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Historical methods of preparing reclaimed sand subgrade beneath Australian airfield pavements

Méthodes historiques de préparation de sous-sol de sable récupéré sous les chaussées d'aérodrome Australien

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ABSTRACT: Current pavement design methods still reference empirical work undertaken in the 1950's which derive a compaction profile for a nominated aircraft gear configuration. This requires an approximation of how stress is transmitted to depth. Historical Australian practice has been to adopt a combination of method and end-product specifications to achieve this compaction profile in areas of reclaimed sand. These methods were developed in the 1970's to replicate the gear group loads of a Boeing 747. The increased depth of subgrade affected by new aircraft means that more of the pavement subgrade influences the pavement design than may have been considered in the early empirical studies. Further investment in trials and new methods of construction verification is required by government agencies or aviation industry bodies to keep pace with advances in aircraft engineering.

RÉSUMÉ: Les méthodes actuelles de conception des chaussées font encore référence à des travaux empiriques entrepris dans les années 50, qui permettent de calculer un profil de compactage pour une configuration d'engin désignée. Cela nécessite une approximation de la façon dont le stress est transmis à la profondeur. La pratique australienne historique a consisté à adopter une combinaison de spécifications de méthodes et de produits finis pour atteindre ce profil de compactage dans les zones de sable régénéré. Ces méthodes ont été mises au point dans les années 1970 pour reproduire les charges d'un groupe d'engins Boeing 747. L'ampleur accrue de la plate-forme affectée par les nouveaux aéronefs signifie qu'une plus grande . Les agences gouvernementales ou les organismes de l'industrie aéronautique doivent investir davantage dans les essais et les nouvelles méthodes de vérification de la construction pour suivre les progrès de l'ingénierie aéronautique..

Keywords: Compaction, Sand, Airfields, Reclaimed land, Super Compactors

1 INTRODUCTION

Historically, airfield pavement design methods assume that the subgrade is prepared to a minimum standard during construction. This standard is comonly described by a relative compaction profile (AC No: 150/5320-6F).
The "compactness" of reclaimed sand is directly related to the resilient modulus of the subgrade which is an important factor in the structural design of pavements. The resilient modulus is estimated from empirical relationships between the effective Californian Bearing Ratio at the surface of the prepared subgrade under a particular aircraft gear configuration.

2 COMPACTION SPECIFICATION

The two main approaches to specifying compaction in the field are known as method compaction and end product compaction.

Method compaction is a previously proven method using equipment of known type and mass. The minimum number of passes and maximum layer thickness are specified for a particular material type. The UK Highway Agency (MCHW, 2016) employs such an approach in the construction of major roads and highways.

The alternative favoured by Australian road practice is the specification of a minimum level of compaction which is measured in the field during the works. Field density tests can be carried out to verify the standard of compaction by measuring, values of bulk density and water content.

3 COMPACTION STANDARDS

Relative compaction (Rc) describes the percentage of dry density (or dry unit weight) to its maximum density (or dry unit weight) achievable under a certain energy level in the laboratory.

$$R_c = \frac{\rho_d}{\rho_{dmax}} \qquad (1)$$

The use of relative compaction is routinely used in construction as a measure of the degree of "compactness" according to some specified standard test, for example, the standard or modified Proctor test. The maximum dry density is only a maximum for a specific compactive effort. This does not necessarily reflect the maximum dry density that can be obtained in the field by the chosen construction method.

The dry density of a cohesionless soil does not necessarily reveal whether the soil is loose or dense. The engineering properties such as strength, stiffness and permeability vary considerably with their state of compactness.

Relative density (Dr) is a measure of the difference in the void ratio (e) relative to its loosest and densest possible soil packing and applies to soils with less than 12% fines. Density index (Id) approximates relative density (Dr) and describes the ratio of the difference between a soil's dry density (or dry unit weight) and its respective minimum and maximum dry density. Both are often expressed as a percentage which along with the terminology can lead to confusion with relative compaction. It may be for this reason why the Australian Standard (AS1289.5.6.1) incorrectly refers to relative density as "density index". The correct definitions as defined by ASTM D4253-14 is as follows:

$$I_d = \frac{\rho_d - \rho_{dmin}}{\rho_{dmax} - \rho_{dmin}} \qquad (2)$$

$$D_r = \left[\frac{\rho_d - \rho_{dmin}}{\rho_{dmax} - \rho_{dmin}}\right] \times \frac{\rho_{dmax}}{\rho_d} \qquad (3)$$

$$Or$$

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \qquad (4)$$

4 LABORATORY METHOD LIMITATIONS

Australian experience has been to favour relative compaction (Rc) over relative density (Dr) in describing the compactness of sands. This approach is mainly due to concerns over the accuracy of obtaining the minimum dry densities in the laboratory. Experience indicated that density in the loosest state as determined in the standard laboratory test was very variable even for small changes in the sand grading. Some authors have estimated the potential errors may be up to 40 percent (Bowles, 1997). By contrast, the maximum saturated vibrated density varied little. Consequently, in-situ densities of compacted sand are often reported as a percentage of its maximum vibrated density (Rc vib) in Australian Airfield construction projects.

