Proceedings of the XVI ECSMGE
Geotechnical Engineering for Infrastructure and Development
ISBN 978-0-7277-6067-8

doi:10.1680/ecsmge.60678

Constraints in using site-won calcareous clayey silt (loam) as fill materials

Contraintes à l'utilisation de calcaire argileux limon pour construire terrassement

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ABSTRACT BSI recently published the revised BS 6031, to include compliance with Eurocode 7. This placed emphasis on fill classification and compaction specifications, while setting the Specification for Highway Works (SHW) 600 series as the default approach for earthworks in the UK. The revised BS 6031 (and earlier documents such as the 2001 manual of BRE Centre for Ground Engineering and Remediation) lack in explaining long-term ground movements in compacted earthworks, particularly when arisings from nearby cuttings are used as fill materials. Unexplained settlements include sudden and long-term subsidence particularly in transient loading environments, when fills are built from sand/silts with small clay inclusions, as well as seasonal subsidence in fills with <20% carbonates. This paper examines some of these limitations through revisiting our recent research, including a recent experimental work. From this paper, specifications can be developed for building fills with site-won materials with an impact on carbon footprint, haulage and maintenance costs.

RÉSUMÉ BSI a récemment publié le BS 6031 révisée, pour y inclure le respect de l'Eurocode 7. Cette mis l'accent sur la classification de remplissage et de compactage spécifications, tout en fixant la spécification pour l'autoroute Travaux (SHW) série 600 comme l'approche par défaut pour les travaux de terrassement dans le Royaume-Uni. Le BS révisé 6031 (et les documents antérieurs, tels que le manuel de 2001 du Centre BRE pour Engi Rez-nierie et assainissement) le manque à expliquer les mouvements du sol à long terme pour les travaux de terrassement compactés, en particulier lorsque chutes de boutures à proximité sont utilisés comme matériaux de remblai. Colonies inexpliquées comprennent l'affaissement soudain et à long terme en particulier dans des environnements de charge transitoire, lorsque les remplissages sont construits à partir de sable / limons avec de petites inclusions d'argile, ainsi que la subsidence saisonnière remplissages avec <20% de carbonates. Cet article examine certaines de ces limitations grâce à revisiter notre recherche récente, y compris un travail expérimental re-cent. De ce document, les spécifications peuvent être développées pour la construction remplit avec des matériaux gagné sites-avec un im-pact sur les coûts empreinte carbone, transport et d'entretien.

1 INTRODUCTION

The performance of the heavily used UK transport infrastructure relies in part on the performance of underlying embankments; many of which have been in service for over 150 years. Furthermore, new embankments are to be built in the coming decades to improve the network, raising the need for better understanding of the impact of placement conditions on planned maintenance costs.

BSi recently published the revised BS 6031, to include compliance with Eurocode 7. This placed emphasis on fill classification and compaction specifications, while setting the Specification for Highway Works (SHW) 600 series as the default approach for earthworks in the UK. The revised BS 6031 (and earlier documents such as the 2001 manual of BRE Centre for Ground Engineering and Remediation) however lack in explaining long-term ground movements in compacted earthworks, particularly when arisings from nearby cuttings are used as fill materials. This paper summarises the recent published works of the authors to illustrate some of the interactions between soil composition, placement conditions and weather.

Dry and wet compressibility of a suite of calcareous and non-calcareous clayey silts and silty clays are here examined against the BRE recommendations, as a baseline of the UK earthwork practice.

2 NON-CALCAREOUS FINES

According to BS 6031:2009, composite fills may be built through pre-consolidation (also BS-EN-14688-2:2007), densification or pre-loading (Jefferson et al., 2005). The efficiency of these methods is a function of compaction water content, service-life water content, clay content, climate, and loading environment (Charles and Watts, 2001). This paper revisits our recent research into the impact of these controls.

2.1 Placement water content

In Fig. 1, oedometer tests on compacted (optimum standard proctor) loam soils (kaolinite and silt-sized quartz) revealed a <1% residual collapse potential (upon wetting at 200 kPa). For dry-of-optimum conditions however, greater residual collapsibility was captured, that can result in long-term settlements.

