

Solving the pothole problem

Investigating the use of geotextiles in reinstated-trench pavements



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Declaration

I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

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Technical Abstract

Current practices in trench reinstatements have been known to cause premature pavement deterioration, yet research into the underlying subsurface mechanisms and their solutions is limited. In newly-built unpaved roads, adding geotextiles in the subgrade-base course interface had been beneficial in supporting the underlying soft subgrades, however application in pavements with reinstated trench had not been investigated. Hence, this paper aims to investigate the effectiveness of incorporating geotextiles in trenched pavements, in reducing the trench-induced deformation in both the surface and subsurface layers.

With the use of the Cambridge Accelerated Pavement Tester (APT), laboratory tests can be conducted on trenched pavement models under repeated traffic loading. The novel use of the surface camera contraption and cross-sectional window in the APT allows measurement of the surface and subsurface deformations respectively. Analysis of soil displacements show that the geotextile reinforcement is effective in reducing displacements below the layer through the tensioned membrane mechanism, while bridging over soil behaviour irregularities caused by the presence of the trench; however, depending on the limiting failure mechanism of the pavements, the benefit in the subsurface may be at the detriment of the surface layers. In well-constructed subgrade-only pavements, the geotextile reduced surface deformations, whilst in the overly-wet pavements, the inclusion of geotextile led to increased surface deformations through sliding failure. In subgrade-base course pavements, the reduced friction from the gravel-soil to gravel-geotextile material interface similarly resulted in the sliding failure of soils above the reinforcement. Thus, the benefits of geotextile can be mobilised when the limiting failure mechanism involves rutting settlement due to the vertical component of traffic loading, but not for soil sliding due to the horizontal component.

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Chapter 1

Introduction

1.1 Background

The United Kingdom had built some of the earliest infrastructure systems in the world, and its 400,000-kilometre [27] paved road network has been vital in delivering economic success and connecting lives. Despite the country's remarkable history, the pressing issue of ageing infrastructure has presented great challenges; after years of underfunding, repairing all England and Wales roads to target conditions will now require over £11 billion and 11 years to complete [4].

Furthermore, population growth has increased the need for transport and utility networks, but the escalating costs of premature maintenance caused by utility cuts – 2 million cuts annually in England and Wales alone [4], are placing serious financial stress on the public, authorities and utility companies. The 2020 ALARM Survey claims that the premature structural failure caused by trench reinstatements had amounted to £250 million of unnecessary expenditure in England and Wales, in the last year alone [4].

The formation of potholes not only strains financial resources, but also poses considerable danger and damage to road users and vehicles. These deformations accumulate water, leading to risk of tyre skidding, and the rough surfaces increase tyre wear. Furthermore, surface potholes are indicative of subsurface structural issues, and the addition of water ingress exacerbates the weakening of the deeper pavement layers [16]. Most of the filled potholes in the UK adopt the “patch and mend” method, which fails to address underlying issues of the pavement failure – this short-term repairs will cause further long-term expenditures. With tight budgets and continuously ageing road infrastructure, the country requires cost-

effective preventative maintenance solutions that attend to both surface and subsurface issues – providing value for money and long-term pavement resilience.

The current UK reinstatement codes and manuals in place are based on empirical knowledge and research on mainly the surface layers; this may result in potential over-design, but in reality, premature failures still occur even when trench reinstatements are constructed in accordance to national guidelines, due to the lack of performance-based and site-specific solutions [30]. Additionally, research on surface deformations hardly gives insight to the required practical standards of trench reinstatements, as up to 30-70% of thinly-sealed pavement surface failures were the consequence of subsurface deformations [47]. Research focussing on the impacts of trenching on pavement deterioration and practical solutions had also been limited; however, researchers agreed that these utility cuts reduce pavement life, up to 30% depending on trench orientation [4],[35].

The need for utility companies to access their apparatus for maintenance and repairs will only increase with demands for improved living standards. Based on the “Potholes Review” by Highways Maintenance Efficiency Programme (HMEP) [25], street works coordination between parties undertaking works will be required to minimise highway openings and road disruption frequencies, and trenching alternatives – trenchless or minimum dig technology, are encouraged and incentivised. However, the millions of existing utility cut reinstatements and additional unavoidable cuts in the future remain in need of solutions to reduce the significant impacts of trench reinstatement-induced premature pavement failures.

1.1.1 Use of Geotextiles in Trench Reinstatements

Geosynthetics had been repeatedly incorporated in pavement engineering projects, especially in heavily trafficked roads, and even more widely used in other civil engineering projects, such as earth reinforced structures, landfills, mining, tunnel and hydraulic engineering. The primary geosynthetic functions, in literature, are many – separation, filtration, lateral drainage, stiffening, and reinforcement [70], in pavement engineering accomplished using predominantly geotextiles or geogrids.

A common issue with trench reinstatements is the discontinuity they cause. The cut and excavation of soils above the buried utility weakens the lateral support to uncut pavement sections [30]; additionally, improper backfill placement and construction procedures, including the use of large equipment in newly-built pavements restricted for use in trench reinstatements due to tight workspaces, lead to weaker pavement structures in comparison

to the un-trenched equivalents, and thus localised failures. Under repeated traffic loading, the weaker trench section may lead to local shear failure, exacerbating the formation of rutting or potholes caused by moisture ingress, poor construction quality or maintenance, and environmental variations [2].

The benefit of geotextiles in pavements had been internationally recognised; however, the current lack of research for geotextile design results in little documented use in widespread pavement engineering practice. Thus, this paper will analyse the effectiveness of geotextiles, in reducing the impacts of trench reinstatements when constructed to bridge over the trench area.

1.1.2 Use of the Cambridge Accelerated Pavement Tester

Past laboratory testing research regarding newly-built pavement, reinstatement design, and even the incorporation of geotextiles, had predominantly focussed on surface analysis; for subsurface analysis, researchers utilised fixed position instrumentation or post trenching methods to analyse deformations in the deeper layers. However, these methods are not comprehensive and are limited in the provided insight.

The Cambridge Accelerated Pavement Tester (APT) was built in 2015 by Bowman and the Schofield Centre team [10]. The equipment allows repeated load testing of scaled pavement models, in a controlled and realistic manner, yet less expensive than full-scale testing. Due to the reduced costs, the APT enables multiple parameters to be tested in various site conditions, which is especially beneficial for fields with limited research.

Particularly novel is the use of a transparent cross-sectional window in the APT pavement model concrete pit, through which subsurface soil images are capturable in real-time. With the additional use of Particle Image Velocimetry (PIV), analysis of the deeper layers can be conducted through the processed displacement or strain fields. Therefore, the research presented in this paper contributes to the study of pavement engineering in the way that trenched pavement structures with and without geotextiles respond to cyclic traffic loads in controlled environmental conditions. The APT equipment will be used for experimental testing, while both surface and subsurface analysis methods will be employed to determine the effect of geotextiles on trenched pavement performance.

1.2 Aims and Objectives

Through laboratory experiments, this project aims to investigate the effectiveness of geotextiles in reducing soil deformations caused by utilities trenching under repeated wheel loading. The specific objectives of this project are:

- To conduct a literature review to assess the current knowledge about trench impacts on pavement performance, and use of geotextiles in pavement structures.
- To conduct laboratory testing using the Cambridge APT in order to understand the impact of poorly-compacted trench reinstatements on the soil deformation mechanism of well-compacted silty-sand subgrade pavements, under repeated wheel loading.
- To assess the performance of incorporating buried geotextile reinforcements in subgrade-only trenched pavements to reduce short-term surface and subsurface deformations.
- To assess the performance of incorporating buried geotextile reinforcements in the interface of subgrade and base course layered trenched pavements to reduce short-term surface and subsurface deformations.

1.3 Research Outline

The report structure is as follows:

- Chapter 1 covers the project background – the importance of the research undertaken, and project aims and objectives.
- Chapter 2 covers the literature review, which is divided into three sections – current knowledge of road pavement design, impacts of utilities trenching, and the use of geotextiles.
- Chapter 3 describes the methodology for both the experimental testing and analysis. The chapter provides an overview of the chosen equipment, test setup, analysis software and conducted test details.
- Chapter 4 presents the processed test results, which are analysed and compared to gain insight as to the effectiveness of the geotextile reinforcement measures.
- Chapter 5 summarises the main findings and conclusion of the research project. Recommendations for future work not covered in this report are also provided.

Chapter 2

Literature Review

This chapter will present an overview of pavement design and deformation, followed by research on utilities trenching and the use of geotextiles in pavement engineering. Literature search on current practices and past research specifically for trenched pavements will be presented in conjunction with un-trenched pavements, to understand the parallel aspects and the added complexities of trench reinstatement over new-build pavements.

2.1 Pavement Design

A pavement refers to an engineered structure that is expected to provide a functional surface for traffic use [39]. Pavement structures have a series of material layers, typically decreasing in strength with depth, that distributes traffic loading stresses and deflections from the surface through to underlying layers, while preventing over-stressing of any layer [39].

Roads in the United Kingdom are predominantly flexible pavements, the structure (Figure 2.1) consists of subgrade, overlain by sub-base and base layers, and topped with "bituminous macadam" layers – asphalt. Flexible pavements allow for slight surface deflections to transmit load downwards over larger areas, to reduce its intensity and cause no significant deformations to the subgrade layer.

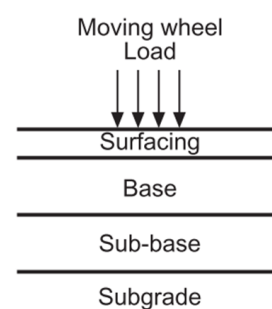


Fig. 2.1 Cross-section of typical flexible pavement structure [12]

Pavement design is vital in insuring against premature pavement failure, defined as a decrease of serviceability that results in fatigue cracking, rutting, and more severely, potholes [2]. Based on literature review, pavement structural capacity ultimately depends on preventing subgrade strength failure. The pavement structural layers need to sustain horizontal, vertical and shear stresses induced by traffic loading and environmental conditions. Otherwise, rutting may occur due to particle crushing, particle damage, near-surface and subgrade shear deformations [16]; the latter two are more predominant, especially in thinly or unsealed pavements.

2.1.1 Pavement Damage Models

Pavement deformations include components of resilient (recoverable) and permanent (irrecoverable) deformations. The resilient component dictates the soil resilient modulus, whereas the permanent component dictates the pavement design to minimise the severity of rutting [12]. Hence, rutting is almost universally defined as the accumulation of permanent strains, and rutting depth calculated by summing permanent deformations in each layer [47].

Modelling rutting behaviour had been researched for decades. The simplified linear-elastic assumptions from more dated research still used in industry have been increasingly proven inadequate in capturing the actual non-linearity of pavement layer behaviours. By comparing numerical and experimental results, Korkiala-Tanttu [34] found that the employed material models significantly affect stress distribution results, suggesting that the Mohr-Coulomb material model is much more effective than linear-elastic, for unbound materials.

Using simple elastic-plastic constitutive law – with Drucker-Prager yield criterion representing Mohr-Coulomb for finite element analysis (FEA), Hambleton and Drescher [22] suggested that wheel sinkage, assumed equivalent to rutting depth for non-driving wheel, could be related to the wheel load based on Terzaghi-Meyerhof formula [41]. This theory is in turn based on Prandtl's bearing capacity theory [45]. From the proposed analytical models, the inclined footing method gave closer predictions to numerical simulations than the inclined force method [22]. Schematic of the rolling wheel and equivalent shallow foundation are illustrated in Figure 2.2. The force Q resulted in tyre embedment, and as it moved forward, the rear resulted in settlement whereas the front is still in the original level, with slight upheaval. The wheel's contact area was equivalent to an inclined rectangular footing, with length h' at angle β .

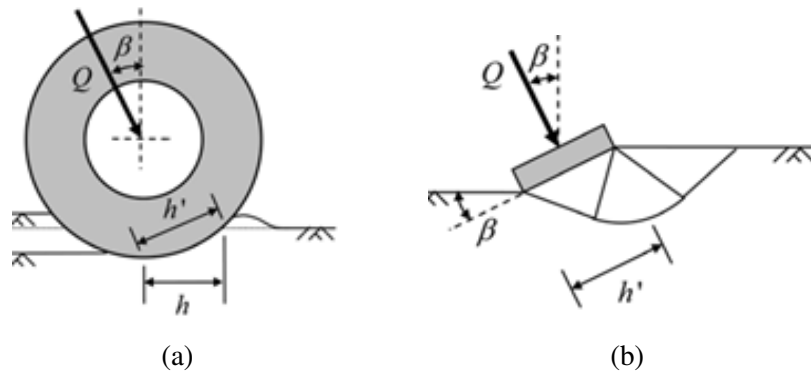


Fig. 2.2 Shallow Foundation Equivalent of Rolling Wheel: (a) Rolling Wheel Schematic (Side View); (b) Analytical Model - Inclined Footing Method [22]

This tyre embedment, due to dynamic loading, induces both vertical and horizontal stresses on the pavement. In the rolling wheel experiments [22], soil material was pushed in front of and to the sides of the wheel, leading to formation of parallel berms along the extending rut. This soil upheaval occurred due to rotation of principal stress direction from active zone under the wheel to passive on either side of the wheel [11]. Additionally, moving wheel loads generate shear stresses within the soil, leading to large, progressive strains [12] in an antisymmetric configuration, resulting in greater deformations at the wheel front than the rear. In literature, there are three modes of foundation shear failure – general, local and punching, classified by Vesic [63] based on soil relative density and foundation relative depth, and by further studies on how well-defined the failure surface, failure load, berm bulging and rut settlement of the modes are. The distinctions between the modes are not precise, and pavement will fail in whichever mode or combination of is weakest. The presence of a weaker trench reinstatement region, as researched in this paper, hypothesises the failure mode as ‘local shear’ – failure surface ends within the soil instead of at the pavement surface, and some upheaval still observable.