ASTM methods (D-4253 and D-4254) of measuring relative density differ from Australian and British standards in how they assess the maximum dry unit weights. The Australian (AS1289.5.5.1) and British standard (BS1377.4) uses a “wet method” to determine the maximum dry density. All methods use a vibrating table to compact the sands. American experience suggests both wet and dry methods should be undertaken initially until repeatable results with less than 2 percent difference are obtained.

An approximate relationship between relative compaction (Rc) and relative density (Dr) is often used as follows:

$$R_c = 80 + 0.2D_r \qquad (5)$$

This relationship was developed from a statistical study of over 47 separate soils (Lee et al. 1971) which looked at the relative compaction (Rc) achieved by vibratory methods compared to that determined by the modified Proctor compaction (Wright et al. 2003). This relationship varies from soil to soil depending on particle density, size, grading and the ability to hold water indirectly determined by fines mineralogy.

A comparison of the relative density (Dr) achieved under the same level of relative of compaction normally employed in earthworks (98 percent Rc) can be derived using a simple parametric study, Figure 1. In this study, the minimum dry density remains the same (1.4 t/m^3) as this is considered the practical lower bound densities of most end tipped sands. The maximum dry density is varied to represent differences in sand sources. This study demonstrates that sand compacted to the same relative compaction (98 percent Rc) can result in a relative density (Dr) of between 98 and 90 percent. As the engineering behaviour is often correlated to its relative density (Dr), this can result in an overestimate of the assumed engineering properties if relative compaction is used as a measure of compaction.

Compaction of a cohesionless soil does not produce a well-defined dry density, soil moisture content relationship. This can result in an underestimation of the maximum dry density. This issue and differences in sand type can result in the compaction achieved in the field being overestimated.

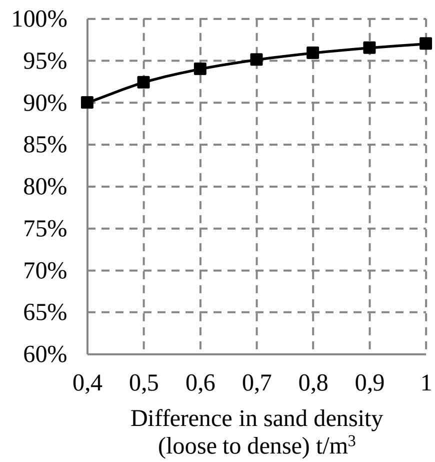

Figure 1. Relative density Dr of different sands compacted to 98 percent relative compaction

Sands compacted in the field using heavy (18 tonne) vibratory rollers can yield relative densities (Dr) over 100 percent, a reflection of the higher dry densities achievable in the field when compared to either modified proctor or vibratory lab method. This may explain why the effect of using relative compaction as a measure of compactness does not necessarily mean that the engineering properties achieved in the field are less than assumed by the designer.

5 FIELD METHOD LIMITATIONS

There is no doubt that the use of relative density (Dr) for construction verification purposes presents some practical limitations. It may be best used during the investigation and specification stage to establish relationships between engineering properties and degree of compactness. The corresponding dry densities derived in these lab trials can be used to establish an equivalent relative compaction to be achieved during construction.

Sands also present difficulties in measuring in-situ dry density in addition to those faced in the laboratory. The two main direct methods used in Australia (the sand replacement and rubber balloon method) both require a hole to be formed in the sand to perform the test. This has been found to be difficult in reclaimed sand sites where the upper layer of the prepared surface can dry out. British experience in these soils is to use a steel core cutter within which sand can be excavated (BS1377-9 2.1.5.3). Density determination using indirect nuclear methods normally require calibration against the direct methods before being employed routinely on projects.

