The assessment of the effects of structure on the compression behaviour of a young alluvial silty soil

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ABSTRACT

A comprehensive series of tests were performed to investigate the effects of the in-situ structure and sample preparation technique on the compression behaviour of a shallow young alluvial silty soil. Two different size distributions were investigated by testing intact, compacted and slurry samples in the oedometer. The compression of slurry samples created at different initial water contents gives a unique intrinsic compression line for one of the two gradings, which is used as a reference to analyse the effects of structure of the compacted and intact specimens. Compacted samples were prepared by means of static and dynamic compaction in one or more layers and also with vertical holes simulating those created by plant roots in the natural samples. The results show that a unique normal compression line is defined regardless of the number of layers and number of holes, with a clear effect of the structure when compared with the slurries. Significant effects of the in-situ structure of the intact samples were observed even at high stress levels. An important finding is the non-uniqueness of the compression line for the second grading. The compression lines remain parallel to each other even at high stress levels for the case of the slurry whereas a unique line is found for the compacted samples. This result shows that contrary to what is often stated in the literature, sample preparation technique can create very robust initial structures resulting in a mode of behaviour that has been called “transitional”. The research also emphasises how the quantification of natural structure is critically dependent on the means of preparing intrinsic samples.

Keywords: Laboratory tests, structure of young silty soils, compression behaviour, quantification of natural structure, transitional behaviour.

INTRODUCTION

Large areas around the world are covered by young alluvial materials. The development and expansion of urban areas on these shallow heterogeneous materials requires a rigorous characterization of their geotechnical properties for reliable support to engineers in designing new structures. The effects of the naturally occurring in-situ structure on their mechanical behaviour are of paramount importance.

The term "structure" in soils is defined as a combination of particle arrangement "fabric" and inter-particle forces "bonding" (Mitchell, 1976). Bonding refers to all the inter-particle forces that are not of a purely frictional nature (Cotecchia & Chandler, 1997). In large parts of the scientific literature it is usual to find terms such as "destructuration" or "removal of structure" to address the processes that occur in soils when they are strained during testing. This terminology was introduced in soil's modelling to account for the effects of structure evolution that take place in natural soils when compared with the structure of reconstituted soils. This could lead to a misunderstanding that a soil has "more" structure than that of the same soil at a reconstituted state which is often said that to be "structureless". In reality all soils have structure and that structure evolves to a different one during straining. A large part of the geotechnical community uses this terminology to explain the real physical behaviour of soils and this causes confusion. In this research an effort has been made to avoid this terminology. It is also common to find in the literature the term "remoulded" as being equivalent to that of reconstituted, but they represent different structures as a consequence of the sample preparation procedure followed in each case. The term "remoulded soil" defines a state where the initial natural structure is broken down at the current water content to produce a more homogeneous structure. Different structures are created depending on the energy applied during the remoulding process, which might influence the soil behaviour, e.g. in the case of natural materials with complex structure (e.g. Dumbleton, 1967; Fearon & Coop, 2000; Madhusudhan & Baudet, 2014). Laboratory remoulded compacted samples are also used as a reference material for predicting the behaviour of silty soils compacted in-situ at the same density and water content. This comparison has been proved to be unreliable due to the different structures created during compaction (e.g. Jommi & Sciotti, 2003).

In fine-grained material, the effects of structure of natural intact samples on the soil behaviour have been evaluated routinely by comparing the intact soil response with that in its reconstituted state (e.g. Burland, 1990; Leroueil & Vaughan, 1990; Cotecchia & Chandler, 1997; 2000). In this comparison it is assumed that there exists a unique normal compression line (NCL) and a unique critical state line (CSL) for the reconstituted soil state from which the intrinsic parameters can be obtained. The unique NCL was defined by Burland (1990) as the intrinsic compression line (ICL). In his Rankine lecture he concluded that if the soil is reconstituted at a water content of between w_l and $1.5w_l$, the ICL is well defined for pressures equal or greater than 100kPa. The key point of this comparison is whether the NCL and CSL are unique or not for a given reconstituted soil state.