In a research by Arnold [8], the Drucker-Prager yield criterion was used to represent the shakedown theory to analyse accumulated permanent strain with loading, and thus rutting behaviour. Shakedown theory suggests that there is a threshold stress ratio above which material no longer stabilise into an equilibrium state, but instead experiences incremental collapse [36]. However, Werkmeister [65] suggested that the shakedown approach could not describe all of the observed experimental responses, and subsequently modified the ranges to A) plastic shakedown, B) plastic creep and C) incremental collapse [66] – pavement stable to risk of rutting if limited to shakedown range A.

A step towards fully mechanistic pavement designs was the 2002 *Mechanistic-Empirical Pavement Design Guide* (MEPDG) under the National Cooperative Highway Research Program (NCHRP) 1-37A initiative [7]. The mechanistic-empirical (M-E) finite element (FE) flexible pavement response model accounted for some site-specific environmental conditions, not as comprehensively considered by previous models [7]. Additionally, the MEPDG was classed as deterministic [18]. Deterministic models had been used extensively in determining pavement failure, but are not accurate enough in predicting uncertain and variable parameters, leading to many proposed probabilistic models – Markov chain methods using Monte Carlo simulations [43] or other less researched techniques [18]. Nonetheless, the difficulty of accurately predicting the dynamic and stochastic nature made attempts non-optimal.

Despite breakthroughs, the mechanistic model employed in MEPDG was only calibrated with linear models – which limitation calls for models that consider non-linear properties. Additionally, pavement reinstatements or inclusion of geotextile layer cannot be analysed with the current model as interface friction is only available in full- or no-friction modes; more comprehensive friction models are being researched [44]. Research specifically for utilities trenching and geotextiles will be presented in the next sections.

2.2 Utilities Trenching

Utilities trenching involves the excavation of existing pavements to install, repair or upgrade sewerage and water pipes, gas pipes, telecommunication cables or other underground services and facilities, and subsequently reinstatement through backfilling of the pavement cut.

2.2.1 Current Trench Reinstatement Guides

Many guides specific to utilities trenching had been published. In the UK, a trench-reinstatement specific guide is provided by the "Practical Guide to Street Works" [23] by HAUC UK under the New Roads and Street Works Act 1991 [24]. Current UK guides, both for trenched and un-trenched pavements, are outdated, essentially empirical, and the significant costs associated to premature failure had warranted more research and consideration of alternative utilities installation and maintenance methods. Specific guides, such as the US DOT FHWA Manual [68] and ASCE C-I 38-02 [59] suggested the use of trenchless technology methods instead of utilities trench cuts, leading to the formation of many associations and committees worldwide.

2.2.2 Past Research on Trenched Pavements

Research efforts over the past two decades had attempted to develop pavement design guides and performance prediction tools based on M-E models for specific site conditions and construction materials and practices, to update the outdated national guides. Based on full-scale accelerated pavement tests, the most-recent NCHRP Synthesis 433 collates the best knowledge available to resolve specific pavement engineering problems [55]; however, the subject of utilities trenching has yet to be considered in such reports.

Specific research on the effects of utility cuts on pavements had been conducted since the 1950s, as collated by Zohrabi and Burtwell [69]. Worldwide research unanimously concluded that patched sections have a lower life expectancy than the unpatched equivalent [4], by 32.4% based on the Pavement Quality Index [35], with compaction control as the major factor to be addressed [53],[40]. Nonetheless, the lack of performance-based research and site-specific existing solutions meant that trenched pavements may experience premature failure even when national guidelines were adhered to [30].

National Research Council Canada and US Army Corps of Engineers, 1999

The inadequacy of the 20th century trench reinstatement-specific analytical models and solutions prompted formation of the 1999 consortium, led by the National Research Council Canada (NRCC) and US Army Corps of Engineers [42]. The 1999 guideline aims to develop effective utility cut restoration guidelines and multi-aspect design and prediction software tool through literature review, questionnaires, field and laboratory experiments, full-scale APTs and analytical modelling.

Published seminar papers discussed the research components for planning and management, issues and considerations of utility cuts [30], and project implementation plan [42]. Based on the project's published papers, the consortium had completed a system for characterising granular materials [31] and had provided material characterisation input to the MEPDG.

Iowa Highway Research Board Project, 2005

Another study by Iowa Highway Research Board (IHRB) identified based on Phase I of Project TR-503 [49] that trench reinstatement causes pavement failure through settlement and upheaval of reinstated regions and weakening of surrounding soils. The investigation deduced

that minimum settlement is achieved with highest backfill relative density, highlighting the importance of moisture and compaction control. Phase II (TR-566) [56] referred to previous research by Al-Suhaibano et al [6], where falling weight deflectometer (FWD) tests were done on 75 random utility cut restorations in Saudi Arabia – monitored at trench centres and edges, and on original uncut pavement. Al-Suhaibano recommended removal of top layer beyond the trench area (later termed zone of influence), increase of utility cut dimensions to allow better compaction, and better material and construction quality management. The IHRB project attempted to address these recommendations, conducting FWD testing at more locations per trench to measure surface deflections and settlement, while determining the surface pavement layer response and the zone of influence – area beyond the trench perimeter affected by the utility cut.

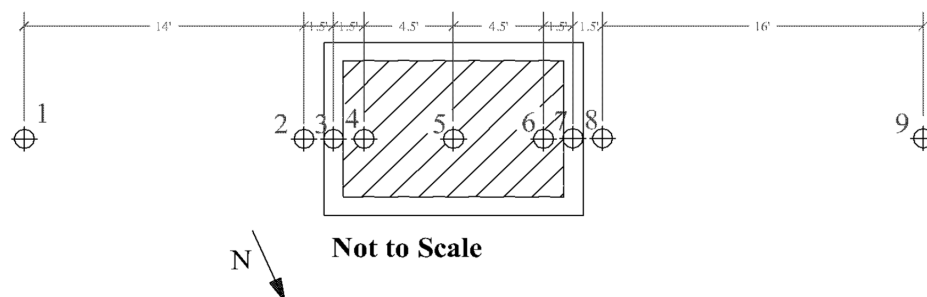


Fig. 2.3 IHRB Project Trench D [56]: FWD test locations (plan view), hatched section represents trench area

The IHRB project team tested multiple backfilled trenches with different construction practices - compaction and moisture control, geometry, and backfill material. Trench D, backfilled in July 2007, had poorly-graded gravel with medium-dense compaction – trench cross-section and FWD test locations are shown in Figure 2.3. The research found, after 4 months, a clear zone of influence at the trench rear (between FWD test *location 1* and *2*), but not at the trench front (between *location 8* and *9*), with traffic direction from *location 1* to *9*. This is contrary to the expected influenced regions, which can be explained by the higher-density trench relative to the surrounding soils, leading to lower trench centre (*location 5*) surface deflection (15.36mils) than the trench inside edge (20.68mils), under 15kips (67kN) loading. Comparing FWD test results with field-test settlement suggested an uplift behaviour, with the stiffer FWD test responses (*location 5* and *9*) correlating to minimum uplift, and the zone of influence to maximum uplift. This resulted in a 63.5mm difference within 4 months, and thus in significant surface damage if pavements were built as such. Further FWD test results until March 2009 showed that the trench centre had minimal added deflection, whereas the zone of influence had continuously increasing deflections.

The existing problems regarding pavement utility cuts had long been identified and verified; governments have responded by introducing policies to reduce pavement cuts or setting empirical parameters in trenching guides. Past trenching-specific research were also mainly conducted for surface performances. Similar to the study of un-trenched pavements, mechanistic models for trench-reinstated pavements warrants subsurface analysis. In particular, analysis of the interaction between the original and reinstated pavement layers, as well as between the inside and outside of trench edges, will provide a more thorough understanding of trench reinstatement issues and potential solution performances. The next section discusses one such method for pavement subsurface analysis.

2.2.3 Cambridge Accelerated Pavement Tester

For the Cambridge APT, Bowman and Haigh [10] used a cross-sectional window at the wheel path's front end to allow observation of subsurface deformations and, for the first time, incorporate digital image correlation (DIC) to measure real-time subsurface deformations. This data is crucial in analysing the effects of surface deformations on the non-linear subsurface pavement layers, to update current design methods. Sim[52] and Tse[60] similarly utilised the Cambridge APT for pavement testing, but instead integrated the window along the wheel path to observe subsurface soil motion along one edge of the tyre, analysing deformations with Particle Image Velocimetry (PIV).

Due to the importance of subsurface analysis for trenched pavement experimental testing, this paper will use Sim's and Tse's setup. To address the research gap, the APT will be used to investigate pavement deterioration mechanism for trenched pavements under cyclic traffic loading, and the effectiveness of geotextiles for trench reinforcement. For a more comprehensive analysis, surface deformations will be analysed through 3-D surface reconstructions, instead of the previously used laser scanner.

2.3 Use of Geotextiles

Significant growth in the use of geosynthetics have occurred since the 1970s [29]. The multifunctionality of geosynthetics has extended its use into many branches of civil engineering and led to international geosynthetic-related publications and associations. In this research paper, the conventional fabric definition of geotextiles will be used, and other geosynthetic products will be referred to by their specific names.

Current use of geotextiles in trenched pavements involve lining the trench edges to improve filtration, but not for reinforcement purposes. Research suggested that geotextiles help to reinforce unpaved roads by preventing outward shear on the subgrade [15], with the ideal location at the subgrade-base layer interface for increased stability [5]; which will be implemented in this paper. In un-trenched unpaved roads, installation of geosynthetic layers was found to reduce permanent deformations by 25-50% [13]. Furthermore, the reinforcing function of geotextiles could be mobilised through the mechanisms of: (a) lateral restraint, with *confinement effect* [19], (b) increased subgrade bearing capacity, through *shear stress reduction effect* [51], transforming local shear failure into general shear, and (c) membrane-type support [21].

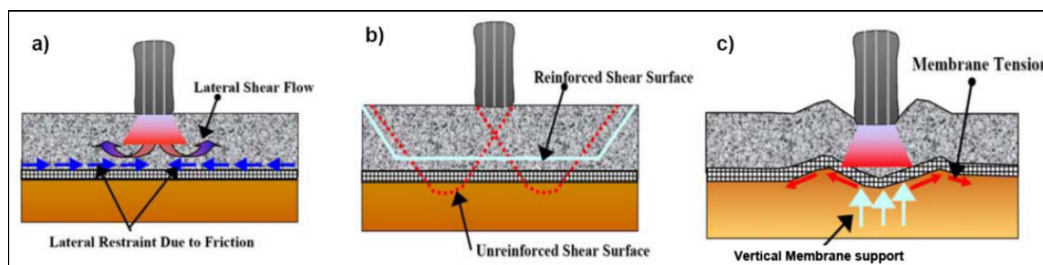


Fig. 2.4 Geotextile reinforcement mobilisation mechanism: (a) lateral restraint; (b) increased bearing capacity; (c) membrane-type support [70]

By utilising its tensile properties, geotextiles could reduce shear forces carried by underlying subgrade, and increase normal stresses acting on potential shear surfaces, which meant the reinforcement was most efficient when inclined in the tensile strain direction (Figure 2.5)[29], but for practical reasons are typically laid horizontally. Additionally, subgrade bearing capacity improvement occurs after the reinforcement experienced sufficient deformation to act like ‘membrane in tension’. The mechanism operates best in rutted unpaved roads[21], or for sinkhole or cavity collapse prevention[19] (Figure 2.6), where localised loading would, if unreinforced, lead to severe deformations [29]. This *membrane effect* is hypothesised to have the most relevance to this research’s trenched pavements.

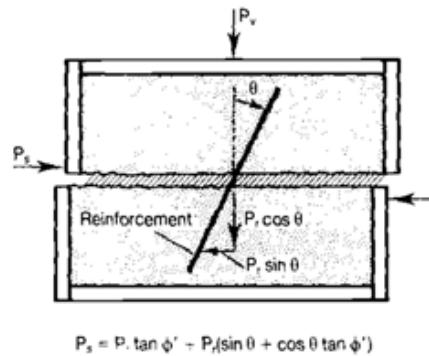


Fig. 2.5 Resultant reinforcement forces in direct shear [29]

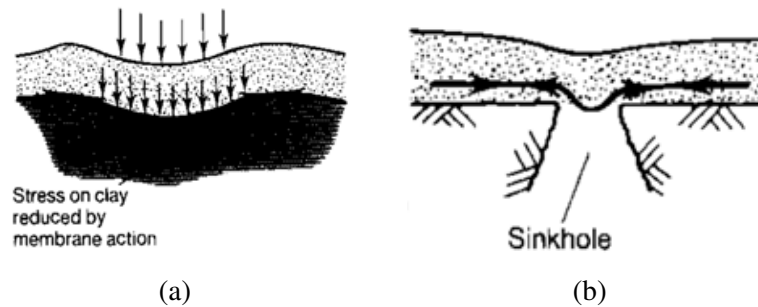


Fig. 2.6 Application of Reinforcement Membrane Action: (a) Rutted Unpaved Roads, (b) Over a Sinkhole [29]

In addition to geotextile properties, the soil-geotextile interaction might be significant in determining the effectiveness of utilised geotextiles. Two limiting interaction modes include direct sliding and pullout [29]. Numerous tests – shear box tests and pullout (anchorage) tests respectively, had been conducted; for geotextiles specifically, research suggested that coefficients obtained from both tests agree closely. Due to the complexity and unreliability of pullout tests, soil-geotextile interaction data are typically obtained from direct shear test results (α_{ds}), whereas geogrids would require both tests due to the different interaction modes under pullout and direct shear [29]. Direct shear tests conducted by Liu et al [38] suggested that ratio of soil-geotextile interface to internal soil shear strength is 0.75 for Ottawa sand ($\phi = 18^\circ$) and 0.9 for gravel; whereas for geogrid, the ratio range is 0.9-1.05. Another study by Abdi [1] for soil-geotextile interface suggested a ratio of 0.89 and 0.88 for soils with original friction angles of 33.8° and 44.8° respectively.

2.3.1 Design Methods: Unpaved Roads with Geotextiles

Literature on the design methods for unpaved roads with geotextile inclusion is limited, even more so for the specific purpose of bridging over weaker trench (or sinkhole) regions. Design charts had been developed by manufacturers for their specific products, and existing design methods include modifications to allow capture of all the required parameters.

