1991; T. L. Youd, 1972). These unique cyclic forces on the particles of material in this zone cause the particles to be displaced bi-directionally (IMRAN, 2016; Masad et al., 2010). Thus, a laboratory compaction test that induces uncontrolled unidirectional cyclic shear strains, such as the NZ compaction test, is axiomatically unable to cause the realisation of the highest compaction level of an UG material (Peploe, 1991; T. L. Youd, 1972). Figure (3) shows the effect of applying bi-directional cyclic shear strain compared to that of one-way cyclic shear strain on the compaction of an UG material. Figure (4) shows the variance in the realized field density due to rolling pattern, overlapping zone and boundary conditions.

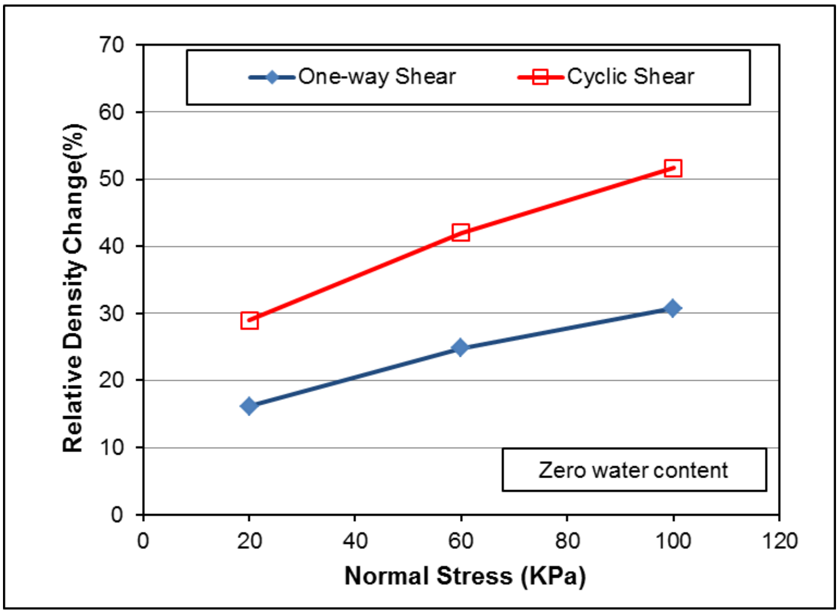


Figure (3): change of relative density with one-way and cyclic shearing disc versus normal stress (Adapted from (Liu, 2012) after (Yang,2002))