All direct methods of verification require direct sampling of the soil. A further difficulty, unique to hydraulically placed sand, is the need to verify dry densities at depth. The original 1976 compaction trials conducted at Sydney Airport (Rodway, 1996) required large open excavations to be formed within the sand subgrade which could only be progressed after water, used to flood and compact the sands, had drained below the base of excavations

Concerns over sample disturbance and costs often rule out high quality thin walled tube sampling as a routine construction sampling method. Leaving only indirect methods, such as Cone Penetration Testing (CPT), as the only practical means of verifying sand consistency with depth. CPT probing contractors often use the following approximation to relative density:

$$R_c = \sqrt{\frac{Q_{tn}}{350}} \tag{6}$$

Where Q_{tn} the net cone resistance (q_n) corrected for overburden pressure.

A decision to move to indirect methods of estimating relative compaction (Rc) needs to be reviewed against the original intent of construction verification. In some cases, it may be simpler to directly measure the engineering behaviour under loading although this in itself also has practical limitations.

Current methods of directly measuring the modulus of subgrade reaction (ASTM D1196-12) use individual steel plates, up to 762mm in diameter. This may not accurately represent the heavier gear loads and wheel configurations of heavier modern aircraft.

6 FIELD METHOD LIMITATIONS

The compaction of cohesionless soils is routinely employed in construction where placed in controlled layers.

Large areas of low lying coastal land is often reclaimed for airfield construction by hydraulically pumping dredged sand into lagoons. The process creates large lifts of sand compacted hydraulically, largely under their own weight, as water drains through them. Relative densities of between 60% and 75% are often achieved by hydraulic placement alone. Specialist equipment is required to improve these soils further.

The objective of compaction is to improve the relative density of the sand to a nominated minimum which can consistently be relied upon throughout the fill. The term “engineered fill” is often used to describe a material placed in a controlled manner to a verified standard. Major emphasis is usually placed on achieving the specified dry density, and little consideration is given to the engineering properties desired of the compacted fill. Dry density and water content are often measured as convenient construction control parameters.

The behaviour of un-engineered fill can be difficult to predict and variable. Hydraulically placed sand can be subject to segregation of finer material in lenses furthest from the point of discharge. Engineering properties such as strength, stiffness and permeability vary considerably with their state of compactness and material grading. Different sources of sands can yield different upper and lower bound dry densities based on their grading, grain shape and whether they break down under compaction or not.

7 DESIGN REQUIREMENTS

World War Two saw a dramatic increase in the payload and frequency of heavy aircraft using airfields. Airfield design methods accordingly were developed to recognise the differences in loading imposed by different aircraft.

The U.S. Army Corps of Engineers (USACE) initially developed criteria relating to the degree of modified relative compaction required in 1943, which was updated following an analytical study in 1956 (Technical Report No. 3-529). These criteria were extrapolated from the performance of in-service pavements and accelerated traffic tests. This early work recognised that different criteria exist for sands and clay soils. The premise of these earlier studies was that the degree of compaction with depth was directly related to the effective design Californian Bearing Ratio (CBR) at the prepared surface. This assumption forms the basis of the CBR method of pavement design. This method was adopted by the Federal Aviation Authority in 1978 (AC No: C 150/5320-6C), and developed as an international standard in 1983 (ICAO Doc 9157) to protect subgrades against damage that might lead to pavement rutting.

These design methods recognised that pavements can comprise one or more different materials and each layer needs to be designed to resist the applied load without causing failure in it or the underlying layers. Initial methods applied the Boussinesq method of calculating the distribution of deflection with depth, which assumed circular loaded points of contact and a homogeneous elastic layer. Since then aircraft designers have increased the number of wheels on individual gears to keep the individual wheel loads down to a practical maximum, which would allow newer, heavier aircraft to operate on older pavements, without causing damage.

Different gear configurations increase the stress at depth as individual stress bulbs overlap. The imposed stress at the pavement surface is equivalent to the imposed tyre pressure. This effect quickly reduces in the upper 1000 mm of the pavement structure as it mainly uses better quality materials in its upper part. The increased depth of subgrade affected by new gear configurations means that more of the pavement subgrade influences the pavement design than has been considered before. Pavement thicknesses calculated using the CBR method have been calibrated using full-scale trafficking tests.