Non-uniqueness of the NCL and CSL have been found in a large range of materials with very different gradings and mineralogy for reconstituted and compacted samples (e.g. Martins et al., 2001; Nocilla et al., 2006; Altuhafi & Coop, 2011; Shipton & Coop, 2012, 2015; Xiao et al., 2016; Xu & Coop, 2017). The term “transitional” has been used to refer to this mode of behaviour in reconstituted/remoulded materials where the initial structure of the soil dominates its compression and shearing response even at very high stresses and large strains. Transitional soils represent a clear example of the effect of robustness of the initial structure, in particular fabric, during compression and shearing, for which the term “intrinsic” properties defined by the reconstituted samples lacks any practical meaning. Many authors concluded that the sample preparation method alone does not produce different structures that result in a non-convergence of the compression paths and therefore they pointed out that the sample preparation method has no effect on transitional soil behaviour (e.g. Martins et al., 2001; Nocilla et al., 2006; Ferreira & Bica, 2006; Shipton & Coop, 2015). This latter conclusion is investigated in this research as will be discussed below.

Soils of similar gradings and mineralogy retrieved from close locations to those tested in this research displayed transitional behaviour (Nocilla et al., 2006; Nocilla & Coop, 2008). A priori, this finding makes them a potential transitional soil which could invalidate the possibility of evaluating its natural in-situ structure in the traditional way. The materials tested in this research consist of shallow young alluvial silty soils from the plains of the Bormida River at Castellazzo, Italy. These materials are referred to as the Bormida River silts (BRS). Similar data for such young natural alluvial sediments are sparse in the literature and so the effects of structure on such young sediments are not well established. Coop & Cotecchia (1995) carried out a series of triaxial tests on intact samples of a relatively young alluvial silty clay, the Sibari clay, and concluded that the non-convergence of the compression lines of the intact soil towards the ICL was attributed to a very stable structure even at high stresses. They also noted that the offset of the intact compression lines with respect to that of the ICL increased with the degree of layering in the samples. Rampello & Callisto (1998) found similar behaviour in compression in their young alluvial clayey silt sediments from Pisa. Although it is very difficult to determine the different mechanical roles of each component of the structure of a soil, that is, fabric and bonding, Coop et al. (1995) suggested that fabric provides the stable component of the structure whereas bonding represents that part which evolves and degrades with strain.

The aim of this research was to give answers to the following questions: (a) Is it possible to find a unique intrinsic NCL for the BRS? (b) How does the sample preparation technique influence the mechanical behaviour of the BRS? (c) How does the in-situ structure influence the behaviour of the BRS? In doing so, a specific experimental programme was defined based on a series of oedometer tests carried out on intact, compacted and slurry samples.

MATERIALS TESTED AND EXPERIMENTAL PROCEDURES

Materials

The material tested consists of recently deposited alluvial silty soils obtained from the foundation level of the Bormida River embankments at Castellazzo Bormida, Italy. Two types of samples were retrieved; an intact block sample (B) taken from a depth of 1.4m below ground level and a remoulded excavated sample (E) from nearby. Six samples of the intact material (B) from different parts of the block plus two samples of the remoulded one were subjected to sieving and sedimentation tests following the BS standards. The material contained in the block (B) was very homogeneous in terms of size distribution, giving an almost unique grading curve for all the samples tested. This homogeneity was also found in the remoulded (E) specimens. Figure 1 shows the average particle size distributions of each material. According to the index properties shown in Table 1, the soils are classified as an inorganic low plasticity clayey silt (B) and an inorganic low plasticity sandy silt (E). A series of X-ray diffraction tests were performed on whole samples and on samples containing only the particles smaller than 4μm. The mineralogy of the silt and sand fractions is mostly quartzitic in nature and the clay fraction is illite and smectite. Visual inspection of the clayey silt intact samples at a macro-structure level showed that organic matter could be found randomly in the form of small plant roots as shown in Fig. 2. In some cases vertical holes from plant roots were found that crossed the entire sample. This in-situ structure was reproduced in the laboratory by creating vertical holes in the compacted samples as will be explained below. The average organic matter content was only 1.1% and so its effects on the mechanical behaviour of the clayey silt (B) are likely to be insignificant (e.g. Booth & Dahl, 1986). Negligible quantities of organic matter were measured in the sandy silt (E) soil.

Sample preparation technique

Three types of oedometer samples were used to investigate the influence of the structure and sample preparation method on the mechanical behaviour of the BRS soils.