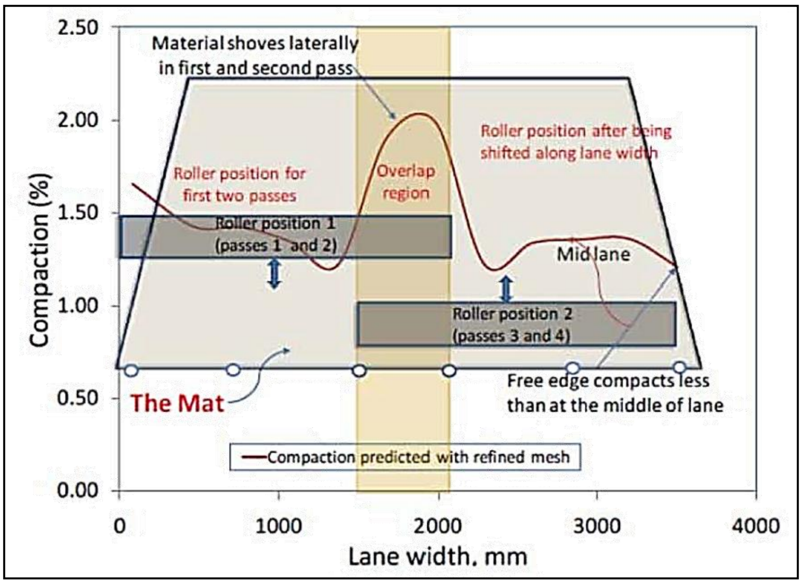


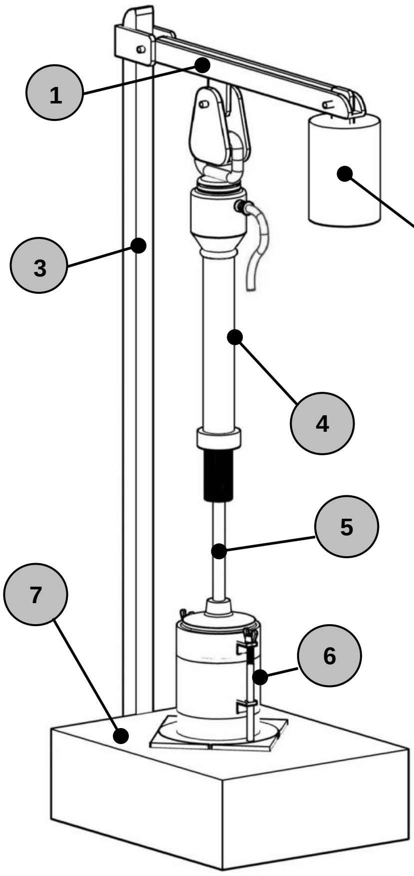
Figure (4): chart representing the final compacted state of the material along the width of the pavement (Masad et al., 2010)

BARRIERS AGAINST DEVELOPING BI-DIRECTIONAL SHEAR STRAIN

In conducting a compaction test in compliance with NZS4402 on an optimum basecourse such as M/4, several barriers preventing the development of compaction-conducive shear strains become evident. Based on the international literature, the authors postulate the erection of a number of barriers that supress compaction. These barriers include the heterogeneity of the physical properties of the particles, the particle size distribution (Cai, 2015; Hefer & Scullion, 2005; Henderson, Herrington, Patrick, Kathirgamanathan, & Cook, 2011), and test equipment design and conditions (Shahin, 2010). The equipment design and testing conditions can limit the particle relative displacement in the lateral directions. Lateral particle relative displacements are essential for realising the highest densification of the material (Chen & Fang, 2008; Huerne, 2004; Peploe, 1991; T. L. Youd, 1972). The characteristics of the compaction loading, specimen size and confinement stiffness of the test mould significantly influence the lateral particle displacements and, consequently, the achievable compaction level of an UG material. Figure (5) illustrates the components of the NZS vibrating hammer compaction test.

The ratio of tamper diameter/mould diameter of the NZS compaction test is almost unity (145/152 ±0.5mm ~ 1) (NZS, 1986; Shahin, 2010). Due to this ratio, the tamper and the mould almost provide full horizontal confinement of a specimen. The equipment design is, in a sense, piston-like. The piston-like design almost totally restricts the motion of the tamper to the vertical. Thus, the vibratory vertical movement of the tamper creates the likelihood of inducing only unidirectional cyclic shear strains around the vertical axis of symmetry. However, as described earlier, an optimum densification can only be achieved if cyclic shear strains of alternating direction are induced during compaction (Peploe, 1991; T. L. Youd, 1972). The use of a smaller ratio of tamper diameter / mould diameter can result in the achievement of a higher density (Drnevich, Evans, & Prochaska, 2007; Kouassi, Breysse, Girard, & Poulain, 2000; Parsons, 1992).

NZS 4402 specifies a flat base tamper for this compaction test (NZS, 1986). The flat base tamper can limit the development of plastic shear strain within the test sample. The tamper and a single surface footing are shown to be analogous (Chen & Fang, 2008). The bearing capacity of dense sands supporting a surface footing can be used for as an aid in understanding the development of plastic shear strain in the sand. As described in the literature, surface foundations with a flat, concave and convex base surface founded on a cohesionless soil may be considered for illustrating the effect of the base shape of the NZS tamper on the compaction of an UG material. The soil under a foundation with a flat base reveals a higher bearing capacity than that under the foundation with a convex base surface (Sandström, 1994). An increase in the bearing resistance of the cohesionless soil, with respect to the surface of contact between the soil and footing, implies an increase in its bearing strength (Graham, Raymond, & Suppiah, 1984; Meyerhof, 1963; Terzaghi, 1943). From this it follows, as a generality that the strain field beneath the footing will decrease (Graham et al., 1984; Meyerhof, 1963; Terzaghi, 1943).



NO.	***Element***
1	*Lever Arm*
2	*Surcharge*
3	*Loading frame*
4	*Vibrating Hammer*
5	*Tamper*
6	*Mould*
7	*Pedestal*