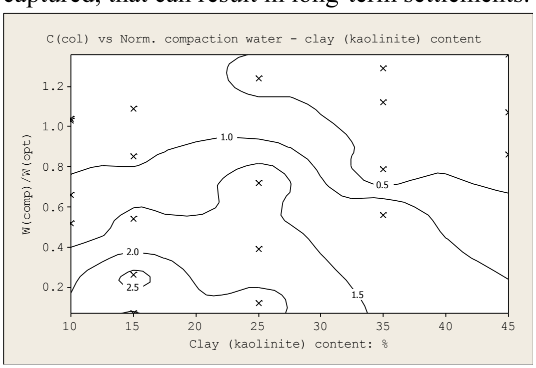

Figure 1. Coefficient of Collapsibility for equal service and placement water contents ($C_{(col)}=\Delta e/(1+e_1)$, e_1 is pre-wetting void ratio, ω_{comp} and ω_{opt} are placement and optimum water contents)

In Fig. 2, for soils containing <25% kaolinite, compressibility (volume change upon incremental loading to 200kPa: roughly analogous to the self-weight of a 10m high embankment) increased with decreasing compaction water content on the dry-of-optimum tail. Subsidence as high as 60cm was predicted for a dry-compacted loamy fill of 15% clay under 200kPa of surcharge. Unlike clayey silts, dry compaction of calcareous loams better destructed the porous structure (Fig. 3). Assadi (2014) attributed this resistance to combined effect of capillary forces and formed secondary crystals, following simultaneous measurement of capillary forces and void ratio for a calcareous oedometer specimen (Fig. 4).

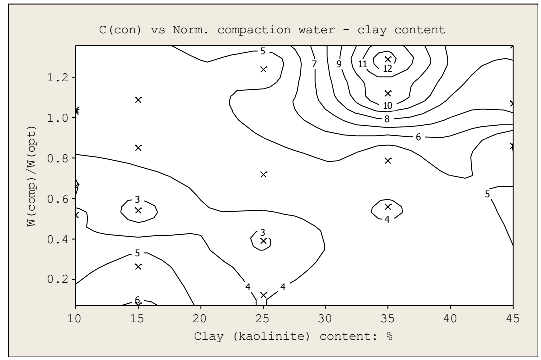

Figure 2. Coefficient of Contraction (for confined loading to 200 kPa in load steps) contours for equal service and placement water contents ($C_{(con)}=\Delta e/(1+e_0)$, e_0 is initial void ratio, e is void ratio)

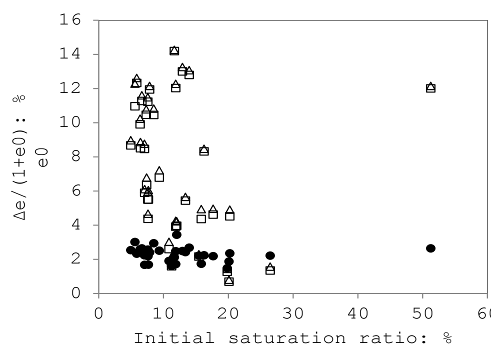

Figure 3. Resistance of soil structure with increasing placement water content (S_r<15%) in soils containing 0-30% carbonates, 10-30% kaolinite, and 45-90% quartz silt: 'e' being the void ratio

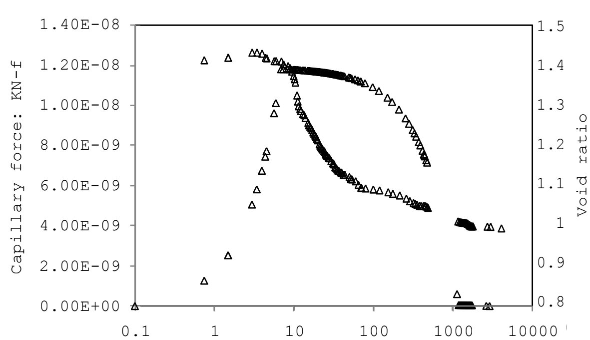

Figure 4. Contribution of capillary force to structural integrity: wetting time vs. capillary force vs. void ratio (Assadi 2014).

2.2 Clay content

Despite the suitability of optimum compaction in loams of <25% kaolinite content (Fig. 1 and Fig. 2), an increase in clay content from 25% to 35% (Fig. 2), made the optimum compaction ineffective in mitigating the dry compressibility.

Risk of sudden subsidence (i.e. collapse) however was removed in loams with >15% clay content (Fig. 1). From a structural perspective, smaller risk of collapse is due to the migration of clays, excess to coating units around grains, from quartz contacts to macro-pore spaces (Fig. 5). Occupied macro-pores leave less open spaces to collapse in the event of wetting. From a micromechanical perspective (Assadi and Jefferson, 2015), increasing clay content reduces the skeletal and hydro-dynamic stress, when net stress and hydraulic gradient remain unchanged. A lower hydrodynamic stress lowers the chance of collapse.