Some design methods for pavements with geotextiles include: Reinforcement Function Design Method (RFDM), Separation Function Design Method (SFDM), Modified CBR Design Method, Houlsby and Modified Houlsby Approach (MHA), and the Giroud-Han Design Method. These methods differ in their assumptions, but generally accepted is the use of modulus and multipliers, and calibration with experimental data.

RFDM by Giroud and Noiray (1981)[21] assumed granular friction coefficient was large enough to maintain mechanical stability and subgrade soil deflection small enough to minimally affect granular thickness design. The model proved to be unconservative by not considering compaction under traffic loading or possibility of surface soil sliding. *SFDM* by Steward et al.(1977)[54] included bearing capacity factor for base layer thickness design, as in shallow foundations, adjusted for geotextiles inclusion. This method was generally conservative, as the reinforcing effect was not considered. Moreover, the *Modified CBR Design Method (WES TR 3-692)*[33] used a reinforcement ratio multiplier to find the equivalent in-situ soil subgrade California bearing ratio (CBR) value, for with geotextile.

For reinforced unpaved roads design, Houlsby et al (1989)[26] assumed the wheel as strip load, with simple load spread angle concept. By assuming a load distribution factor, the vertical stress at base-subgrade interface were computed, with plane strain conditions assumed. Horizontal stresses held in equilibrium by shear stresses at the gravel base placed the geotextile in tension, and so only vertical loading is transferred to the subgrade below, allowing mobilisation of its full bearing capacity. The *MHA* by Bhosale and Phatak (2000)[9] instead estimated base course vertical stresses by using Boussinesq's equation for strip loading, also assuming plane strain conditions.

Calibrating with field and laboratory testing data, Giroud and Han (2004)[20] derived a unique design method for base course and subgrade pavement with geosynthetics inclusion under repeated tyre loading. Originally for geogrids, the design method could be adapted for geotextiles by neglecting aggregate interlock and material in-plane stiffness, and in roads with traffic loading by subtle judgment. The principle relied on serviceability failure criterion

– allowable rut depth of 75mm for unpaved roads, which depended on subgrade deformation and thus applied stresses on subgrade surface.

Research closest in spirit to this project were sinkhole tests by Kinney and Connor (1987)[32] and Villard et al (2000)[64]. Both involved theoretical research, backed by full-scale experiments on geosynthetic-reinforced unpaved roads over a total void, under vehicle loading. The design method by Kinney and Connor suggested that available geosynthetics can span up to 3m of void width under reasonable loading (test section shown in Figure 2.7a)[32]. Whereas, that by Villard et al was based on formation of stable arch effect, in addition to the more widely researched membrane effect, with permissible surface settlement of 0.05m (road experiment schematic shown in Figure 2.7b)[64]. While these application are of considerable interest for the gradual collapse due to underground cavities, the design methods are not directly applicable for trench-reinstated pavements.

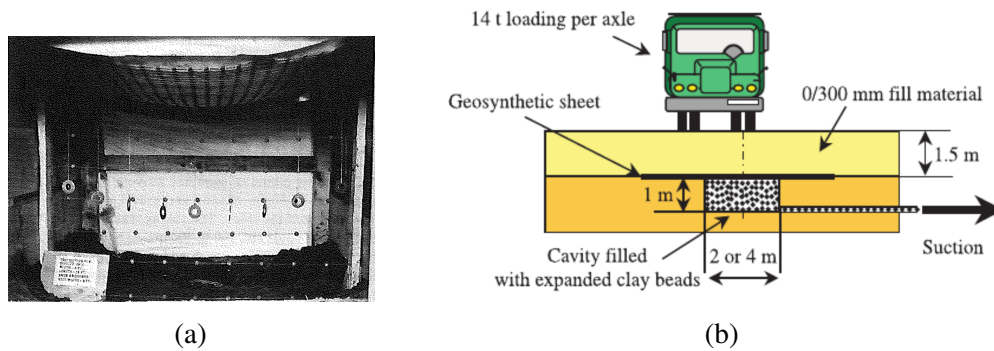


Fig. 2.7 Past Research on Sinkhole Tests: (a) Geosynthetic-reinforced test section in Kinney and Connor (1987) [32]; (b) Schematic of road experiment (SCET1 to SCET3) in Villard et al (2000) [64]

As presented in this chapter, there was substantial research on newly-built pavements, and some on the effects of trench reinstatements as well as the inclusion of geotextiles in many civil engineering structures; however, publications about the design or construction methods for trench-reinstated pavements, with the inclusion of reinforcement, had been limited. Geotextiles had been found to be good at providing tensioned membrane support over pavement sections with otherwise significant deformations, such as rutted unpaved roads and over sinkholes. Hence, to address the research gap and reduce premature pavement failure due to trench reinstatement, as in the project aim, the inclusion of geotextiles will be analysed the effectiveness of.

Chapter 3

Methodology: Experiment and Analysis

3.1 Experimental Equipment

3.1.1 Accelerated Pavement Tester (APT)

This research utilised the Accelerated Pavement Tester (Figure 3.1) in the Schofield Centre, by Bowman [10]. The equipment allowed physical modelling of trenched pavements subjected to repeated traffic loading. Cyclic load was applied on the pavement through a single tyre attached to the APT beam. Computer softwares - WMEMOC and Data Acquisition System Laboratory (DasyLAB), controlled instrumentations to allow change of test parameters and real-time monitoring of pavement response.

Test parameters included tyre loading, speed, start and end positions. Loading was controlled by a pneumatic actuator, which cylinder controlled the vertical movement of one end of the APT beam - lifting to remove load and lowering to impose load through the attached tyre. After specifying parameters, instrumentations networked into the APT, including strain gauges and actuator, used feedback loops to ensure parameters were kept constant for the entire test. To mimic one-quarter of a vehicle load, 4.5kN was imposed by the tyre on the pavement, which tyre was assumed to be rigid. The loading process began with the tyre system locating *position 0* through the use of sensors and linear drive actuator, followed by the tyre applying a defined load until it reached *position 2*. Guide rails ensured the tyre path was in-plane through the cycle. Subsequently, the tyre was lifted off the pavement in *position 2*, before returning to *position 0*. The process was repeated until a user-defined number of cycles or maximum pneumatic actuator stroke was reached [10].

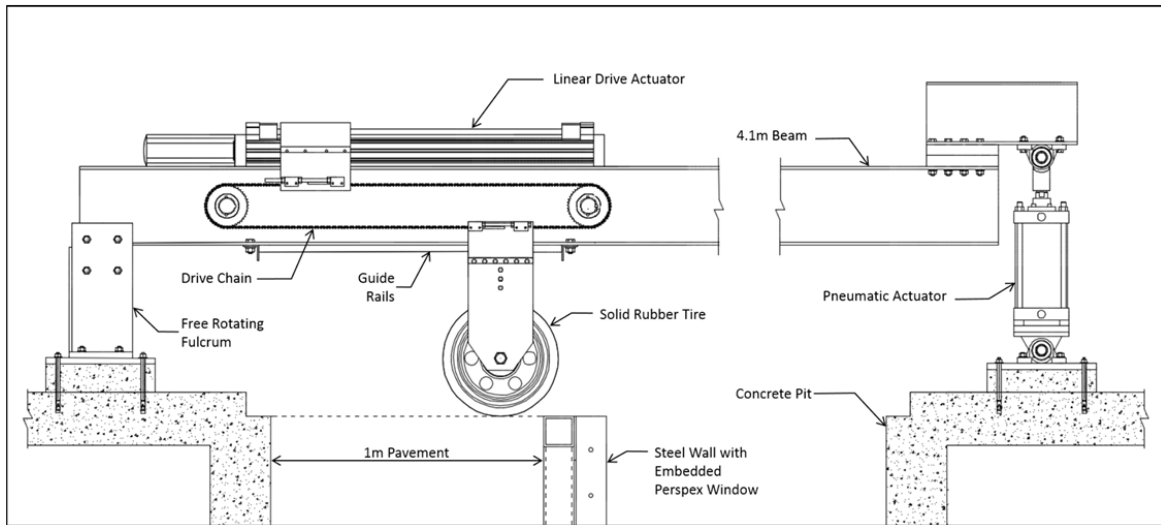


Fig. 3.1 Schematic of APT (elevation view) [10]

3.1.2 Installation of Cameras

Elevation Cameras

The six elevation Raspberry Pi cameras had been set-up by Sim [52] and Tse [60], to capture subsurface soil movement from the elevation view through a Perspex window. Due to the objective of capturing occurrences caused by the backfilled trench and added reinforcements, the metal plate was adjusted from the original position (moved vertically up by 70mm) to better capture the near-surface soil and the interface between the poorly-compacted trench and well-compacted soil.

The cameras were networked into computer software Putty, where image capture was triggered and capture rate was defined. A maximum number of images per test was also set to avoid computer storage overload.

Surface Cameras

In addition to previous research, six cameras were set-up to capture surface images to create 3-D surface reconstructions. The final camera positioning was chosen to optimise considerations for the capturable area of interest and software quality constraints. The area of interest included the trench and surrounding soil captured from a height, whilst the angle between cameras had to be minimal to produce acceptable reconstructions. Figure 3.2 depicts the final surface cameras positioning; to place the cameras at height, four Raspberry Pi

cameras were screwed onto metal plates on wooden blocks and the remaining two cameras under the APT beam to capture from plan view. A total of ten reference markers were placed on the protruding wooden plank screwed on the concrete floor and on the Perspex window.

The cameras were connected to the computer network; through DasyLAB, 2 images per camera were automatically captured with each tyre cycle - when tyre was in *Position 0* and 2.



(a) Camera set-up



(b) Cameras under APT beam

Fig. 3.2 Image of Surface Cameras (individual cameras highlighted by red circles)

3.2 Experimental Methods

3.2.1 Construction of Pavement Models

From elevation view, the soil models to physically construct are shown in Figure 3.3. Soil model (a) shows a simple trenched pavement, (b) overlain by a stiff subgrade layer or gravel base layer, and (c) with buried geotextile layer to bridge the trench surface and corners nailed.

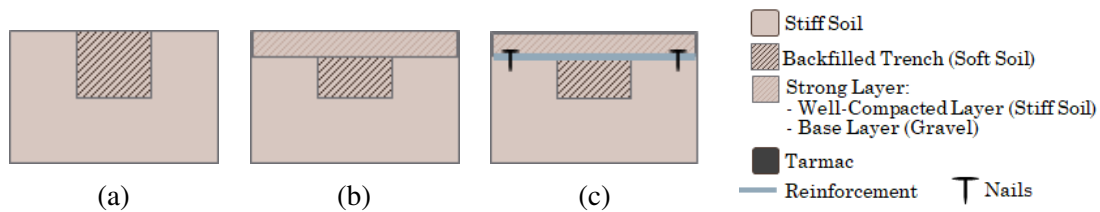


Fig. 3.3 Schematic of Pavement Models for Experimental Testing:

(a) Simple trenched pavement, (b) Trenched pavement overlain with strong layer (well-compacted silty sand or gravel), (c) Trenched pavement overlain with geotextile and strong layer

The pavement was constructed in a $1000 \times 800 \times 860\text{mm}$ concrete pit (Figure 3.4). The bottom 500mm of soil was permanent throughout this project research, whilst the top 500mm of soil was fully dug and backfilled between test sets.

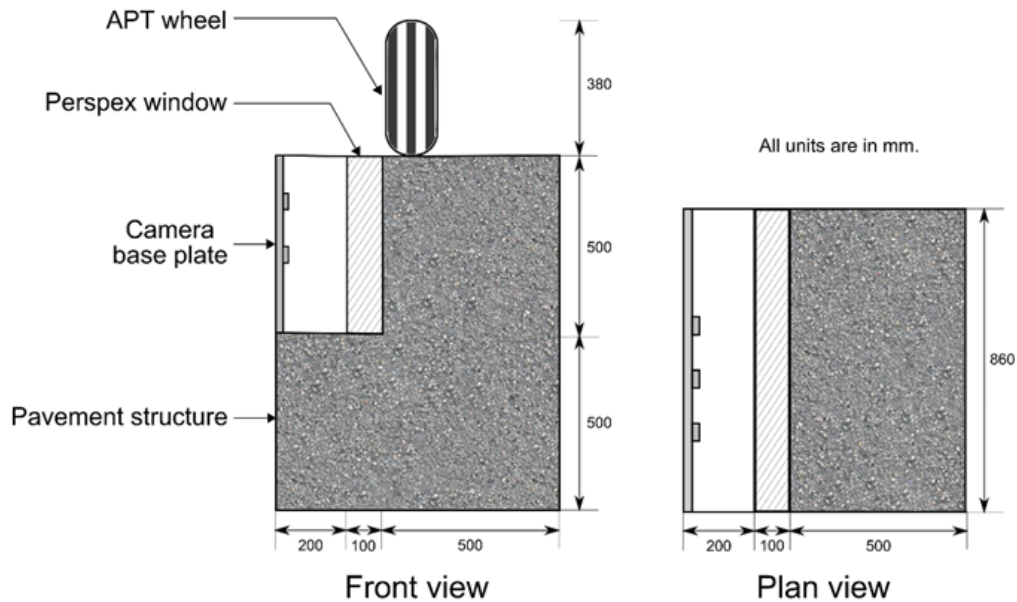


Fig. 3.4 Schematic of Soil Model Layout [60]

1. At least 24 hours prior to soil model construction, water content tests - place soil samples in oven at 100°C for at least 24 hours, were conducted for the silty sand. Optimum water content for the Kazakhstan silty sand used was 9.8% [60], and to achieve this target, water was added or soil was dried on a heating tray accordingly.
2. With the help of technicians and use of forklift, the APT beam was dislodged and moved away from the concrete pit to allow a clear workspace for pavement preparation.
3. The soil was shovelled into the concrete pit by hand in 150mm uncompacted layers and compacted with an electric plate compactor with at least the recommended 3 passes per layer [17]. The soil filled the pit up to the top surface of the Perspex window (Figure 3.5a) and was levelled with use of a spirit level.
4. To model real-scale small utility trenches, a trench of surface width 240mm and depth 280mm was dug out, and backfilled with loosely compacted layers. With about 100mm uncompacted layers, silty sand was shovelled into the trench and compacted with 100 hammer hits to a wooden block across the trench area.