Current design methods employed on Federal Aviation Authority (FAA) funded projects employ layered elastic design of flexible pavements (Munce, 1983). The method can accommodate Boeing 777 tridem, and Airbus A380 Tandem/tridem gear geometry and individual wheel loads up to 32 tons (A350-900) and tyre pressures up to 1660 kPa (241 psi). The structural pavement design assumes that the subgrade depth is infinite and characterised by a modulus which is either input directly or estimated empirically from an equivalent design CBR. The method uses the maximum vertical strain at the top of the subgrade and the maximum horizontal strain at the bottom of all asphalt layers as the predictors of pavement structural life. This updated method has incorporated revised subgrade fatigue criteria based on full-scale FAA trials, though the method for estimating the compaction requirements below flexible pavement remains based on the original 1959 empirical study. The current version of this method provides a direct output of the subgrade compaction requirements assumed by the loading conditions. An example of the compaction requirements assumed by these methods are provided in Table 1.

Table 1. Sand Compaction Requirements (mm)

Gear	100%	95%	90%	85%
B777	609	1067	1448	1803
A380	635	1118	1626	2057

Note: Relates to modified relative compaction below prepared subgrade level

The method assumes that sand is either placed at the densities shown or compacted from the surface to achieve the required densities to achieve equivalent design CBR value assessed at the 85 percent confidence level.

8 PROVEN METHOD SPECIFICATIONS

The two extensions to Sydney Airport's north-south Runway (16/34) were undertaken between 1966 and 1972 to accommodate the introduction of the Boeing 747 "Jumbo Jet" into commercial service. At this time, the aircraft imposed dual tandem gears with individual wheel loads of 22 tonne imposing tyre pressures of up to 1.28 MPa. Up to 10m of dredged sand was required to be placed hydraulically. To support this work construction trials were undertaken to study the effect of the method of placement and compaction on hydraulically placed sand. The results of these trials were published in 1976 (Rodway, 1976).

Sand was pumped into a series of cells which were allowed to drain through a break in the cell wall. This method achieved very high average densities of 75 percent (94 percent of its vibrated maximum dry density). These trials aimed to ensure the sand was sufficiently densified under simulated aircraft loadings to limit any potential for significant rutting.

A method of compaction was trialled which comprised saturating the dredged sand fill by flooding the area to a depth of 150mm then compacting using a 15 tonne, drawn single steel drum vibratory roller (Pannel Plant 96T).

The method also incorporated a "proof roll" designed to detect any "weak" spots such as silt layers that might have been allowed to form if water was unable to flow from the area during placement. It was termed a "proof roll" as it employed a four-wheel pneumatic tyred "Super-Compactor" drawn and pushed by two D9 dozers. Its configuration imposed up to 45 tonne per wheel under tyre pressures of 1 MPa which was designed to exceed to a depth of 1.5 metres the vertical stress imposed by a Boeing 747 dual tandem gear.

This study concluded that compaction with 20 passes of a 15-tonne vibratory roller achieved a percent relative density of 90 percent up to 1500 mm depth (97 percent of its vibrated maximum dry density). Relative densities approaching 100 percent up to 900 mm below subgrade level were only achieved once 8 passes of the fully laden (180 tonne) Super Compactor was incorporated into the methodology. The upper 300 mm of the sand was subject to large shearing and loosening due to this heavy construction plant. This was only improved to similar relative densities following final trimming by compaction through a "sacrificial" 75mm layer of fine crushed rock. This rock layer was referred to as "working platform" and was considered to form part of the subgrade. More recent practice has seen the omission of working platforms by re-grading, trimming and compacting the sand surface with lighter 11t rollers before paving the initial course of fine crushed rock base.

An alternate method was employed during the construction of Brisbane Airport in the 1980's [11]. This method comprised eight passes of the 15-tonne vibrating roller, eight passes of a 120 tonne Super Compactor (tyre pressures of one MPa) and a further eight passes of the vibratory roller. The last four of these were applied to a 300 mm crushed rock layer over which a further 12 passes with the Super Compactor was undertaken, laden up to 160 tonnes as a means of "proofing" the pavement's capacity to resist the heaviest of the aircraft mix (the B747). The coefficient of subgrade reaction, 'k', was verified by conducting plate bearing tests on the top of the compacted sand fill. The coefficient was found to increase with increasing thickness of compacted sand fill over soft mangrove mud. The 60 kPa/mm used for rigid pavement thickness design was reliably achieved provided that the sand fill thickness was at least 1500mm.

The Super Compactors were initially used to simulate realistic aircraft loadings and provide assurance that densities at depth during pavement construction would be suitable to sustain aircraft pavement loading. The Super Compactors were no longer in use in Australia after comparative testing indicated that similar densities could also be achieved using more efficient and convenient steel heavy vibrating rollers. The use of heavy vibratory rollers alone has been justified based on the successful performance of pavements prepared in this manner over similar sands at Sydney, Brisbane, Adelaide, Cairns and Perth. Larger self-propelled vibrating rollers able to apply single drum loads up to 20 tonnes are now available. These are expected to produce higher densities to greater depths than were previously obtained.