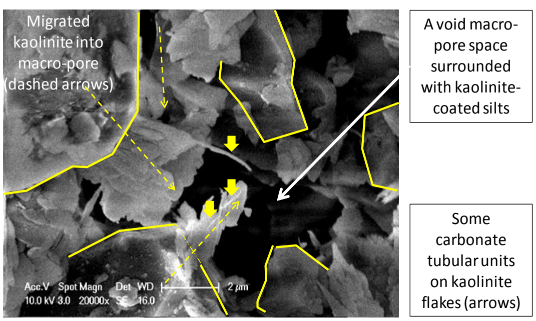

Figure 5. SEM image of a clayey silt at 10% kaolinite and 5% carbonate immediately after wetting-drying

2.3 Service Water Content

Experiments showed a maximum of 1% collapse potential in specimens containing <20% kaolinite and <1% in specimens containing >20% kaolinite when compacted at optimum water content (Fig. 1). That admissible collapsibility however increased to 3% in loams with <20% kaolinite and 4-5% in loams with 25 to 40% kaolinite content when after a course of drying during the service life (Fig. 6).

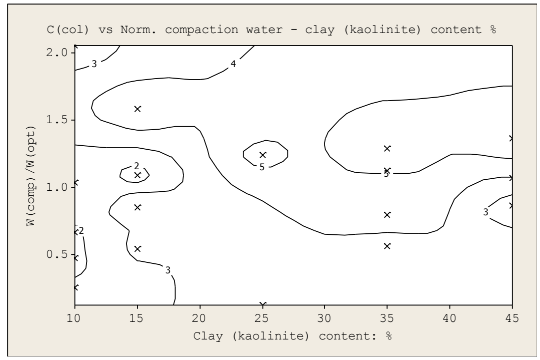

Figure 6. Collapsibility contours in dried clayey silts (analogous to Fig. 1 after a course of drying)

For loams containing >30% kaolinite, wet compaction in particular appeared ineffective (Fig. 6). This agreed with our earlier findings (Assadi and Yasrobi, 2010) for residual clayey sandy silts containing 30% clay content (PI=38%) and residual moderately plastic sandy silty clays containing 55% clay content (PI=41%) – Fig 7.

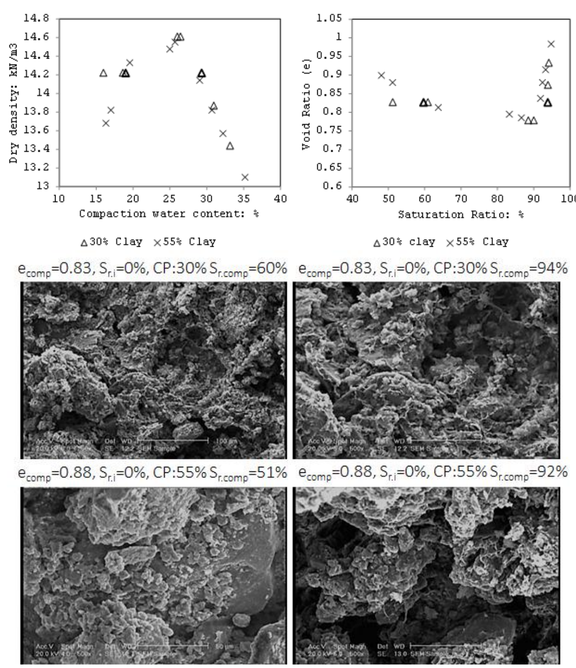

Figure 7. Two dried clayey silt and silty clay soils; pairs viewed at constant void ratio and varied placement water content

For a specimen pair compacted at 60% and 96% saturation ratio to 0.8 void ratio (PI=41%, clay=30%), Assadi and Yasrobi (2010) showed through electron microscopy imaging that wet compaction leaves behind a lesser volume of macro-pores than dry compaction. At the greater 55% clay content, wet compaction was found to results in, higher volumes of macro-pores than those of dry compaction.

2.4 Climate

A new form of the principle of effective stress for unsaturated collapsing mediums was recently introduced in Assadi and Jefferson (2015b) that justifies the increasing void ratio in non-engineered silt fills upon wetting-drying. The slight restoration of soil open structure was also captured on a number of free wetting-drying oedometer tests conducted on clayey silt loams.