5. For model variations with stiff soil, base or reinforcement layers, the silty sand was only filled to the defined height and the variation layers constructed accordingly. For stiff soil, the compaction method in *Step 3* was followed. For base layer, gravel was compacted sub-optimally as the material cannot be compacted well with an electric plate compactor. For reinforcement layer, a single sheet of geotextile was nailed down in the corners to prevent horizontal slip, as shown in Figure 3.5d.



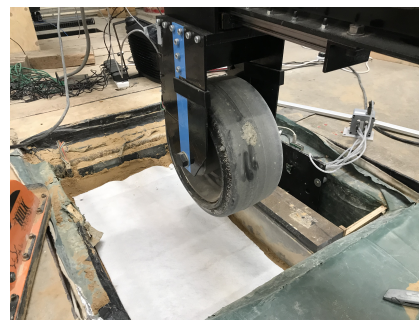
(a) Simple trenched pavement (without APT)



(b) Trench (with APT tyre)



(c) Gravel layer (with APT tyre)



(d) Geotextile Layer (with APT)

Fig. 3.5 Image of Pavement Models

3.2.2 Testing Procedures

1. To conduct testing, the APT beam was lifted to place above the concrete pit and connected to the correct instrumentations. The surface cameras were placed as in Figure 3.2 and cables connected to the computer network. LED lights were turned on to illuminate the Perspex window and pavement surface for better image capture.
2. Pressure valve for the pneumatic actuator was turned on. One test cycle was done to ensure elevation and surface cameras, and the APT instrumentations, were functional.
3. Full experimental tests could begin once checks had been completed. The APT was stopped by turning off the actuators and image capture.

3.3 Experimental Issues

Multiple experimental issues led to changes in experimental set-up. Where appropriate, recommendations for future research were proposed.

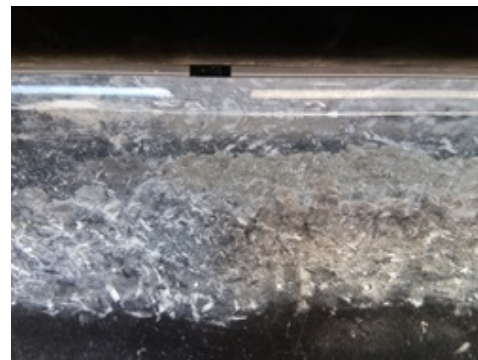
- Perspex Window

The main 100mm Perspex window was initially scratched by the hand shovel, thus was polished and 2 additional layers of 5mm Perspex were installed to be easily removeable for polishing or replacing between test sets. However, refraction and reflection within multiple Perspex layers caused the captured elevation images to be too dark for PIV analysis (Trench 2 Tests), and water and soil had seeped in between the perspex. For future research, protective glass films could be used instead of the additional Perspex.

Subsequent tests were done with only the main Perspex. Due to the angular shape of the gravel, its contact against the Perspex window resulted in scratches. As in Figure 3.6, minimal scratches are visible in test T4T1 but the gravel can still be relatively clearly discerned; the gravel scratched the window during the test, and scratches became more numerous in the test T4T2 elevation images. Thus, questionable PIV tracking could be observed in some areas of the displacement fields for Trench 4 and 5 tests. For future research, scratch-resistant anti-fogging coatings [37] could be considered to solve the during-test scratching problem. Alternatively, a removeable barrier could be placed during base course compaction, and removed prior to conducting the experimental test.



(a) T4T1



(b) T4T2

Fig. 3.6 Camera 'Bronn' Elevation Images of Trench 4 Tests

- Water content

The silty sand water content was crucial for pavement compaction. Above-optimal water contents led to lower soil strength – forming deformations more rapidly and severely, whilst below-optimal water contents might lead to brittle soil – cracking. For future research, the water content should be closely monitored and a mixer would be recommended to achieve consistent water contents across the soil pavement. Tilting the mixer to empty the soil into the concrete pit would also reduce the labour involved with hand shovelling.

- Compaction

The compaction issue might potentially be a combination of or either of three reasons: (i) lack of compaction force, (ii) lack of Proctor compaction due to the non-optimal subgrade water content, (iii) short period between pavement construction and testing. The first will be discussed below; the second might be solved by controlling the water content rigorously – taking measures to ensure water content is close to optimal and using a mixer to ensure uniformity in the subgrade water content. It should also be noted that the water content may be controlled during the pavement construction stage, but not when subjected to local environmental conditions. The third would require more research time, and determination of the optimal waiting time.

The issue of non-optimal soil compaction provided by the electric compactor might have distorted the obtained experimental results, as observed by the unexpectedly immediate surface deformations when testing begun; whilst this highlights the importance of compaction in a laboratory setting, this observation may not apply to real roads. For compaction of real pavements, petrol-powered static or vibrating rollers are usually utilised to compact asphalt, gravel and even well-graded sand. In view of this however, the fumes released from large petrol-powered equipment are not suitable to use in a ventilated lab and its size may also be ineffective in compacting the small experimental model area. To minimise compaction issues in future experiments, a steel roller could be installed across the width of the concrete pit (500mm) onto the APT wheel attachment in place of the tyre. This roller could utilise the APT pneumatic actuator and lever arm mechanism, which could apply loads between 2.5-38.0kN, providing a much greater compaction force than that of the currently used 26kg-electric compactor.

3.4 Analysis Methods

3.4.1 Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV) allows measure of velocity by tracking test patches through a series of digital images. Adapted from PIV used in fluid mechanics testing [3], GeoPIV is a Matlab module written for use in geotechnical testing. The code tracks spatial variation in brightness of each soil mesh patch in one image, then repeated for all images in a series. Complete trajectories of each mesh patch are produced in ASCII format, to be further processed for displacement vector data [67].

Through extensive experimental test and GeoPIV result comparisons, White and Take [67] determined that software precision was a strong function of patch size and a weak function of image content. Thus, accuracy of any resulting outputs is highly dependent on user-inputted image quality and understanding of the PIV technique constraints.

The codes [58] used for the elevation camera image analysis required two input ASCII files – mesh and launcher. Due to the large displacements between the images captured, Mode 3 was used instead of Mode 1 (point-by-point) and Mode 2 (leapfrog) - appropriate for small displacement analysis. The output file contained horizontal and vertical coordinates, which were subsequently used for creating displacement vector or contour plots.

3.4.2 Agisoft Metashape

Agisoft Metashape is a computer vision software which allowed for cloud reconstruction of images to produce an optimised 3-D visualisation of the captured images. The cloud reconstruction consists of sparse and dense clouds through integrating structure-from-motion (SfM)[62] and multiview-stereo (MVS)[50] algorithms. Result precision was determined from extensive comparisons of laser scanning and traditional photogrammetry to SfM results; James and Robson [28] found that comparable data was captured by the SfM method, with a reduced time of about 80%.

With respect to defined reference marker points, the Agisoft Metashape software was used to combine captured surface camera images to construct a 3-D model of the pavement surface for a certain tyre pass. The area of interest was captured from different positions with consideration for texture and image factors. As reconstruction depends on matching textures between static images, for better reconstruction quality, LED lights illuminated the pavement

surface to reduce tyre shadows and create optimal lighting conditions. Additionally, camera zoom or angle variations were limited to reduce surfaces to appear different between images, which might otherwise reduce SfM-MVS reconstruction capabilities.

The cloud reconstruction began with aligning and calibrating images to the camera pixel size and focal length, taking distortion parameters into account. Sparse clouds were initially constructed through SfM by calculating camera parameters and orientations, representing the most prominent image features [28]. The sparse clouds were then filtered by reducing reconstruction noise and optimising camera. After this adjustment, dense clouds were formed through MVS, which involved higher-level triangulation. The dense clouds increased reconstruction points by two or three order of magnitudes to create high quality surface reconstructions. Additionally, reference measurements were inputted to scale the cloud models spatially. In this project, the software outputs were used to visualise the lab test initial and final states, and to identify changes in soil material deformations.

3.4.3 CloudCompare

CloudCompare[14] is an advanced point cloud processing software, developed in C++. For this research project, the ASCII point cloud files created by Agisoft Metashape software for both initial and final images of a certain test were exported to CloudCompare. Equivalent point pairs were picked to align the ten reference markers in the final image point cloud to the initial image point cloud. Subsequently, test soil deformations were computed by cloud-to-cloud (C2C) absolute distance computations. The software used the 'nearest neighbour distance' method, where each point in the compared cloud (test final image reconstruction) was searched against the nearest point in the reference cloud (test initial image reconstruction), and their Euclidean distances computed [14]. Due to the compared cloud searching the reference for each cloud point, the reference cloud had to overlap the compared cloud to avoid boundary errors, while maximum density cloud should be used for more accurate results. The distance calculated produced a single heat map between the two test frames, giving insight into soil distances travelled between the test initial and final states.

3.5 Experimental Test Overview

For this research project, a total of 14 tests were conducted. Divided into columns of project objectives: analysis of influence of trench on pavement deformations and effectiveness of added reinforcement, Figure 3.7 summarises the soil models used for each test. The test labelling is Trench # - where the entire 500mm of soil is shovelled out, backfilled to compaction standards, and trench constructed, and Test # - after which only the top soil layer is shovelled out to replace with the required layer for the next test. Furthermore, Figures 3.8 and 3.9 depict each test in more detail, presenting the soil model profiles and test details for the tests analysed in the next section.

3.6 Methodology Overview

Overall, the research methodology involved experimental set-up, experimental testing, result processing and analysis. Pavement models of backfilled trench and added reinforcement were initially constructed and pre-testing checks were conducted. Subsequently, testing utilised the APT equipment and Raspberry-Pi cameras, and captured images were further processed with multiple software. The 3-D surface reconstruction, soil displacement heat map and subsurface soil PIV analysis results were further analysed to achieve the project objectives.

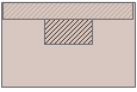
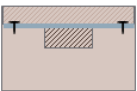
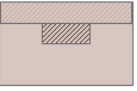
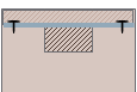
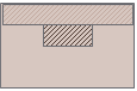
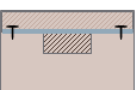
Issue: Pothole Formation		Solution: Reinforcement Type	
TRENCH #1 Simple trench	Test #0 Preliminary test Test #1 Test on simple backfilled trench pavement structure		
TRENCH #2 Simple trench and added reinforcements	Test #1 Test on simple trench (slow cycle) Test #2 Test on simple trench (normal cycle)	Test #3 Test on base layer (gravel) on backfilled trench structure Test #4 Test on geotextile layer and well-compacted top layer on backfilled trench structure	 
TRENCH #3 Simple trench and added reinforcements	Test #1 Test on simple backfilled trench structure	Test #2 Test on base layer (gravel) in addition to backfilled trench structure Test #3 Test on gravel underlain by geotextile layer on backfilled trench structure	 
TRENCH #4 Reinforcement layers		Test #1 Test on base layer (gravel) underlain by backfilled trench structure Test #2 Test on gravel underlain by geotextile layer on backfilled trench structure	 
TRENCH #5 Cycle Speeds	Test #1 Test on simple trench (slow cycle) Test #2 Test on simple trench (normal cycle)		
TRENCH #6 Tarmac layer		Test #1 Test on cold tarmac on backfilled trench structure	