- Intact samples

The block sample of the clayey silt (B) was divided into small pieces that were large enough to obtain a sample for oedometer test. The position of each piece within the block was identified to check the homogeneity of the material contained in the block since for alluvial soils rapid changes in depositional environment can make them highly heterogeneous (e.g. Coop & Cotecchia, 1997). Intact specimens were trimmed from each piece of material. The oedometer ring, with a sharp edge, was placed on the top of the soil piece and a small pressure was applied on the ring pushing it against the sample at the same time as the trimming was carried out, trying to advance the ring and cutting at the same time to avoid disturbance. Once the sample was inside the ring, the top and bottom were trimmed carefully, paying special attention to have a very flat surface on both sides. During the trimming process all the remaining material was collected and later used for preparing slurry and remoulded samples. The intact samples are identified as B_I in Table 2.

- Slurry samples

Slurry specimens were prepared by adding distilled water to the trimmings from the intact samples of the clayey silt (B) and remoulded samples of the sandy silt (E) and mixing thoroughly to achieve a uniform consistency. Following Burland (1990), the soil trimmings were not oven-dried before mixing. Different specimens were prepared by adding different amounts of water from the liquid limit to 1.5 times the liquid limit. Special attention was paid to the possible segregation of the sandy silt (E) during the mixing process. The slurry was placed inside the oedometer ring avoiding any air entrapment. The slurry samples tested in this research are identified in Table 2 as B_S and E_S for the block and remoulded excavated materials.

- Compacted samples

In the case of the clayey silt (B), the trimmings from the intact specimens were remoulded by hand using a spatula, maintaining the initial water content of the intact samples. The same procedure was followed for the sandy silt (E). The samples were compacted inside the oedometer ring either statically or dynamically. The following types of samples were prepared; dynamically compacted (DC) samples in three layers and statically compacted (SC) samples. For the case of the SC specimens, different samples were created such as samples compacted in one layer, samples compacted in one layer with vertical drilled holes, samples compacted in one layer with vertical pushed holes and samples compacted in several layers but with very different values of void ratio for each layer. These latter samples were called “layered samples”. For the case of the statically compacted (SC) specimens, compaction was carried out using a specifically designed equipment and shown in Fig. 3(a). Each sample was compacted inside the ring by applying a constant rate of displacement to the base pedestal. A static flat ended rod connected to a load cell was used to create the reaction to apply the static pressure to the sample and the maximum static load was recorded. For the layered samples, the surface between each layer was scarified before continuing with the next to ensure a good continuity in the whole sample. All the samples were allowed to rest for 5 minutes before placing the oedometer ring in the cell in order to permit them to rebound. Both the bottom and top of the samples were trimmed flat before starting the test.

Holes and plant roots were often found during the trimming of the intact specimens of the clayey silt (B) as described above and shown in Fig. 2. They were mainly vertical holes and in some cases they extended from the top to the bottom of the sample. In order to reproduce these vertical holes, drilled or pushed holes were artificially created. The difference between the two procedures is that the drilled holes were created by extracting material from the sample and the pushed ones by displacing the material inside the sample. A temporary top platen was used to avoid any sample volume change during the drilling and pushing procedures. The number and location of the holes inside the sample was randomly distributed. Figure 3(b) shows an oedometer specimen after the holes had been drilled.

Micro-structure studies were carried by using SEM images taken from different specimens of the clayey silt (B). Figure 4 shows the initial micro-structure of the intact, slurry and compacted samples before testing. The micro-structure of the intact sample is characterised by a fabric where clear aggregates of particles can be identified, which are bonded by bridges of particles of smaller sizes. This aggregation of soils particles resulted in an open structure with large inter-aggregate pores. In the case of the slurry sample, a more homogeneous structure can be distinguished, so it appears that the aggregates of particles found in the intact specimen were destroyed during the reconstitution process to create the slurry. The disturbance of the intact structure towards a more homogeneous one seems to be less efficient in the case of the compacted specimen. In this case the intact material was remoulded at its natural water content by hand-mixing with a spatula. The structure of the remoulded sample exhibits a similar aggregated structure to that of the intact samples, with a bi-modal pore size distribution characterized by large inter-aggregate pores and smaller intra-aggregate pores.