Figure (5): NZS laboratory vibrating hammer compaction test assembly

Also, lateral confinement is a very significant influence on the bearing capacity of cohesionless soils under surface foundations (Fattah, Shlash, & Mohammed, 2014; Graham et al., 1984; Lee & Eun, 2009; Stuart, 1962; Yadav, Saran, & Shanker, 2017). The effects of confinement entails stress interference, stress redistribution, blocking of the radial stress zone and arching (Fattah et al., 2014; Graham et al., 1984; Lee & Eun, 2009; Lee, Salgado, & Kim, 2005; Loukidis & Salgado, 2009; Meyerhof, 1963; Stuart, 1962). For a foundation built on a cohesionless soil, lateral confinement can develop due to adjacent foundations or walls. Interpenetration of adjacent inner passive Rankine zones of the footings and a contraction of the inner radial zones can take place, depending on edge-to-edge distance (Graham et al., 1984; Stuart, 1962). Comparatively, the case of zero distance between footings or between a footing and an inserted wall (the compaction mould) shows the highest increase in the bearing capacity of cohesionless bed soils (Fattah et al., 2014; Graham et al., 1984; Lee & Eun, 2009; Stuart, 1962; Yadav et al., 2017). Figure (6) shows the changes in stress distribution underneath a foundation due to adjacent foundations or walls.

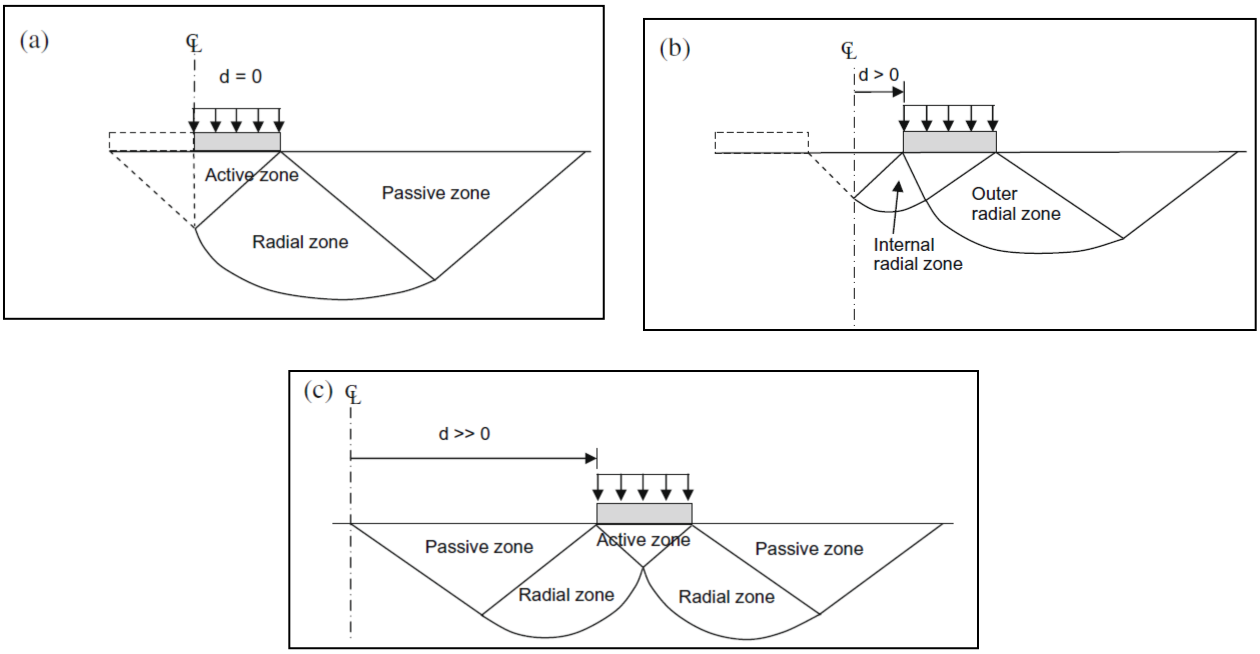


Figure (6): Failure mechanisms of multiple footings for (a) in-contact condition; (b) intermediate condition; and (c) isolated condition (Adapted from (Lee & Eun, 2009))

Similarly, in the compaction mould, the build-up of these stresses and strains adjacent to the mould wall can speed up hardening of the material in the vicinity of the wall (T. L. Youd, 1972). A static state occurs when the induced shear stress cannot overcome the friction force between the adjacent granular medium and the steel surface (Peploe, 1991). At this stage, the particles adjacent to the mould wall can act as an annulus since the normal stresses are higher and inadequate to produce plastic strain compared to that at the core of the specimen (Tutumluer, 1995), in other words a bifurcation takes place in the material properties, i.e. there is an inner circular column and an outer annulus. A sharp increase in the pressure applied to the annulus occurs and at the material-tamper interface. Most of the compaction load is now applied to material adjacent to the mould wall. If this process continues the columns may fail in shear when the shear strength is reached. The particles comprising these columns at yield can either move inward towards the core of the specimen or be degraded to smaller sizes. If inward movement from the mould wall occurs, the particles moving inward can collide with those moving outward from the core due to a continual redistribution of the compaction load over the bearing area i.e. the material-tamper interface. If volumetric constraint develops in this transition zone and the particles cannot inter-mix into a more dense state then particle degradation follows. This particle degradation is more likely to occur in a small mould. A small-scale laboratory compaction test can be devised to simulate field compaction by a vibrating rolling drum. The diminishing or contraction of some components of the field compaction-i.e the induced failure zone (the passive Rankine zone and radial zone and its consequent influence on shear strain), not only can affect the realised level of compaction but also can affect the micro-structure of compacted materials. Figure (7) illustrates the stress zones in UG materials under a vibratory rolling drum in the field and the corresponding level of densification with depth.