Fig. 3.7 Schematic of Test Overview

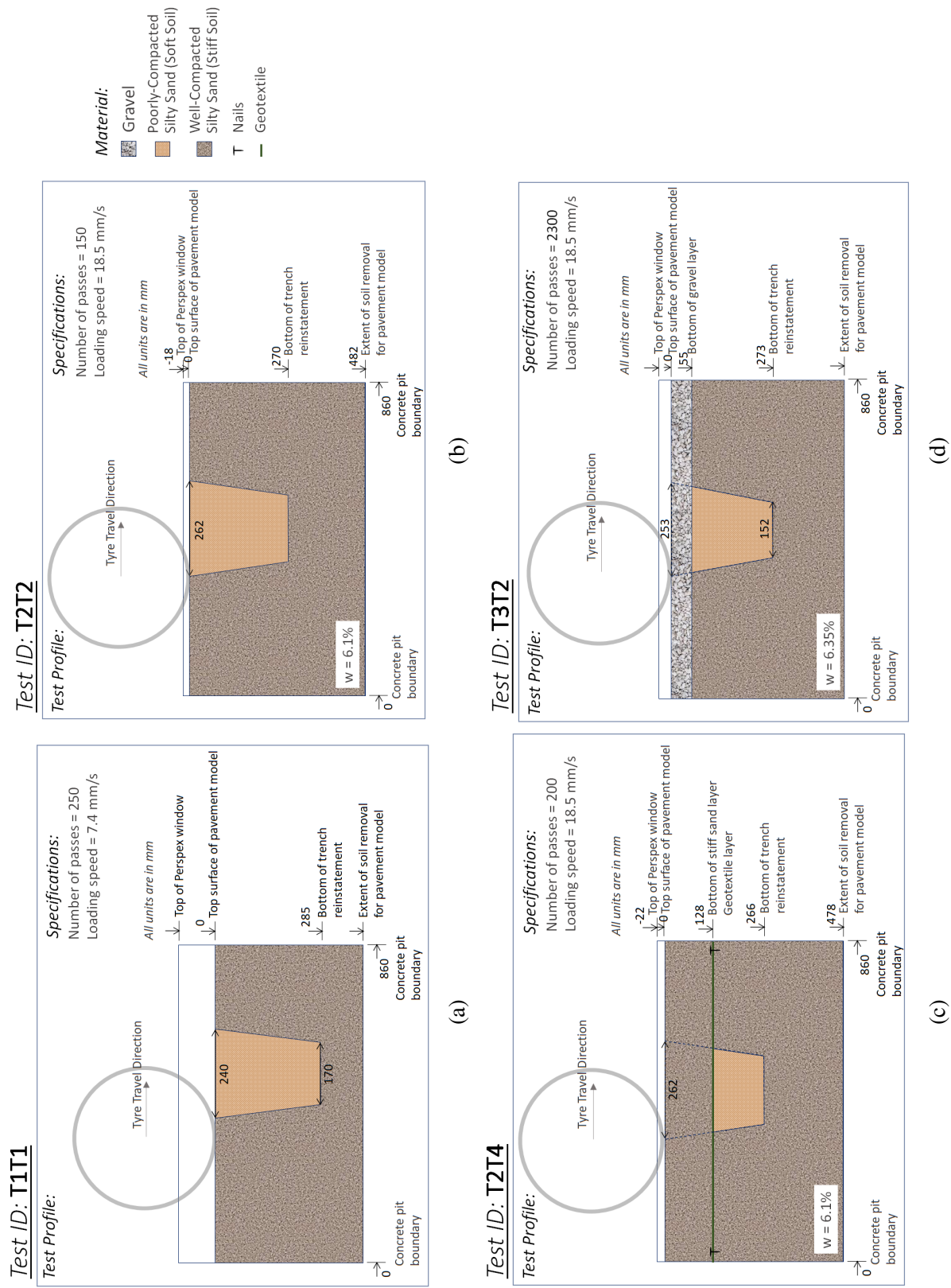


Fig. 3.8 T1T1-T3T2 Test Detail

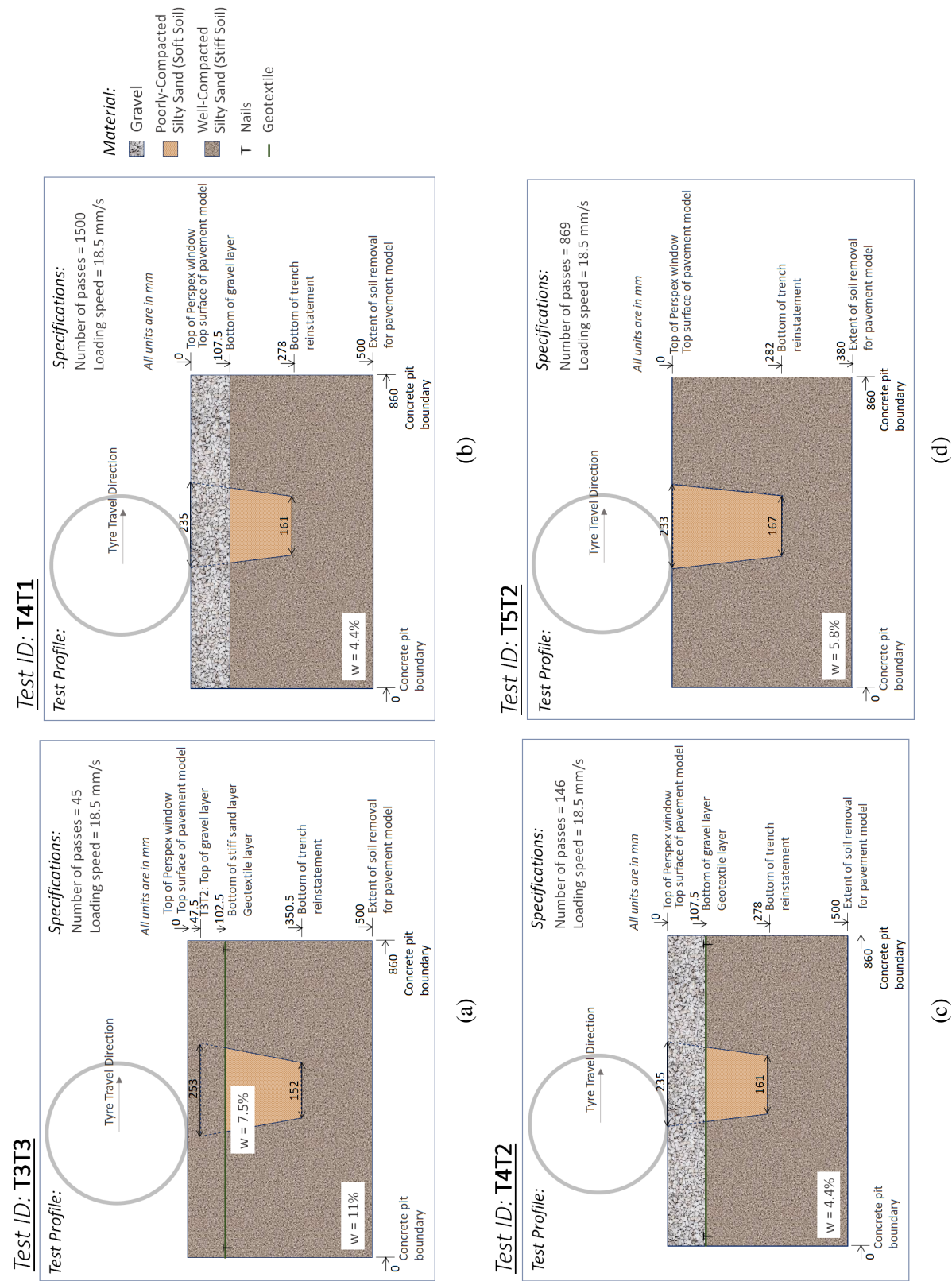


Fig. 3.9 T3T3-T5T2 Test Detail

Chapter 4

Results and Analysis

14 tests were performed in total, however only 8 relevant tests were analysed. This chapter is sectioned into the two types of pavement structure: trenched subgrade-only and trenched subgrade-base course pavements in sections 4.1 and 4.2 respectively. Each section presents the surface and subsurface results, followed by analysis of pavements without and with geotextiles – to ultimately deduce the effectiveness of geotextiles in trenched pavements. Surface reconstructions were available for Trench 1, 2, 3 and 4 tests, whereas PIV analysis were only applicable to Trench 3, 4 and 5 tests. The tyre direction for the PIV plots is from left to right (in the direction of decreasing X-value). The test ID T#T# represents Trench#Test#. Between each new ‘Trench’ the top 500mm of soil was excavated, backfilled and trench reinstated, whereas each new ‘Test’ on the same ‘Trench’ only involved the necessary surface layer reconstruction, required for the next test.

4.1 Subgrade Trenched Pavement Response

Tests T1T1, T2T2 and T5T2 had subgrade-only trenched pavement structure, whereas T2T4 and T3T3 included a geotextile layer to assess its performance as a mitigation technique. Test details – including number of passes, loading speed and soil material water content, and test profiles – layer structures and trench dimensions, are shown in Chapter 3.

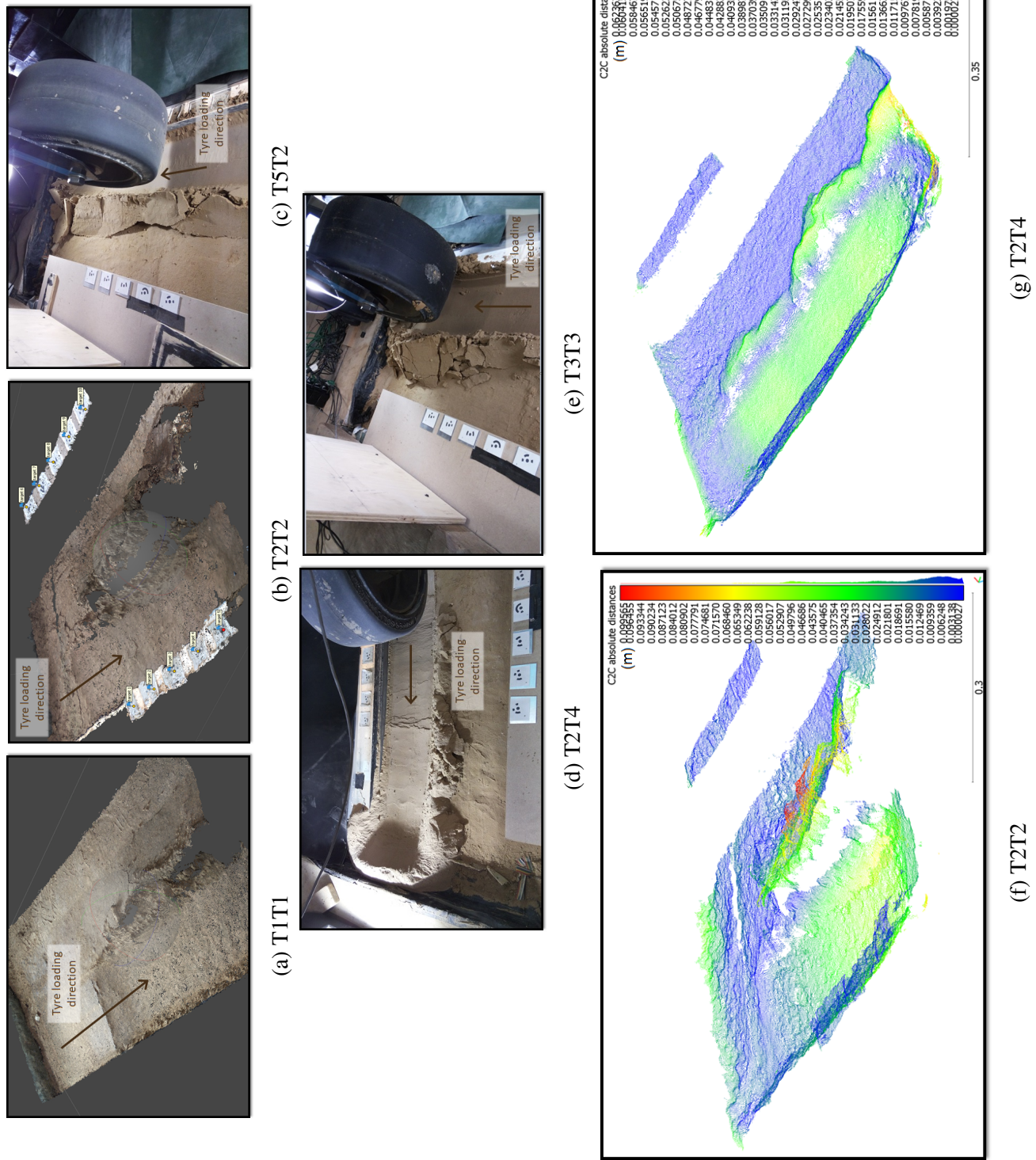


Fig. 4.1 Subgrade-only Pavement Surface Processed Results: Agisoft Surface Reconstruction - without geotextile (a)T1T1, (b)T2T2, (c)T5T2, with geotextile (d)T2T4, (e)T3T3; CloudCompare C2C Absolute Distance Heat Map - (f)T2T2, with geotextile (g)T2T4

4.1.1 Surface Reconstruction Analysis

The 3-D surface reconstructions for subgrade-only pavement tests are shown in Figure 4.1. It can be observed that the pavement surface deformations had components of both vertical and horizontal soil motion.

Along the tyre path, rutting occurred in all the tests, resulting in a distinct vertical settlement where the tyre load was applied. The rut began to worsen at the trench edge, most obvious in test T1T1 (Figure 4.1a), where a large differential settlement over the rear trench edge could be discerned. The rut then extended to beyond the trench area, in the direction of wheel travel, through to the concrete pit boundary. Moreover, the repeated loading helped distribute displaced soils from previous passes along the path, and re-compact soils in-path, to form a relatively uniform rutting surface.

Laterally, the tyre movement displaced soils towards the tyre's outside edge and along the tyre path, leading to soil accumulation. Upheaval of soil led to side berms forming along the extending rut; Bowman[11] suggested soil upheaval was due to principal stress rotation from the active to passive zone. However, due to the window positioning, the side berm could only be formed towards the free field on one side, instead of both sides, of the tyre edge. Additionally, soil accumulation at the front end, towards the concrete pit boundary, could be attributed to the tyre 'sinking' into the pavement surface due to the lack of soil strength [60],[22]. Thus, to traverse, the tyre had to laterally push the soil, likened to a *shoving action*.

Deformations due to tyre loading presented similar occurrences to foundation shear failure, where the tyre 'punches' into the pavement to push the soil from that contact area away. Based on the types presented in literature, the observed surface failure most resembles local shear failure [63] – some bulging around the footing, in this case tyre, and intensified by the presence of the weak trench within a better-compacted subgrade pavement.

Influence of test model construction

The test model construction might influence the pavement deformation behaviours. Test T1T1 behaved in a brittle manner, different to other tests of similar structure or testing characteristics. The "well-compacted" subgrade layer of the prepared T1T1 model was observably drier and harder than in subsequent tests, resulting in the expected brittle cracking and trench potholing. In contrast, test T2T2 experienced a more ductile failure, where the soil appears to be yielding. Considering test T2T2's subgrade water content (6.1%) was below optimal (9.8%), based on Proctor compaction theory, a brittle mechanism would have

been expected. Additionally, compaction for all test models were conducted with the same equipment – an electric vibrating compactor. Thus, an explanation for this occurrence would be the time left between construction and testing. Soil strength gain through consolidation is correlated with time, to allow the dissipation of excess pore pressure under ‘long-term’ static loading (soil self-weight). The constructed test T1T1 model was left untouched for 6 months, whereas experimental work for this research project could only be conducted over 6 months; the time limitation meant other test models had much less waiting time. Moreover, the stress history of the un-trenched T1T1 pavement was not known, thus any previous loading might also favourably strengthen the pavement. The period soil was left to dry, and potentially harden, in addition to soil stress history, might have resulted in Trench 2-5 tests having a weaker subgrade than Trench 1.

Furthermore, test T1T1 ended prematurely due to the vertical limitation of the APT, where the pressure cylinder was “out-of-stroke”, hence, results might not have captured the full extent of failure. For subsequent tests, the pavement surfaces were constructed much closer to the top of the Perspex window level.

