Geoderma 209–210 (2013) 226–232

Contents lists available at SciVerse ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

The influence of soil gravel content on compaction behaviour and pre-compression stress

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ARTICLE INFO

Article history:
Received 21 January 2013
Received in revised form 30 May 2013
Accepted 31 May 2013
Available online 21 July 2013

Keywords:
Gravel content
Gravel shape
Precompression stress
Soil compaction
Dry bulk density
Fine earth bulk density

ABSTRACT

Many arable soils have significant horizon-specific gravel content levels. Just how these influence compaction behaviour, and in particular precompression stress as an important criterion of a soil's susceptibility to compaction, has yet to be sufficiently clarified. This article is intended to contribute towards answering this question. Firstly, three different fine earths, from the "Clay", "Silt Loam" and "Sandy Loam" soil texture classes were mixed with staggered proportions (0, 10, 20, 30, 40% by volume) of a quartz gravel (the shape of which was subrounded to rounded, average weighted diameter 6 mm). Soil core samplers were filled with the mixtures at a typical density for a natural site. In the case of the 30% by volume variant only, in addition to the quartz gravel an angular to subangular limestone gravel with the same size graduation was also used. The tests were supplemented by 20 samples from a natural site; the gravel content of these varied between 0.1 and 23.5% by volume. All of the disturbed and natural samples were adjusted to a water content at a matric potential of −6 kPa. Subsequently, an oedometer test was used to apply loads to them in stages (5–550 kPa). Precompression stress was calculated using the resulting stress–bulk density functions.

While fine earth bulk density remained constant, the staggered addition of quartz gravel led to an increase in the whole soil density after packing, and thus also to a vertical shift in overall stress–bulk density functions. However, the stress–density functions of the fine earth do show that the overall compaction of fine earth decreased as gravel content increased. In the case of low gravel content levels of no more than 10% by volume, the increase in precompression stress (log) in the disturbed samples was, on the whole, very low. In the disturbed samples, however, as gravel content increased precompression stress (log) increased exponentially. Contrary to this, a continuous linear increase in precompression stress (log) could be observed with increasing gravel content in the natural samples. The angular to subangular shape of the gravel only resulted in greater precompression stress (log) in the "Silt Loam".

At gravel-rich sites, gravel content influences soil compaction behaviour and precompression stress very strongly. For this reason, it is essential that it be considered when assessing such sites' risk of compaction damage.

1. Introduction

Many soils contain varying horizon-specific amounts of gravel. A data-set by Batjes (1997) based on FAO–UNESCO soil units includes C-class (6–15 vol.%) gravel content levels for phaeozems and yermosols, M-class (16–40 vol.%) gravel content levels for lithosols, regosols and rankers as well as A-class (>41 vol.%) gravel content levels for rendzinas. Re-cultivated soils, for instance following an open-cast tunnel construction (Kaufmann et al., 2009), can also have average gravel content levels. The distribution of gravelly soils varies highly from region to region. In Western Europe, according to Poesen and Lavee (1994), it is mostly Mediterranean areas that are characterised by large amounts of gravelly soils, although gravelly soils can often also be found in Europe's low mountain ranges.

The external shape and the quantity of the gravel in these soils vary considerably. A distinction is made between angular, subangular, subrounded, rounded and well rounded shapes (Mitchell and Soga, 2005). Gravel includes all particles larger than 2 mm. In addition to actual gravel (USDA system: diameter of 2–76 mm), cobbles (USDA system: diameter up to 254 mm) can also be found at arable sites. Only in exceptional cases is arable farming practised on soils with a high proportion of stones larger than 254 mm in diameter. Apart from affecting root penetration behaviour (Babalola and Lal, 1977), infiltration properties (Brakensiek and Rawls, 1994) and the water retention curve (Ingelmo et al., 1994), gravel content in the soil matrix also has an impact on a soil's mechanical properties.

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http://dx.doi.org/10.1016/j.geoderma.2013.05.030

Until now, studies examining the impact of gravel content and its shape on the compaction behaviour of soils have largely only been conducted using Proctor tests, or modified procedures based on these (e.g., Chinkulkijniwat et al., 2010; Donaghe and Torrey, 1994). The purpose of most of these studies was to determine the maximum achievable dry bulk density and water content for optimum compaction of the soil material, for example in the context of construction work. As gravel content increases so does the maximum achievable dry bulk density, while the optimum water content for compaction drops (Chinkulkijniwat et al., 2010).