Experimental procedures

Oedometer tests were carried out by applying incremental loading using oedometer rings with a 50mm diameter and 20mm height. In some cases a 38mm ring was used to reach higher stress levels in the range of 12 to 13MPa compared with the 8 to 9MPa for the 50mm ring. For both the intact and compacted specimens an initial load that ranged from 2 to 52kPa was applied and thereafter the cell was filled with water, varying the initial load in order to study its effect on the swelling properties. After filling the cell with water the samples were left for 24 hours before applying the next load. During this time, the swelling behaviour was monitored. It was common to see that the volume change due to swelling stabilised very quickly, although, as mentioned above, the samples were all subsequently left for 24 hours to allow them to saturate.

In the case of the slurry samples, after the preparation of the specimen, the soil was placed directly into the oedometer ring paying special attention so as not to trap any air. After applying the first load the water bath was flooded. Some of the oedometer cells were modified to be able to flush water through the sample, at a pressure of 10kPa. This procedure was applied to some intact and compacted specimens to compare the results with the conventional procedure where the water bath was only flooded to saturate the sample, but no differences were observed. Special attention was paid when dismantling the cell at the end of the test, as the water in the cell could be sucked into the sample after the last load was released. To avoid this, all the water that surrounded the sample and porous stones was dried before dismantling to minimise the error in the final water content.

The calculation of the initial void ratio (e_o) of a sample is most important when analysing the results of an oedometer test. Accurate e_o are essential when investigating the possible effects of structure to ensure the correct location of the compression data. Equations (1) to (4) were derived to calculate the initial void ratio of the sample at the start of the oedometer test and before first load was applied, where Gs is the specific gravity, w_i and w_f are the initial and final water contents, ε_v is the volumetric deformation measured during the whole test, ρ_{di} is the initial dry density and ρ_{bi} is the initial bulk density. They are related to independent parameters that can be measured (Rocchi & Coop, 2014). These independent measurements are the initial water content, the initial wet mass, the initial height, the initial diameter, the final water content and the final dry mass. Equations (2) and (3) were only applied for the slurries, where the samples are assumed to be fully saturated at the start of the test. When the sample was saturated from the start, as in the case of slurry, all four equations were used and an average value was obtained. For the intact and compacted samples, as they were not initially saturated, only equations (1) and (4) were applied.

$$e_o = \frac{G_s \times \rho_w}{\rho_{di}} - 1 \qquad (1)$$

$$e_o = G_s \times w_i \qquad (2)$$

$$e_o = \frac{\rho_s - \rho_{bi}}{\rho_{bi} - \rho_w} \qquad (3)$$

$$e_o = \frac{w_f \times G_s + \varepsilon_v}{1 - \varepsilon_v} \qquad (4)$$

EXPERIMENTAL RESULTS

Compression behaviour of the clayey silt (B)

- Slurry samples

A series of oedometer tests were performed on slurry specimens prepared at different initial water contents from around 1 to 1.5 times the liquid limit, using the trimmings. Table 2 shows the details of each test. The objective was to investigate the influence of the initial water content of the slurry samples on the uniqueness of the normal compression line. The compression behaviour of the slurry samples is shown in Fig. 5. Although there is some small scatter in the compression lines, a clear tendency towards to a unique normal compression line can be seen, regardless of the initial water content and therefore the initial structure of the specimens created during the reconstitution process. The small scatter could be associated with the accuracy of measuring the initial void ratio of the samples. An estimated unique normal compression line is drawn in Fig. 5. Following the definition given by Burland (1990), this is the one-dimensional intrinsic compression line (1D-ICL*) of the clayey silt (B), whose slope is C^{*}_{c}=0.25. It is important to point out that the estimated straight 1D-ICL* deviates from that of the curved shape of the ICL proposed by Burland. During swelling, the behaviour is essentially the same in all the samples with an average swelling index of C^{*}_{s}=0.05 which gives a ratio of C^{*}_{s}/C^{*}_{c}=0.2. The asterisk denotes the intrinsic properties of the material which are inherent to the soil and independent of the initial structure (Burland, 1990). These intrinsic properties will be used as a reference for assessing the initial structure of the intact and compacted samples. Burland proposed an equation to correlate C^{*}_{c} with the void ratio at the liquid limit (e_{LL}), for soils above the A line on the plasticity chart. The plasticity characteristics of the clayey silt plots slightly below and very close to the A line on the plasticity chart and, although the equation proposed by Burland was derived for clays, a good approximation is obtained with a value of C^{*}_{c}=0.21.