Based on the surface reconstructions, test T2T2 had more severe deformations than T1T1. Considering test T2T2’s lower loading passes and higher testing speed – 250passes and 7.4mm/s for T1T1, 150passes and 18.5mm/s for T2T2, the occurrence was most likely due to the previously identified consolidation period rather than test T1T1’s premature end. Like test T1T1, test T5T2 also exhibited soil cracking and rigid lateral soil movements – especially near the end of the tyre path, suggesting a brittle failure. Despite the minimal time between construction and testing, brittle deformations might have occurred in test T5T2 due to the low water content – 5.8%, significantly less than optimal (9.8%).

Influence of geotextiles

Tests T2T4 and T3T3, for pavements with geotextile, exhibited similar surface deformation mechanisms to pavements without geotextile. Geotextiles had been repeatedly incorporated in civil engineering projects for many different functions, in literature, but for this research paper, only the reinforcement function were analysed the influence of. Most importantly, the question is whether geotextiles can reduce the impacts of trench reinstatement, when constructed to bridge over the trench area.

The CloudCompare cloud-to-cloud (C2C) absolute distance heat maps for between the initial and final states of each Trench 2 test are displayed in Figures 4.1f and 4.1g. Both tests experienced rutting settlement, lateral upheaval, and soil shoving in the tyre travel direction.

The geotextile appeared to minimise surface soil displacements in these subgrade-only tests. For test T2T2 (without geotextile), the maximum was the 100mm (red) lateral displacement and rutting settlement was above 60mm (green-yellow), whilst for test T2T4 (with geotextile), maximum displacement due to shoving was 62mm (red) and rutting settlement was under 40mm (green-yellow).

4.1.2 Subsurface PIV Analysis

The processed subsurface results for tests T5T2 and T3T3, without and with geotextiles respectively, are presented in Figures 4.2 and 4.3. Each figure depicts the combined six elevation camera images and the resulting vectorial displacement field (from the initial to final captured images) in subfigures (a) and (b). For better representation of the soil displacement components, subfigures (c) and (d) present displacement contour maps for the vertical and horizontal directions.

Influence of trench reinstatement

In the surface reconstructions, the presence of the trench was observed to have increased rutting along the loading path. In the cross-sectional PIV analysis (Figures 4.2b and 4.3b), the influence of trench reinstatement was depicted through the increasing participating soil depth in the direction of tyre loading (decreasing X-value). With the tyre shoving the surface soil along its path during loading, thus shear stresses and large, progressive strains, were generated [12], pushing failure towards the front end of the trench ($X < 346\text{mm}$ for T5T2 and $X < 355\text{mm}$ for T3T3). The deformations being more severe at the wheel front than rear highlighted an antisymmetric deformation mechanism, exacerbated by the trench.

The deformations near the surface were predominantly in the direction of tyre loading with some upwards motion, which explained the lateral sliding and upheaval observed in the surface reconstructions; with depth however, the soil behaviour changes. Deeper in the subsurface, soil motion direction was heavily dependent on its location relative to the trench.

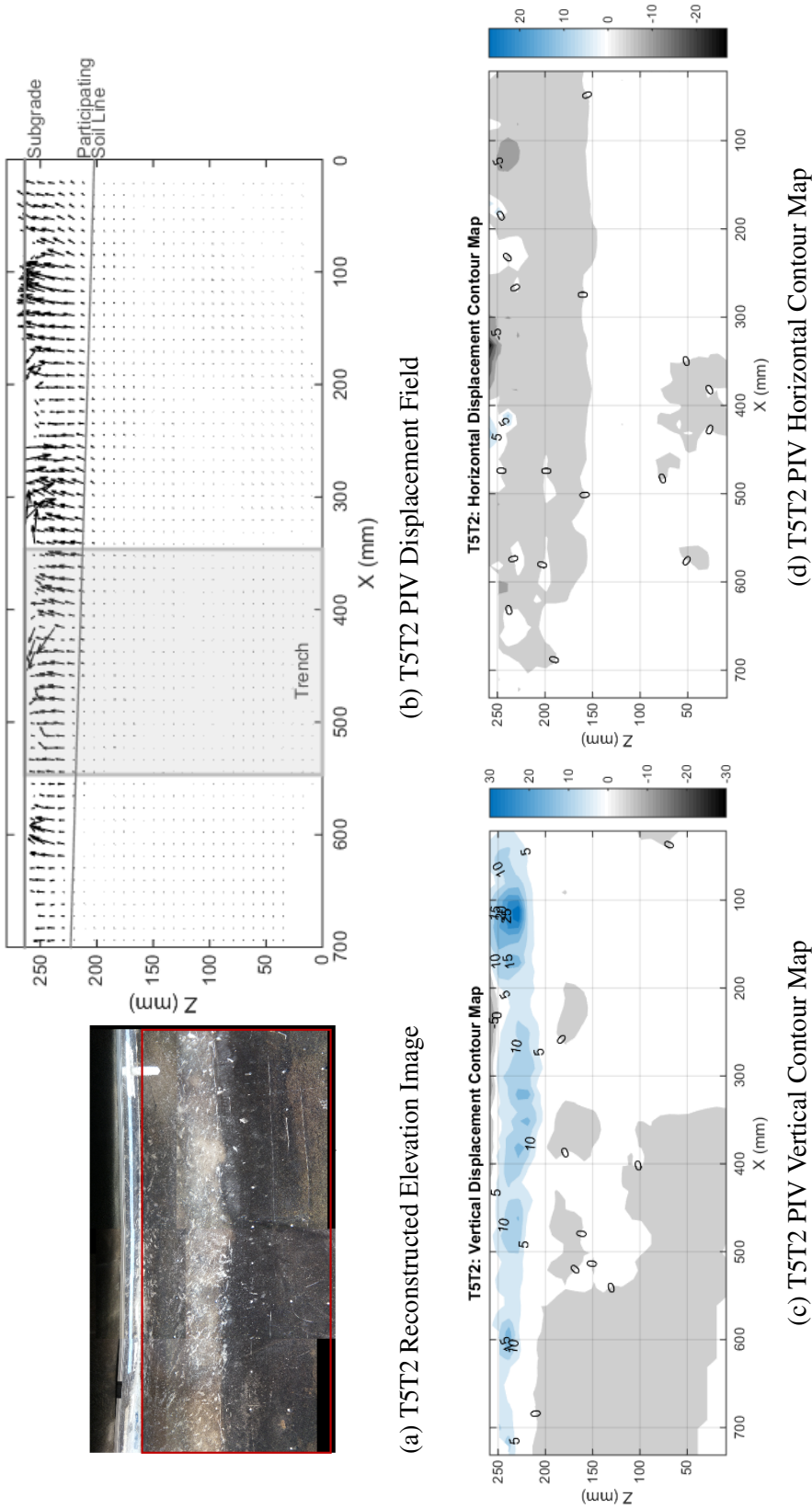
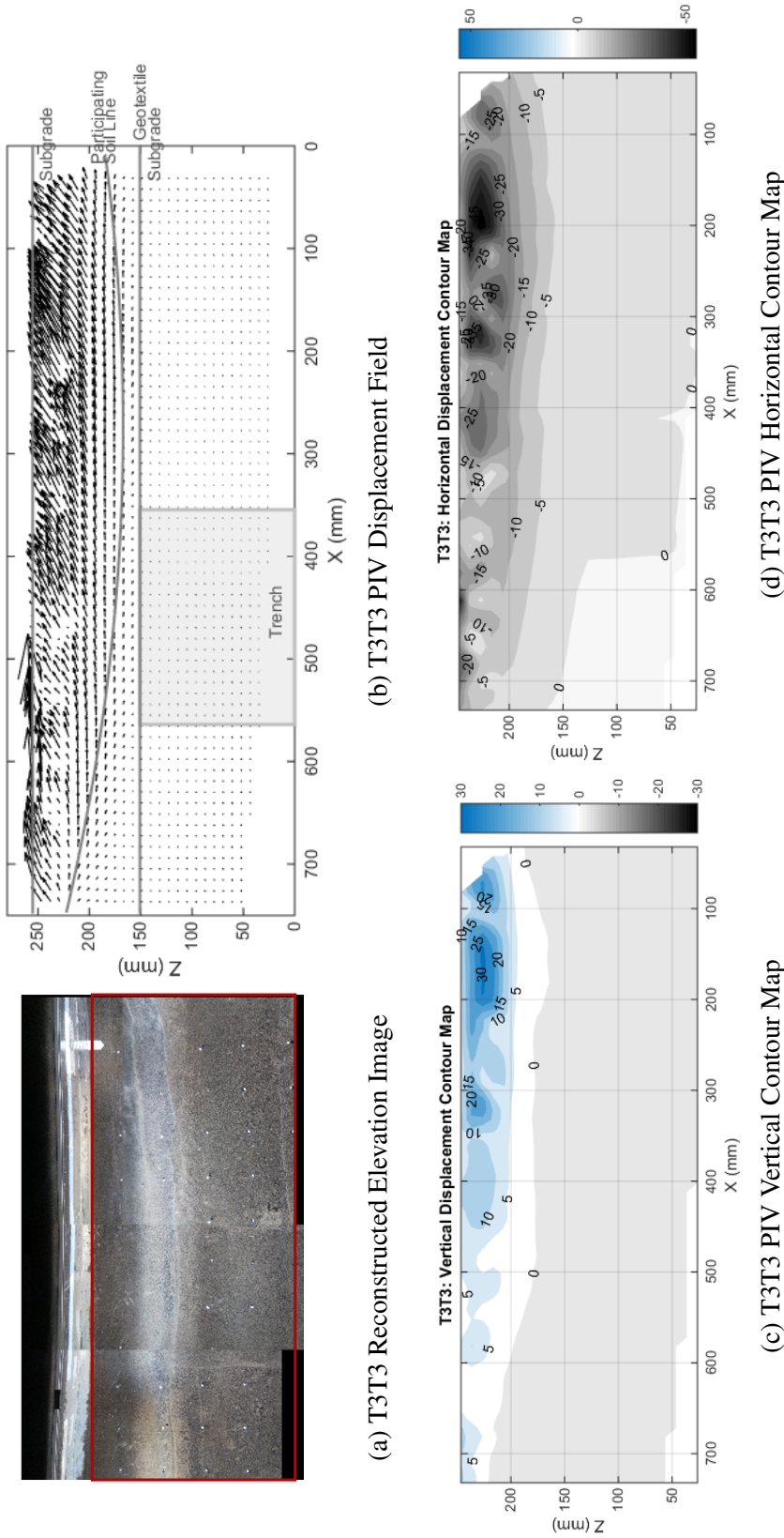


Fig. 4.2 Subsurface PIV Analysis: Test T5T2, red box indicates region of interest (ROI) for PIV analysis. For analysis purposes, the trench is represented by a vertical cut, instead of the actual diagonal cut.



In test T5T2's subsurface ($Z < 175\text{mm}$), at the trench rear ($X > 547\text{mm}$), soil motion was generally vertically downwards under tyre load compaction, with minimal horizontal displacement. Within the trench edge ($547 > X > 346\text{mm}$), the surface upheaval transitioned into settlement, with more horizontal displacement. At the trench front ($X < 346\text{mm}$), soil motion became vertically upwards. The transitions were highlighted by the contour maps in Figures 4.2c and 4.2d. The upwards motion of soil at depth suggested swelling at the trench front; this might be because the tyre removed soil from the trench area to be accumulated at the pit boundary. The soil removal, equivalent to an unloading from reduced soil self-weight, resulted in the soil rebounding. The accumulation at the end of the tyre path, equivalent to increased loading, did not however induce the opposite behavioural change. Instead, the loading alleviated, decreased the magnitude of, soil upheaval near $X = 0\text{mm}$.

The trench reinstatement weakened the pavement, especially at the surface where most deformations could be observed; with increasing load repetitions, the pavement could have accumulated permanent deformations and could no longer contain the failure to only the surface layer, and thus affected the deeper subgrade layers as well. The soil removal and addition at different surface locations had also led to different subsurface behaviours.

Influence of test model construction

For objective comparisons with geotextile test T3T3, the different testing conditions will first be highlighted. Ultimately, contributed by the over-optimal water content at 11% (optimal at 9.8%), test T3T3 performed worse than all comparable tests – Tests T1T1, T2T2, T2T4 and T5T2. The test 'failed' after 45 passes, where the APT pneumatic cylinder ran out of vertical distance. This overly wet soil led to poor pavement compaction, in addition to the previously discussed lack of compaction force and short construction-testing waiting period. Considering the same compactor equipment, procedure and effort were used, and similar period between pavement construction and testing, differences between tests T3T3 and T5T2 would most likely be due to the different water content, in addition to the incorporation of geotextile.

Influence of geotextiles

Due to the data unavailability for Trench 1 and 2 tests, test T3T3 results were instead analysed for the subsurface influence of geotextiles. From Figure 4.3b, the geotextile coincided with a very distinct change in displacement magnitude; the soil above ($Z > 151\text{mm}$) experienced much larger deformations than that below. Divided into the vertical and hori-

zontal components, Figures 4.3c and 4.3d show that above the geotextile, subgrade motion was mostly lateral in the tyre loading direction, and any vertical displacements pointed upwards. Below the geotextile, the vertical components all pointed downwards, regardless of the soil patch X-value; the horizontal magnitudes were significantly reduced, and directions were slightly affected by the trench. At the trench rear ($X > 564\text{mm}$), the subsurface soil displacement had minimal horizontal component; within the trench edge ($564 > X > 355\text{mm}$) and extending to the trench front ($X < 355\text{mm}$), the subgrade displacement had increased horizontal component, in the direction of tyre path.

By comparing the analysis to that of test T5T2, the geotextile might help limit surface load stresses from being transferred into the subgrade below; however, test T5T2 suggested that even without the geotextile layer, soil displacement was already localised to the surface layers. More importantly, the geotextile might help minimise the trench influence on the pavement. In test T5T2, the trench reinstatement resulted in subgrade layer settlement transitioning to upheaval in the tyre loading direction, while in test T3T3, the trench had less influence – under the geotextile, soil displacement was almost uniformly settlement.