3 CALCAREOUS FINES

Dry compression (K_0-condition), as shown in Assadi and Jefferson (2013), to 2100 kPa (equivalent to an energy of about three times the standard static Proctor compaction, 600 kPa), was shown to cause grain breakage (formation of 10-20 µm silt – see Assadi et al. (2014)), loss of micro- and meso-pores (0.001-0.25 µm and 0.25-2 µm), agglomeration and formation of macro-pore spaces (2-20 µm).

Wet compression was shown to cause strong coagulation in sub-30 µm silts, carbonates and clays, and a consequent increase in macro-pore spaces. Tracing the ESEM images before and after wetting, Assadi and Jefferson (2013) also showed re-stored inter-particle carbonate bonds on drying, with a risk of sudden settlement. Cyclic wetting and drying continuously decreases the void ratio.

The findings were consistent with a recent work of Roohnavaz et al. (2011) on natural calcareous clayey loams of Northwest Kazakhstan. They reported a series of tests aimed at mitigation of collapse and prolonged compressibility, and to reuse the site-won soils as earthworks material. Proctor compaction however, reportedly, failed to reduce the air volume from the in-situ extents. The lower-bound void ratio after compaction was found above the in-situ values, while the upper-bound dry density fell below the in-situ values. Although additional passes of compaction at standard energy resulted in 5% air volume at 16% optimum water content, soil swelled on wetting. Additional passes of compaction at a modified energy failed to reduce the air volume beyond 5% and soil showed a remarkable swelling potential.

According to Assadi (2014), inefficient compaction of calcareous soils is partly due to the soil's extremely high dry stiffness, formation of 2-20 µm macro-pores under load (as high as 3-times standard proctor energy), and restoration of carbonate tubular connectors upon wetting-drying.

4 CONCLUSIVE DISCUSSION

4.1 Aging

Soil structure alters with time with a direct impact on its mechanical properties. Age strengthening corresponds with chemical bonding, grain breakage and increased interlocking.

From a geological perspective, prolonged flow of high di-electric Ca^{++}-enriched groundwater through a Na^{+}-enriched soil is evidenced (Jefferson and Assadi, 2013) to form nodular carbonates and hence decrease the collapsibility. In case of thermal weathering, amorphous silica interacts better with kaolinite and sulphates over longer periods of time and in milder climates (Assadi, 2014). The latter can increase the risk of sudden settlements. Similarly, in slightly alkaline environments, carbonate chemically interact with kaolinite, building inter-particle soluble bonds and hence a risk of sudden settlements.

4.2 Placement and service water content

With calcareous loams, compaction at sub-PL placement water content under controlled compactive effort can minimize the air volume at low carbonate contents (or in soils with carbonate contents less than the clay content). Wet compaction, however, fails to fully remove the soil's open structure. This is due to the strong chemical cementation and the tendency of carbonates to migrate with over-saturated bulk fluid and re-precipitate as secondary connector units.

Referring to Lawton et al. (1989), Charles and Watts (2001) concluded that compaction at optimum or slightly wet of optimum water content can fully remove the open porosity and inter-particle chemical bonding system for 'all usual stress levels'; a matter arguably entirely true, as service water content and chemical composition have major controls on the post-compaction response of fills.

Lowering of groundwater may cause settlement due to an increase in the effective stress. It is generally believed (Charles and Watts, 2001) that higher levels of effective stress may lead to a higher chance for soil to collapse. This however was argued within the context of the newly proposed form of the effective stress principle as explained in Section 3. At a constant external net stress, constant micro-scale matric suction and zero hydraulic head gradient, effective stress decreases upon drying. This was reflected in wetting-drying oedometer experimental results, where an increase in the void ratio was recorded during the second and third drying cycles. Loss of void ratio over drying occurred only upon the first drying cycle, over which the contribution of enhanced electric conductivity and hence coagulation of clay fragment was more pronounced that the stress relief - see Assadi and Jefferson (2015b).

Charles and Watts (2001) indicated three major controls on sudden settlements, namely: placement conditions (compaction conditions), water content history and stress history. The manual referred to a laboratory test programme, showing that proctor compaction to 95% of maximum density at slightly dry of optimum water content can fully mitigate the collapsibility in colliery spoil and mudstone fills (i.e. coarse-grain fills), but may result in a maximum of 2% collapse potential in clayey fills. Our recent work has evidenced a swelling potential of 10 to 15% for compacted kaolinite fills at close-to-zero service water content. For silt loams, we measured 0.5 to 1.0% collapse potential when containing up to 30% kaolinite content at a service water content equal to the placement water content. This increased to 3-5% in dried fills (Assadi 2014). Charles and Watts (2001) concluded that there might be a need for a criterion of a placement water content greater than standard Proctor.