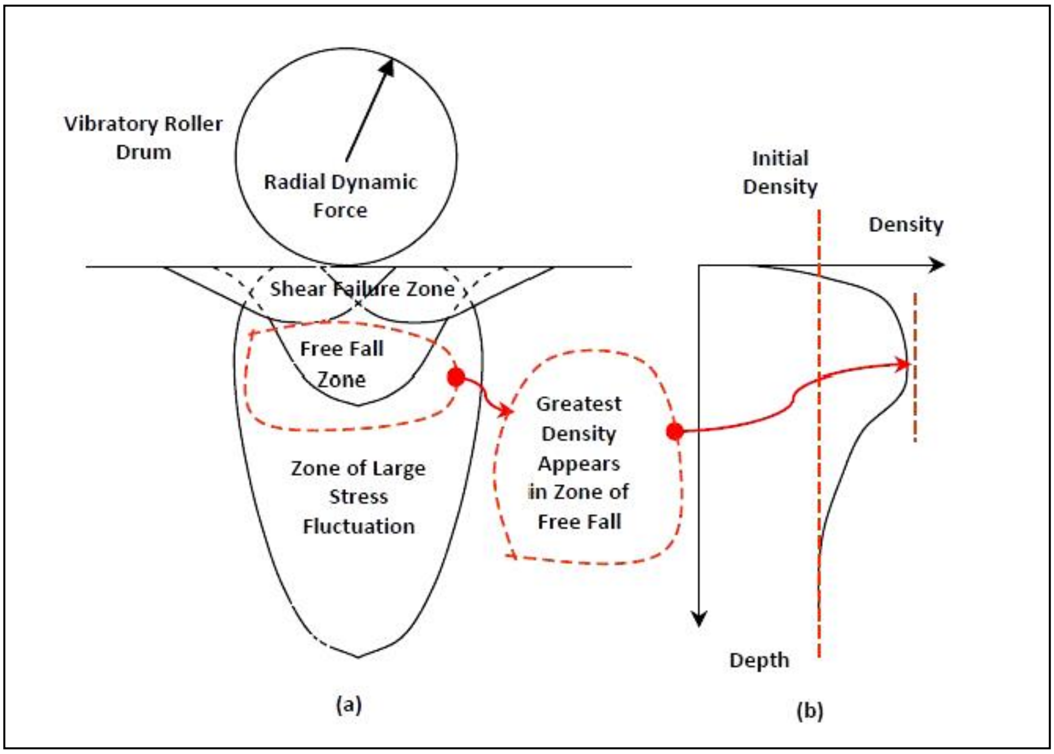


Figure (7): (a) Diagrammatic illustration of Zones under Vibratory Roller (b) Qualitatively predicted density profile(Adapted from (T. L. Youd, 1972))

PREVIOUS EFFORTS FOR IMPROVING LABORATORY COMPACTION

In their effort to reduce the gap between the end-results of laboratory and field compaction, many researchers have developed laboratory tests to attempt the realistic simulation of field compaction. The laboratory tests can be classified into two categories.

The first category contains attempts to simulate the conditions the UG is under in the process of compaction. The focus is on parameters such as rolling (Bodin, 2013; Bodin & Kraft, 2015; Partl et al., 2012) and the boundary conditions (Brown, 2004; Coni, Thom, Isola, & Edwards, 2005; Dyvik, Zimmie, & Floess, 1981; Huerne, 2004; Nazzal, 2007; Tutumluer, 2013; Zeilmaker & Henny, 1989). Rolling-based tests produce prismatic specimens which are incompatible with other strength-indicating and characterising laboratory tests such as CBR and RLT tests (Bodin, 2013; Bodin & Kraft, 2015; Partl et al., 2012). Also, rolling-based tests produce specimens of highly variable density (Bodin, 2013; Bodin & Kraft, 2015; Partl et al., 2012). However, some of these tests are suitable to produce specimens with a similar internal structure to that produced in the field (Bodin, 2013; Bodin & Kraft, 2015; Partl et al., 2012).