- Compacted samples

Table 2 shows the details of the tests conducted on the compacted samples. The layered samples were compacted to have a different initial void ratio for each layer to create a heterogeneous structure (Table 2). These ranges were to simulate the slightly heterogeneous void ratios within the natural samples, although more extreme variations were used with e_o from 0.6 to 1.0. It is important to point out that the definition of a layered soil given here is not the same as the one that can be usually found in the literature, where a layered sample consists of soils with different gradings, e.g. layers of clay and sand such as varved clays. The compression lines of the compacted samples shown in Fig. 6(a) converge onto a unique NCL regardless of the compaction method used and the number of soil layers created during compaction. This is surprising given the large differences in the e_o of each layer, which varied from 0.6 to 1.0 (Table 2). Therefore, although the initial structure of each sample is expected to be different, the deformation induced during compression was enough to ensure that any differences of structure were not sufficient to affect the macro-behaviour of the soil significantly. This result is important in terms of the robustness of the unique NCL regardless of the heterogeneities created at a meso-structure and micro-structure levels during the sample preparation process. Moreover, this does not mean that the structure of each sample became the same at the end of the test.

As described above, some of the intact samples tested in the oedometer had vertical holes inside. In order to simulate the possible effect of these holes on the compression behaviour, a few oedometer tests were conducted on statically compacted samples with vertically drilled and pushed holes (Table 2) (Fig. 3b). The vertical holes were randomly distributed across the specimens. As described before, the main difference between the drilled and pushed holes is that a drilled hole was created by extracting material from the sample and a pushed one by displacing the material inside the sample, possibly creating a more dense structure around the holes. A plant root might tend to displace rather than remove soil. Figure 6(b) shows the compression behaviour for all the samples with holes together with that of a compacted specimen without holes, B_SC3, which is included for comparison. A clear unique compression line is identified showing that the vertical holes had no significant effect on the compression response of the clayey silt at higher stress levels. It is also shown in Fig. 6(b) that the number of holes created for the same procedure has no effect either, as can be observed when comparing the compression lines for samples B_SC_H1 (3 drilled holes) and B_SC_H3 (17 drilled holes). The comparison of the compression lines of the compacted sample without holes, B_SC3, with the compacted specimens with holes, B_SC_H4 and B_SC_H5, shows that for a similar average initial void ratio there is no significant effect of the holes on the soil behaviour. Consequently, it appears that the root holes, by themselves, found in some natural samples are most unlikely to have any significant impact on their behaviour.

Figure 6(c) shows the compression lines for all the compacted samples tested. The unloading behaviour has not been included for clarity. As can be observed, the specimens with the highest e values display a stiff response at the start of the compression stages followed by an abrupt change in their compressibility after yield. The change in the stiffness after yield resembles the behaviour of bonded sensitive clays but here the effect of bonding is expected to be negligible as a consequence of the remoulding process. As the initial density of the specimens increases, this apparent effect of the initial structure is less evident. For stresses beyond yield, all the curves converge towards a unique NCL regardless of the initial structure.

Traditionally, for reconstituted fine-grained materials, the yield stress (σ'_y) observed during one-dimensional compression has been associated with the maximum stress level that the soil has been subjected to during its history, called the preconsolidation pressure (σ'_p). In the case of uncemented coarse-grained materials the yield stress occurs at the onset of major particle breakage. During the preparation process of the statically compacted samples it was possible to measure the maximum vertical stress applied to some of the specimens and identified as σ_v:kPa^a in Table 2. The yield stress for each test was estimated using the Onitsuka (1995) method, the values being compared with the maximum compaction stresses in Table 2. It can be seen that there is no correlation between the maximum vertical stress applied during compaction and the yield stress, meaning that the soil did not “remember” its maximum stress that it had been subjected to. In fact, the maximum vertical stress applied during compaction can not be compared with the yield stress because during compaction the samples were not saturated and therefore the vertical effective stress applied is not known, as it is expected.