A combination of mechanisms might be occurring due to the inclusion of geotextile. The primary expected mechanism was that the geotextile provides a membrane action to help distribute vertical stresses onto a wider area, to reduce deformations being transferred into the especially weak trench. This mechanism might have been dominant in test T2T4. However, a second mechanism might instead be weakening the pavement, especially in the wet-subgrade pavement test T3T3. The inability for the geotextile to transfer friction, as observed by the shear stress reduction below the layer, might mean that a plane of weakness had instead been created, leading to a shallower critical mechanism. The concentration of deformations due to the surface layer ‘sliding’ across the geotextile from the reduced friction, in addition to the particularly weak surface soil, may instead be worsening the pavement overall performance.

4.2 Subgrade and Base Course Trenched Pavement Response

For the pavement structure with trenched subgrade overlain by base course, the tests analysed were T3T2 and T4T1 for without geotextile, and T4T2 for with. Test T3T2 had 55mm of gravel base course layer, while the other two tests had 107.5mm, and all with tyre loading speed of 18.5mm/s. Test details and test profiles for this pavement structure are shown in Chapter 3.

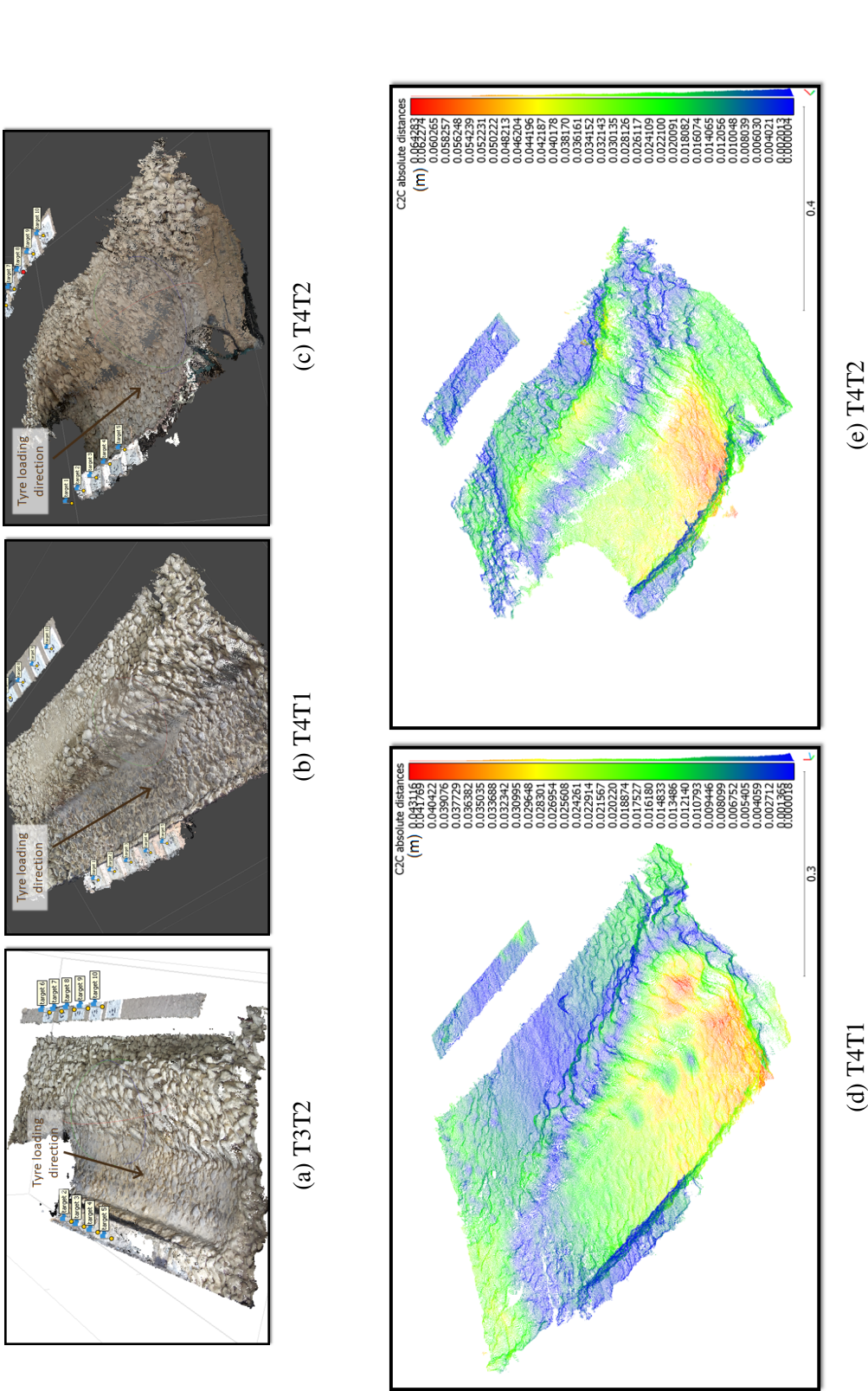


Fig. 4.4 Subgrade-Base Course Pavement Surface Processed Results: Agisoft Surface Reconstruction - without geotextile (a)T3T2, (b)T4T1, with geotextile (c)T4T2; CloudCompare C2C Absolute Distance Heat Map - without geotextile (d)T4T1, with geotextile (e)T4T2

4.2.1 Surface Reconstruction Analysis

The 3-D surface reconstructions for subgrade-base course pavement tests are shown in Figure 4.4, all of which show comparable surface deformation conclusions to that of the subgrade-only pavements. Surface rutting settlement beyond the trench edge and lateral soil displacement towards the tyre edge and along the path could be observed. With each subsequent pass, the channelised tyre loading allowed re-compaction of gravel, increasing rutting depth at a decreasing rate with more load passes [57]. The rut deepening also increased locally displaced soil, to form the widening side berm in the surface reconstructions. Unlike in subgrade-only pavements, the tyre embedment into the stiffer gravel layer was reduced[60]; this led to decreased surface soil shoving – less severe surface deformations, although not eliminated completely as the gravel layer was initially uncompacted. As soil motion was stopped by the pit boundary, accumulated soil by the boundary hindered the tyre from reaching its end position, which resulted in test T4T2 ending prematurely. Another difference with the subgrade-only pavement tests was that the brittle cracking of Trench 1 and 5 tests was not present in these two-layered pavement tests.

The CloudCompare distance heat map for each Trench 4 test are displayed in Figures 4.4d and 4.4e. In comparison to the subgrade-only pavements, the gravel arguably reduced surface deformations; however, the influence of geotextiles differ between the two pavement structures. For test T4T1 with 1496 passes, the maximum absolute displacements were over 40mm, due to soil movement along and outside the tyre path. For test T4T2 with 142 passes, the maximum displacement of over 60mm were due to both tyre shoving and vertical settlement. It can be concluded that even with much fewer loading passes, test T4T2 resulted in more severe surface deformations, and thus the geotextile was not effective in reducing surface rutting, for the specific testing conditions. In subgrade-base course pavements, the angular shape of gravel interlocks into the silty sand surface; with the inclusion of geotextile between the gravel-silty sand interface however, interlock was prevented. The reduced interface friction led to 'sliding' of the gravel layer, resulting in greater displacements in pavements with geotextile than without.

4.2.2 Subsurface PIV Analysis

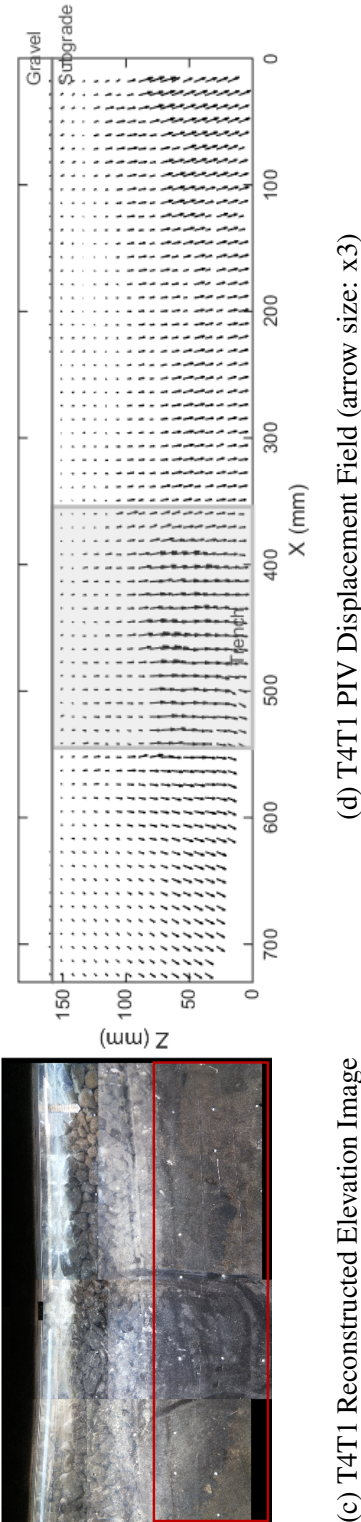
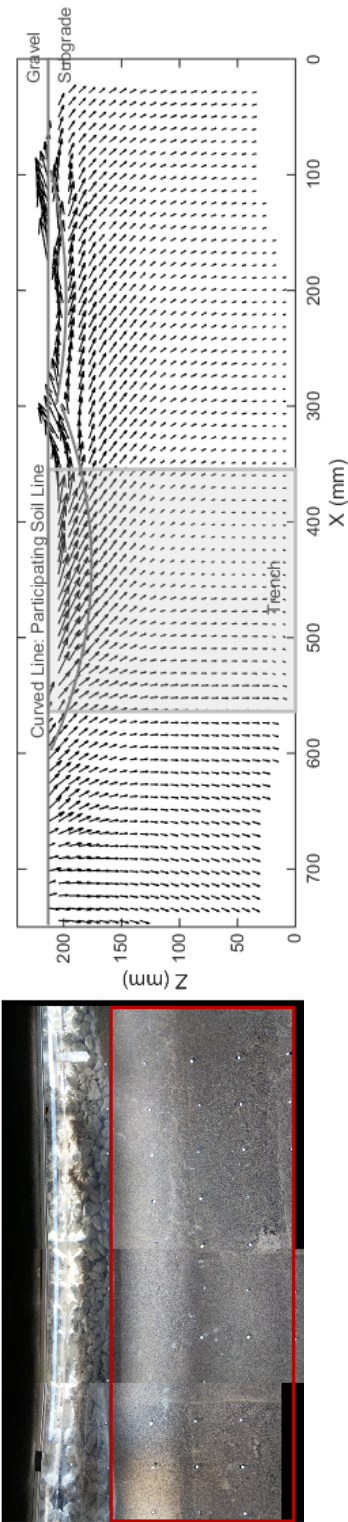


Fig. 4.5 Subsurface PIV Analysis: Tests T3T2 and T4T1

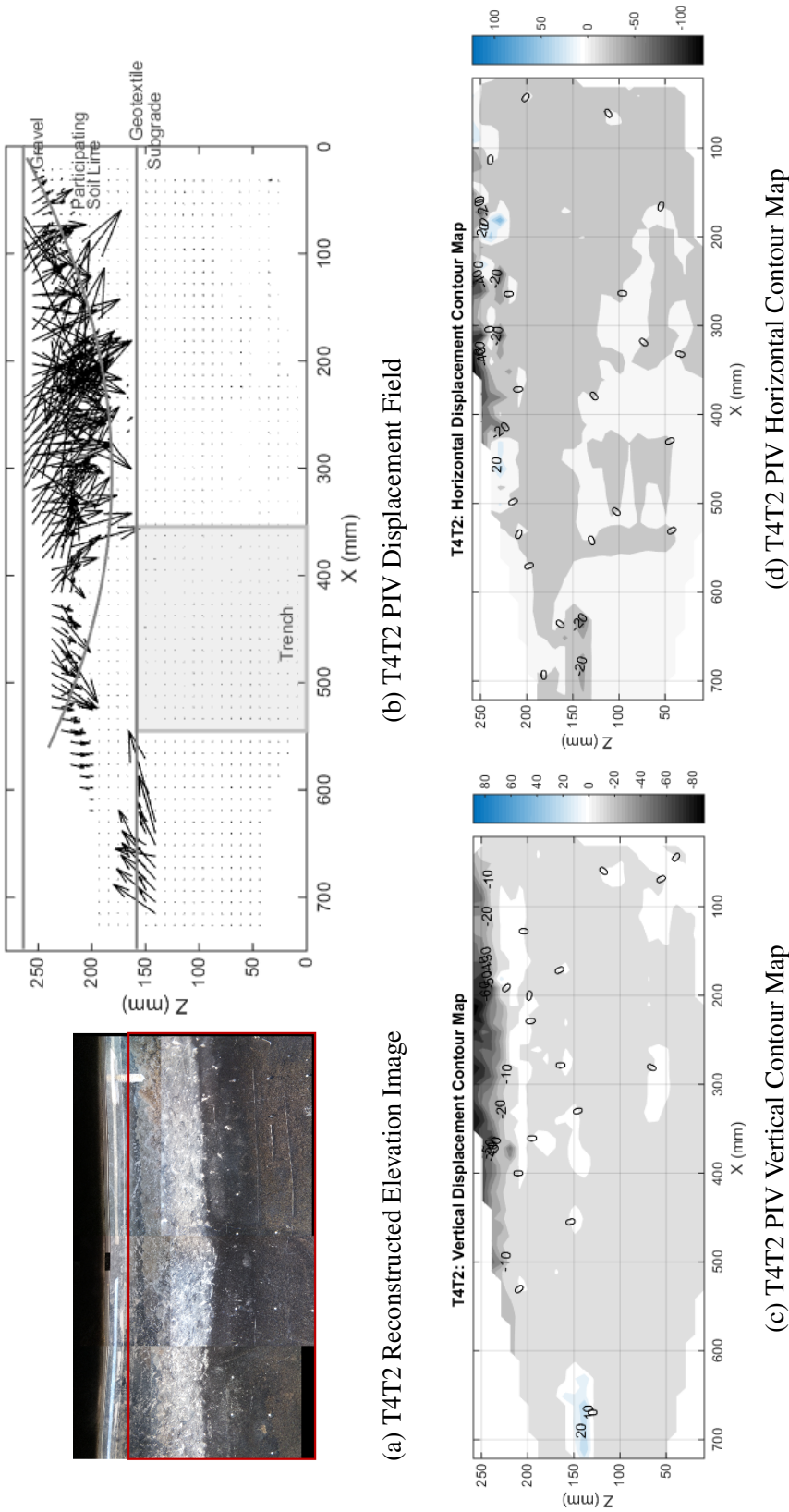


Fig. 4.6 Subsurface PIV Analysis: Test T4T2

Figures 4.5 and 4.6 illustrate the processed subsurface results for subgrade-base course pavements without and with geotextile respectively. The former figure includes the reconstruction elevation-view images and resulting PIV displacement field for tests T3T2 and T4T1, which PIV analysis were only conducted for the layers below the base course-subgrade interface, and arrow size multiplied by 3 for better vector visibility. The latter includes that for test T4T2, along with its resolved vertical and horizontal contour maps.