However in soil science, specifically concerning protecting soil from compaction, it is important to know the maximum mechanical load capacity of a soil at which essential soil functions (e.g., hydraulic and air conductivity) are still adequately preserved. This question applies particularly to arable farming sites where agricultural machinery with a constantly increasing weight is used. Oedometer tests are thus performed in order to map a soil's stress–strain behaviour. In these experiments, the soil sample, which is adjusted to a specific matric potential (e.g., −6 kPa), is subjected in stages to increasing loads, and the resulting settlement accurately measured. Details about how these experiments are performed can be found in Bradford and Gupta (1986). The resulting stress–settlement curves identified in a semi-logarithmic graph, or indeed stress–dry bulk density curves or stress–void ratio curves of pre-compacted soils derived from these, can be used to determine precompression stress. In soil mechanics, this is a direct criterion of a soil's susceptibility to compaction (Arvidsson and Keller, 2004). According to Topp et al. (1997), precompression stress corresponds to the maximum stress that has acted on the soil in the past, if it is determined under the same load conditions. In the topsoil layer, it results from pressure exerted when machinery is driven over the ground, from tillage activity aimed at loosening the soil and from the formation of microstructures caused by drying and shrinkage processes, the effects of frost and biogenic aggregate formation. In the subsoil, precompression stress is also due to the load from overlying soil layers as well as previous coverings of ice.

So far, there have been only very few results on the effect of soil gravel content on precompression stress, and at times these contradict each other. For example, Horn and Fleige (2003) report higher precompression stress as gravel content increases, whereas Kaufmann et al. (2009) describe a negative effect of gravel content in multiple regressions. The aim of this study is, therefore, to investigate the question of just how an increasing gravel content and different gravel shapes affect precompression stress and compaction behaviour in soils of different texture classes.

2. Materials and methods

2.1. Preparation of artificial samples

The experiments were based on artificial soil core samples with three fine earths from different soil texture classes (Table 1). Only by preparing disturbed samples is it possible to exclude naturally occurring variability, particularly that of fine earth bulk density. The soil was extracted in the field using a small shovel. It was then carefully divided using a sieve with an opening size of 20 mm; until the experiments were carried out, the soil was stored in closed buckets and kept cool. Variants with gravel contents (GRs) of 0, 10, 20, 30 and 40% by volume were created for each soil type (8 soil core samplers per variant). According to Holtz and Lowitz (1957, as cited in Donaghe and Torrey, 1994), gravel particle diameter in soil–gravel mixtures should not be larger than 1/5 to 1/6 of the compaction mould diameter. The soil core samplers used in this study (volume 220 cm^3) have a height-to-diameter ratio of 1:3.6 (28 mm high, 101 mm in diameter). For this reason, a very fine quartz gravel (particle density 2.64 g/cm^3) with an average weighted diameter of 6 mm was used (particle size distribution 65 g kg^{-1} at a size of 8–10 mm, 714 g kg^{-1} at a size of 5–8 mm and 221 g kg^{-1} at a size of 2–5 mm). In this way the size ratio of the gravel – not only to the diameter but also to the height of the soil core samplers – is kept largely uniform. The shape of the gravel was subrounded to rounded (Fig. 1).

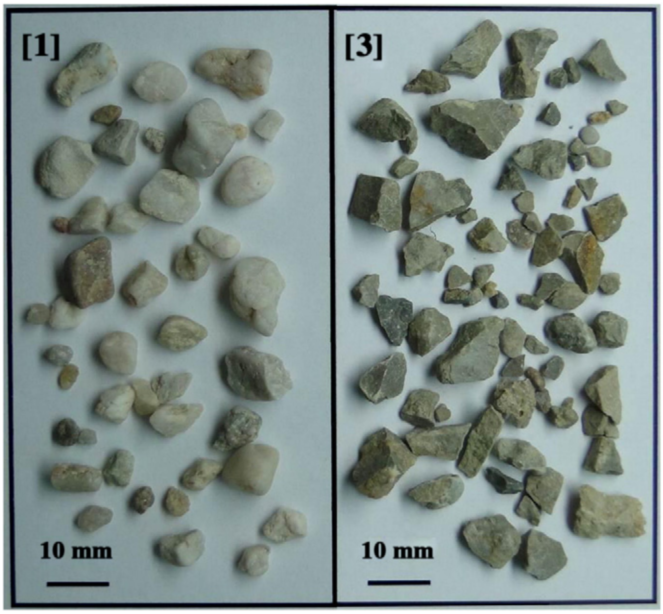

Fig. 1. Shape and size distribution of the gravel for the tests with disturbed samples: [1] subrounded/rounded shapes, [3] angular/subangular shapes; each rectangle containing 10 g of gravel.

Additionally, in the variant with 30% gravel by volume, all three fine earth soil core samples were created with limestone gravel (particle density 2.72 g/cm^3), which has an angular to subangular form and the same size graduation as with the quartz gravel (Fig. 1). It was not possible to use the limestone gravel for all the gravel content variants, because not enough limestone gravel with the same properties was available.

Table 1
Description of the test soils for the disturbed and naturally extracted samples, USDA classification system (Gee and Bauder, 1986), mean values, and ranges of measured values.

Texture class[a]	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	Organic carbon content (g kg^{-1})	$CaCO_3$ content (g kg^{-1})
Disturbed samples					
Clay	460	370	170	28	3
Silt Loam	130	780	90	12	0
Sandy Loam	100	310	590	11	0
Natural samples					
Silt Loam	220[b] (150–280)[c]	600[b] (410–740)[c]	180[b] (70–350)[c]	16[b] (11–21)[c]	93[b] (3–210)[c]

[a] USDA classification system (Gee and Bauder, 1986).
[b] Mean values.
[c] Ranges of measured values.