Construction verification now commonly employs a combination of method and end-product specifications. End-product verification of achieved densities is usually only employed in the upper parts of the fill.

9 CONCLUSION

Early empirical studies by USACE in the 1950's related modified relative compaction to the design CBR which are used by FAA design methods and in-turn international standards for assessing airfield pavement subgrade strength. These correlations are still used today for FAA funded projects, though the method now allows for direct input of the modulus of subgrade reaction.

These design methods require a minimum level of compaction to be employed with depth below the pavement. Parametric studies have shown that the actual compactness of sand indicated by relative compaction can be under-estimate the actual compactness by 10 percent. It is difficult to verify that this has been achieved in where hydraulic fill is compacted from the surface only. To address this, trials were undertaken in the 1960's and early 1970's which underlined the importance of the method of dredging and hydraulic placement in establishing high initial in-situ densities.

The heavy pneumatic tyred Super Compactors, previously employed by these early methods, are no longer used. The use of modern self-propelled vibratory rollers and direct verification of density within the upper 600 mm of subgrade is used based on successful past performance of pavements prepared in this manner. Further full-scale compaction trials are only warranted if compaction standards cannot be set based on this prior experience.

Aircraft development may start to challenge the robustness of the early empirical studies which current design methods still reference. The intent of the original USACE 1956 was to derive a compaction profile for a nominated gear configuration. This requires approximation of how stress is transmitted to depth and how soil stiffness is related to compaction.

Direct verification of subgrade performance has practical limitations. Current methods allow for the measurement of the modulus of subgrade reaction using individual plates of up to 762mm diameter which do not replicate the heavier gear loads accurately.

Laboratory trials should be undertaken to derive the relationship between the compactness and soil stiffness for each different source of sand. End-product requirements can be extrapolated from full-scale trials using computer modelling of the relative contribution of individual layer stiffness to the effective stiffness at subgrade level. The relative improvement of sand consistency with depth can now be undertaken using a combination of CPT probing calibrated to density measurements.

The investment required for full-scale trials is likely to be prohibative unless borne by large scale projects or avation industry bodies.

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11 REFERENCES

AC No: C 150/5320-6C, 1978. *Airport Pavement Design and Evaluation*, FAA advisory circular.

AC No: 150/5320-6F, 2016. *Airport Pavement Design and Evaluation*, FAA advisory circular.

AS 1289.5.6.1. 1998. - Compaction control test - Density index method for a cohesionless material. Australian Standards.

AS 1289.5.1.1-2003 - Determination of the dry density/moisture content. Australian Standards.

BS 1377-4. 1990 *Methods of test for soils for civil engineering purposes. Compaction-related tests*. British Standard.

BS 1377-9. 1990 *Methods of test for soils for civil engineering purposes. In-situ tests*. British Standard.

D1196-12 2012. *Nonrepetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements*, ASTM standards.

D4253 -14. 2014. *Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table*. ASTM standards.

D4254 – 16. 2016. *Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density*. ASTM standards.

ICAO Doc 9157, 1983. *The Aerodrome Design Manual, Part 3, Pavements*, International Aerodrome Manual.

Lee, K., Singh, A. 1971 *Relative Density and Relative Compaction* Journal of the Soil Mechanics and Foundation Division, ASCE, 9(SM7), 1049-1052.

MCHW, 2016. Manual of contract documents for highway works. *Volume 1 specification for highway works. Amendment Series 600*.

Munce, B. R. 1983. *Flexible Pavement Design for the Brisbane Airport Redevelopment*, 5th International Asphalt Conference, Australian Asphalt Pavement Association, Perth WA, 13 to 17, 2

Rodway. B. L., 1976 *Compaction of Sand in Thick Lifts*, ARRB Proceedings, Volume 8.

USACE Technical Report No. 3-529. 1956. *Compaction Requirements for Soil Components of Flexible Airfield Pavements*. United States Army Corps of Engineers.

Wright. S. G., Arcement. B., & Benson. C. H. 2003. *Comparison of Maximum Density of Cohesionless Soils Determined Using Vibratory and Impact Compaction Methods*, Proc. Of the 12th Panamerican Conference on Soil Mechanics and Geotechnical Engineering.