Influence of trench reinstatement

For test T3T2, the subsurface analysis (Figure 4.5b) illustrates a pronounced pothole-like ‘dip’ below the base course-subgrade interface ($Z=213\text{mm}$), as outlined by the participating soil line. The soil ‘dip’ suggests that the base course layer was unable to contain all the deformations, and thus some was experienced by the subgrade. The ‘dip’ shape mimics tyre shoving, which began within and extended to beyond the trench region ($X<564\text{mm}$). This suggests that the trench might have exacerbated failure, while contributing to the increasing displacement along the tyre loading direction.

Deeper in the subsurface, both T3T2 and T4T1 tests suggest that the subgrade experienced predominantly vertically downwards displacement with slight horizontal motion. The vertical direction suggests that the base course contained most of the upheaval deformations, albeit not entirely. The magnitude suggests that the gravel help reduce stress intensity in the subgrade, while involving the deeper ‘participating soil’ as well. In the horizontal direction, the trench influenced the subsurface soil displacement, from against the tyre path direction before the trench rear, transitioning to in the tyre path direction after the trench front – as in subgrade-only pavements (test T5T2). The analysis between tests T3T2 and T4T1, with the same pavement structure, differed for the trench influence on the subsurface horizontal displacement. In test T3T2, the trench did not influence the magnitude, with displacement field arrow sizes remaining relatively uniform across the tyre path. For test T4T1, the displacement magnitude within the trench boundary was higher than outside, especially in the lower subgrade layers, $Z<80\text{mm}$. This would be expected due to the weaker material used for the trench relative to the surrounding subgrade material.

Influence of test model construction

For test T4T1, the subsurface analysis suggested the subgrade soil response increases in magnitude with soil depth (decreasing Z -value). This unexpected occurrence could be due to the following reasons. Firstly, small particles from the gravel mixture, a form of silty

paste, might travel down into the subgrade's top layer, then sticks to the window. Thus, if PIV tracked this stuck paste instead of the silty-sand behind, minimal displacement would be recorded. Secondly, the window instils a 3-D slice of the mechanism. The window was not located at the tyre axis centre, with a small 10mm gap between the tyre outer edge and the window. Therefore, the captured mechanism was not a plane strain problem. The smaller magnitude for the top subgrade layers might be attributed to the soil travelling predominantly perpendicular to plane, and thus appeared from the window as if to have smaller displacements than the deeper layers.

The subgrade analysis for tests T3T2 and T4T1 differ, despite having the same pavement structure and comparable traffic loading repetitions – 365 and 390 passes respectively. Whilst this may be attributed to the differing base course layer thickness or pavement testing conditions, more importantly, the differing mechanism highlighted how small changes or imperfections in construction might lead to significant changes in pavement performance.

Furthermore, the tracking issue due to the base course layer scratching the window (explained in 'Methodology' chapter) might have also affected geotextile test T4T2 results. Unlike the consistent displacement magnitudes in test T4T1, the data for test T4T2 appear much less consistent, with some wild data and unexplainable discontinuities. Despite the questionable tracking in some regions of the displacement field, general conclusions could still be made regarding the influence of geotextile in two-layered pavements.

Influence of geotextiles

With the inclusion of geotextile, test T4T2 PIV analysis (Figure 4.6b) indicates that the base course gravel layer experienced a much higher deformation than the subsurface subgrade layers. As in single-layered pavement test T3T3, the geotextile ($Z=158\text{mm}$) coincided with a distinct displacement magnitude change. Resolving test T4T2 displacement fields into vertical and horizontal components, Figures 4.6c and 4.6d show that above the geotextile, subgrade motion was mostly lateral in the tyre loading direction, and any vertical displacements pointed downwards, as opposed to the upwards surface layers motion in test T3T3 – suggesting the influence of base course. Below the geotextile, the vertical and horizontal magnitudes were significantly reduced, and directions unchanged – with exception of some observable “wild” data. With the help of the base course layer to minimise deformations from reaching the subgrade layer, the geotextile minimised the influence of trench on the subgrade below the reinforcement by bridging over the weaker section.

Testing conditions for test T4T2 were most similar to test T4T1 – pavement layer thickness, trench location and soil water content, differed only with the inclusion of geotextile. Comparing the two tests, the geotextile appeared to help limit vertical and shear stresses from the tyre loading from being transferred into the subgrade below, suggested by the larger subgrade displacement magnitude in test T4T1, without geotextile, than in test T4T2, with geotextile. Additionally, the geotextile minimised the trench influence on the subgrade layer. In test T4T1, the presence of trench led to an arguably larger displacement magnitude within the trench than the surrounding soils, while affecting the displacement direction. This irregularity was smoothed out by the geotextile in test T4T2, where subgrade displacement magnitude and direction appeared relatively uniform.

Nevertheless, the geotextile might have increased surface deformations, resulting in larger surface displacements in test T4T2 with geotextile (Figure 4.4e) than in test T4T1 without (Figure 4.4d). For the single-layered pavement with geotextile (test T3T3), the inclusion geotextile layer might have resulted in a combination of mechanisms – (i) tension membrane action, to reduce intensity of vertical and shear stresses in the layers below, and (ii) reduced subgrade-base course interface friction, introducing a plane of weakness that the material above ‘slides’ across and hence weakening the surface layers.

The base course layer had helped distribute stresses to reduce the intensity experienced by the subgrade below, as shown from test T4T1. Hence, the geotextile in the two-layered pavement would have contributed to this first membrane action mechanism less than that in the single-layered equivalent – the gravel reduced the geotextile benefit. The slip surface in test T4T2, as outlined by the participating soil line, did not reach the geotextile layer, thus the pavement failure had occurred before the geotextile experienced enough tension to fully mobilise its tensile strength [61], and thus reducing the effectiveness of geotextiles even further. Additionally, the second mechanism might be more prominent in the two-layered than single-layered pavement as the change from gravel-silty sand to gravel-geotextile-silty interactions resulted in greater friction reduction, and hence lateral restraint loss and pavement weakening. This was suggested by the clear shear plane of weakness towards the surface (Figure 4.6b), most likely due to the inclusion of geotextile.

Review of literature shows that under direct shear tests, the inclusion of geotextiles consistently led to reduced soil-geotextile interface shear stresses, and thus friction, in comparison to the internal friction of the tested soil materials [48], [46]. In a test conducted by Abdi [1] on soils with internal friction of 44.8° and 33.8° , the soil-geotextile interface friction is reduced to 39.3° and 30.2° respectively.

4.3 Analysis Findings

All the pavements tested resulted in surface rutting and lateral soil shoving, which deformations were predominantly localised to the surface layers. The trench reinstatement clearly weakened the pavement; in the tyre path direction, the trench contributed to participating soil depth increase, exacerbating the antisymmetric deformation between the tyre front and rear. Deeper in the pavement subsurface, the trench influenced the soil motion direction. Soil settlement observed at the trench rear was transformed into upheaval and horizontal displacement towards the tyre travel direction, which influence was minimised with the addition of base course, and even more so with the inclusion of geotextile.

Ultimately, the geotextile helped to minimise the stresses experienced by the underlying soil, while bridging over the trench-induced irregularities over the pavement structure. However, this benefit was at the expense of introducing a plane of weakness at a shallower critical depth for the subgrade-base course pavements, resulting in more significant surface deformations. The reduced interface friction, in addition to the relatively weak surface layer, allowed ‘sliding’ of the surface layer under repeated tyre loading. The stiffer base course layer helped reduce surface rutting and better contained accumulated deformations in the surface layers. However, the reduced friction prevented the beneficial behaviour of geotextiles from being fully observable in the two-layered tests.

In order to fully mobilise the benefits and minimise the disadvantages of the added reinforcement, the reinforcement-soil interface friction will have to be increased to avoid introducing a distinct plane of weakness – with the use of geogrids for increased aperture interlock or inclusion of nails along the reinforcement area. Additionally, a stronger surface layer, such as paving the pavement with asphalt, might potentially change the limiting mechanism of pavement failure.

Chapter 5

Conclusions and Future Work

5.1 Research Conclusion

The detrimental influence of trench reinstatements on road pavement performance had long been identified and verified; however, there had been limited investigation into the underlying subsurface issues, and less so into the inclusion of reinforcements to minimise trench-induced deformations. To address the gap in literature, this research project was conducted for pavements under repeated tyre loading, to explore the effectiveness of geotextiles in bridging over the weaker trench areas to reduce both the surface and subsurface deformations.

Results presented in this report were obtained from laboratory testing of subgrade-only and subgrade-base course pavement models, with use of the Cambridge Accelerated Pavement Tester (APT). The equipment, in addition to a network of cameras and instrumentation, allowed repeated load testing of scaled pavement models, in a controlled and realistic manner, yet less expensive and time-consuming than full-scale testing. The budget and time constraints of this research, along with the novel approach to measuring subsurface deformation, made the APT ideal for delivering the research objectives.

The research findings show that the trench induced antisymmetric deformations between soils on either side of the trench, which discontinuity resulted in increased pavement deterioration in both the surface and subsurface levels. The inclusion of geotextile provided a tensioned-membrane mechanism to minimise stresses experienced by the underlying soil, while bridging over the trench-induced deformations. The benefit for soils under the geotextile might, however, be at the expense of soils above the geotextile. Depending on the interface friction reduction, due to the relatively smooth geotextile, a plane of weakness

might be introduced, which allowed the surface layer to slide under loading. This occurrence was more dominant in the subgrade-base course pavements as the geotextile prevented the interface interlocking between the two materials. Whereas, in the subgrade-only pavements, the subgrade interface interlocking was originally minimal, thus the tensioned-membrane benefit provided by the geotextile was dominant. To some extent, the severe surface deformations were also due to the lack of a strong enough surface layer that prevented the beneficial behaviour of geotextiles from being fully mobilised.

5.2 Future Works Recommendation

The scope of further studies for the inclusion of reinforcements in trench-reinstated pavements is extensive. The recommendations for future work include:

1. The geotextile introduced a plane of weakness, by preventing the interlocking of the gravel particles into the sand subgrade, and thus reducing friction. To increase the soil-reinforcement interface friction, future studies could attach nails onto the geotextiles, or use different reinforcement types – geogrids, which open mesh may allow better shear coupling and interlocking between pavement layers.
2. The unpaved structures in this research project prevented the full observations of the geotextile inclusion benefits; thus, future works could add asphalt layers to potentially change the limiting failure mechanism and allow the benefits of added reinforcement to be fully mobilised.
3. To better understand the implications of added reinforcement subjected to environmental conditions, field testing could be conducted. Additionally, this will allow use of petrol-powered compactors that may be dangerous to use in a ventilated lab.
4. Due to the different trench geometry and dimensions that exist in practice, testing should be done with different depths in which the geosynthetic layer is placed.

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Appendix A

Risk Assessment Retrospective

In retrospect, the identified hazards in the risk assessment and safe system of work implemented were appropriate for the conducted research. Additionally, a health and safety briefing was conducted before any experimental work took place in the Schofield Centre.

The originally identified hazards included the moving wheel actuator of the Accelerated Pavement and Tester (APT) handling of heavy components - electric compactor, handling bags of soil, and shovelling soil in and out of the concrete pit. The former risk was minimised by the use of barrier, to be closed when the APT was in operation. Any lifting of the APT beam, to remove and to lift back in place, were done by the lab technicians. Moreover, correct manual handling practices were implemented when handling heavier items.

An additional hazard not listed in the risk assessment was the risk of Hand-Arm Vibration Syndrome (HAVS) associated with excessive exposure to the vibrating plate compactor. However, the risk of HAVS can be mitigated by limiting use of equipment to minimal time periods in a session. Also associated with the compactor is the vibratory noise, which risk can be reduced by use of ear defenders.

Appendix B

Covid-19 disruption

Due to covid-19, over 1TB of images¹, the single computer-licensed Agisoft Metashape software, and Accelerated Pavement Tester (APT) equipment in the Schofield Centre cannot be accessed. In this report, captured images were processed to obtain surface reconstructions and subsurface PIV analysis. Some analysis had been done throughout the year; however, as there are 14 tests in total, the processed results presented in Chapter 4 may differ in completeness. Test comparisons may involve varying analysis depths, yet all available substitutes were included to help present the report in a more cohesive manner.

Additionally, the inaccessible software meant that some surface reconstructions cannot be obtained, and in turn, displacement heat maps. For the initial tests, only the reconstruction screenshots were saved but not the cloud files, thus further processing cannot be done. PhD student Eichhorn managed to bring his licensed computer out of the lab, and have helped process some of the available images, albeit incomplete.

Final tests involving geotextile inclusion in paved roads - with a stronger asphalt surface layer, as recommended in the future works section, could not be conducted. Paved road test without geotextile had been conducted at the end of Lent term, while the test with geotextile was scheduled to be conducted during the Easter break.

Furthermore, exact dimension measurements of camera placement and captured image area could not be taken; thus, the displacement field graphs, scaled from pixel units to millimeters, are estimated based on the trench lines visible from the image. Other data and instrumentation specifications (surface elevation 2-D plot, exact loading force per test, temperature), although not crucial towards the research objectives, had to be omitted from the report. Where applicable, the recorded preliminary data for the first test were assumed constant for all the tests.