4.3 *Apparent versus true cohesion*

Plastic limit is analogous to the critical collapse water content on the dry stress-state surface. Soil at its plastic limit, beyond which capillary forces fail to sustain the open structure, is susceptible to disintegration (collapse).

4.4 *Grain strength*

Charles and Watts (2001) had a cursory glance at the significance of particle strength. Assadi et al. (2014) showed that a clean quartz assemblage with internal crystalline defects (i.e. Quartz from a eutectic graphic granite source and a high-to-low quartz transformation under varied temperatures background) tend to crush over time and under applied stresses to form a final pronounced mode of 10-20μm. Prolonged stressing or short-term high-content stressing increases the population of 10-20μm grains. Finer fragments may either accommodate in macro-pores or flow through the network of pores. Under a steady state flow and in the absence of clays, >10μm grains can potentially drain out of the soil in presence of a favourable drainage condition (clean gravel beds).

4.5 *Placement stress history*

It is conventionally accepted that (Charles and Watts, 2001) where a fill is preloaded to a stress level beyond the design load, stiffness improves and hence less subsidence would be expected.

Wetting/drying disturbs soil's packing and engineering behaviour. Assadi and Jefferson (2013) showed that maximum densification in soils containing non-clayey non-capillary cementing bonds (e.g. salts) can be reached through over-consolidation at a non-zero flooding stress. In other words, pre-loading of a saturated ground does not necessarily results full densification.

Assadi (2014) showed that for loams of low clay contents, an increase in the number of loading-unloading cycles from two to three decreases the stiffness (i.e. increases BBM-κ parameter). This was attributed to the fatigue effect and the continuous breakage of quartz grains. At the high 2100kPa stress level however, stiffness improved by an increase in the number of cycles from two to three. This exception corresponds with the fact that most quartz internal defects mobilize on the first loading cycle to 2100kPa and in the absence of further crushing, interlocking forces improve in proceeding cycles.

5 CONCLUSION

Seasonal deformations in non-engineered fills when made up of site-won clayey silt loams are well known and recently explained, in terms of effective stress in Assadi and Jefferson (2015b). Engineering of site-won loams also cannot always benefit the earthworks in reducing deformation.

Building embankments through dry compaction of clayey silt loams gives rise to both sudden and long-term settlement risk, the former applying also to wet compaction particularly when kaolinite constituent reaches >30% values. Settlement can be as great as 60cm for a 10m high embankment built by dry compaction of loam of 15% kaolinite inclusion. On other note, loams with low clay contents were found to degrade in stiffness with time in transient (e.g. traffic) loading environment. Dry compaction of calcareous loams results in a fractal pattern of grain breakage and hence formation of new macro-pores with a risk of sudden settlements. Any increase in placement water content forms a stiffer structure in calcareous loams and saves the open structure from compaction effort. At low carbonate contents (or in soils with carbonate contents less than the clay content), compaction at water contents below plastic limit could account for the best practice, however this needs to be explored further. Very wet compaction encourages coagulation and development of macro-pores, with some risk of sudden settlement. Field results on similar soil type agreed with lab-scale findings, although several passes of compaction at modified energy were found effective in reducing the air volume to 5%. Water treatment under low external loads can maximize the densification. For non-calcareous loams of <25% kaolinite, optimum compaction was found effective in removing both sudden and long-term settlements, although over dry seasons, sudden subsidence of up to 3-5% was predicted. For mudstone fills, despite the optimum compaction to 95% maximum dry density slightly dry of optimum is generally accepted as a good practice, a 10-15% swelling potential needs to be included in serviceability limit state analysis.

Volumetric response of soil is strongly a function of its micro-structure. Hence, simple speculations on the impact of ground water table and effective stress change on heave/contraction of soil might not always be true. The answer to many unexplained ground movements is in structure-based formulation of effective stress for unsaturated soils, and emerging concepts including clastic soil mechanics. On the latter account, we recently evidenced the continuous breakage of quartz grains under low-but-prolonged loads into 10-20μm grains, with significant implications on soil long-term deformation.

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