The focus of the second category is simulation of the response of the UG under compaction. The focus of this category concerns material mechanical behaviour during field compaction such as normal stress, shear stress and displacement (Partl et al., 2012; Peploe, 1991). Mechanical response controlled tests can produce cylindrical specimens which are advantageous for the other laboratory tests mentioned above (Partl et al., 2012). The well-recognised equipment of the latter category is the Gyratory compactor test. Even though this test is standardized for the laboratory compaction of asphaltic mixes, it has been used to compact UG materials (Cary et al., 2014; Henderson, Herrington, Patrick, Kathirgamanathan, & Cook, 2011; Ping, Leonard, & Yang, 2003). The gyrating mould and the consequent vertical eccentric loading over the specimen surface can induce shear stresses which are a function of the gyration angle (Bayomy, Masad, Dessoukey, & Omer, 2006; Partl et al., 2012). The Gyratory compactor test can produce a compaction curve almost identical to that of the field compaction (Cary et al., 2014; Lambert, Denny, Sukumaran, & Mehta, 2009; Ping et al., 2003). Also, it can produce specimens of internal structure reasonably close to that produced in the field (Partl et al., 2012) except when the approved ratio of mould diameter to maximum particle size is disregarded (Henderson et al., 2011). However, particle size degradation and air voids segregation can occur (Bozorgzad, 2017; Cary et al., 2014).

In the literature, there is a consensus that no laboratory compaction test can reasonably replicate all the end-results of field compaction (Bozorgzad, 2017; Henderson et al., 2011; Partl et al., 2012). However, the basic principles, strengths and highly realistic correlation with field density support the adoption of the Gyratory compactor test as a focus of further development towards unification of field and laboratory compaction results.

LESSONS LEARNT AND RECOMMENDATIONS TO MODIFY THE NZS COMPACTION TEST

Based on the literature, the paramount effect of the nature and magnitude of cyclic shear strain on the compaction of granular materials is broadly acknowledged (Peploe, 1991; T. Youd, 1973; T. L. Youd, 1972). An induced high magnitude cyclic bi-directional shear strain causes the particles of a granular material to rearrange into a more stable and dense structure, with a resultant change in void ratio, until further volumetric change is constrained.

In field construction, during the compaction of a granular material, implementing a field compactor consisting of a rolling drum can induce alternating bi-directional cyclic shear strains in the direction of rolling and perpendicular to the rolling path (Huerne, 2004; IMRAN, 2016; Kassem et al., 2012; Masad et al., 2010; Tutumluer, 2013). Figure (8): depicts how a rolling pattern of an overlapping zone can provide more than one opportunity for cyclic shear strain to occur. In the NZS compaction test, when a base course material is concerned, the application of a vertical, cyclic, centric compaction load does not provide conditions conducive to the development of a compaction favourable shear strain field due to the almost total lateral and base confinement. Thus, there is a need for a technique and/or technology for increasing the development of plastic shear strain within an UG material specimen during a NZS compaction test. Any approach to be suggested should consider the gradual development of lateral confinement during the compaction of a basecourse material and the rolling pattern of a roller compactor in the field. This avenue is worthy of further investigation.

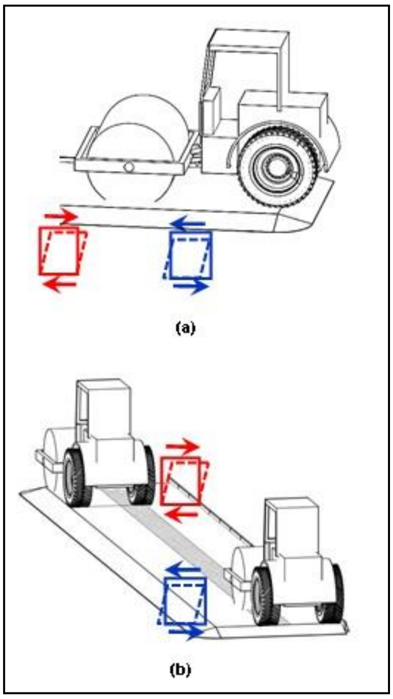


Figure (8): Rolling pattern effects on material compaction (a) cyclic shear strain in the direction of a rolling path (b) cyclic shear strain in the overlapping zone

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