An attempt to correlate the initial void ratio of each sample after soaking with the measured yield stress is shown in Fig. 7. Although there is some of scatter in the results, a relatively good correlation is found with an $R^2=0.98$. The slope of the linear regression in the $e:\log\sigma'_y$ plane is 0.34 which is equivalent to the average value of the slope of the estimated unique NCL of the compacted samples plotted in Fig. 6(c). It could be said that the comparison of both slopes is another way of trying to check the uniqueness of the NCL and also shows that the yield stress of the compacted samples is simply correlated with the initial density or void ratio.

- Intact samples

One of the main objectives of this research was to investigate the effect on the compression behaviour of the in-situ structure of the recently deposited alluvial clayey silt (B). Table 2 summarises the details of each oedometer test performed on the intact samples. Although the intrinsic index properties of the material contained in the block sample were the same for each of the samples tested, its in-situ structure seems to be slightly more heterogeneous as revealed by the differences of the initial void ratios, which range from 0.713 to 0.808 with an average value of 0.751 (Table 2). This variability in the initial void ratio might be associated with a combination of different factors such as a possible heterogeneous initial structure inside the block, the error introduced in calculating e_o, and the structural damage induced to the samples during the preparation process. These latter two factors are unlikely to be the main source of the variability in e_o due to the very small error obtained in the calculation of the initial void ratio and the very careful trimming of the samples. During the trimming of the specimens, the granulometry inside specimen was found to be homogeneous with no layering of materials with different gradings, supporting the idea that the variability of the initial void ratio is not associated with the granulometry and is most likely to be a possible layered structure. Another important factor that influences the range in the initial void ratio is the presence of the root holes.

The compression behaviour of the intact samples is shown in Fig. 8. The initial parts of the compression lines run almost parallel to each other, with a very stiff response similar to the behaviour of a coarse-grained material, where the initial structure controls the compression response, in particular the fabric. Consequently, in the range of engineering stress levels (<1MPa) a non-unique compression behaviour can be identified. After yield, no abrupt changes are observed in the slope of the NCLs, with the samples displaying a slow tendency to converge towards to a unique NCL at high stresses, exhibiting a clear effect of the robust initial natural fabric.

The intact samples were initially partially saturated with a degree of saturation that varied from 62 to 80%. A suction of 90kPa was measured in two of samples using the suction probe technique (Ridley & Burland, 1999). In order to saturate the samples, the oedometer cell was flooded with water after applying the first load. A different procedure was followed with specimen B_I8, where it was subjected to a circulation of water with 10kPa pressure difference across the sample for one week after applying the first load and flooding the oedometer cell. A comparison with sample B_I4 shows that the compression behaviour is the same regardless of the saturation method applied.

The initial swelling response of the intact samples was also measured by monitoring the axial displacement of the specimens after the first load was applied and the oedometer cell was flooded with water. Figure 9 shows the relationship between oedometric tangent modulus (M_{oed}) and vertical effective stress (σ'_v) of some of the intact samples. It can be observed that all the M_{oed}-σ'_v curves converge onto a single line at stresses higher than the estimated yield values. The effect of the initial swelling due to flooding is also seen. The initial in-situ structure of the intact samples was weakened during swelling with a consequent reduction of the initial stiffness as the swelling increased. This shows that part of the initial structure was disturbed during swelling but the effect disappears quickly even at stresses of about 20kPa.

The yield stresses for the intact samples were also estimated, the values of which range from 230 to 400kPa, as shown in Table 2. All the yield stresses are much higher than the estimated in-situ vertical effective stress of the block sample σ'_v=75kPa. The yield stress ratio (YSR), defined as the ratio between the yield stress and the in-situ vertical effective stress, varies from 3 to 5.3. It is very unlikely that the in-situ sample had a maximum past stress level of the same value as the measured yield stress and therefore it is believed that the measured yield stresses can not be correlated with the pre-consolidation pressure. One factor that could have had an important effect on the high values of the yield stress could have been desiccation processes due to the shallow depth (1.4m) from where the block was retrieved. In fact, the liquidity index (I_L) values of intact specimens are negative with an average value of I_L=-0.6. The yield stresses of the intact samples are plotted in Fig. 7 together with the values measured for the compacted samples. A slightly larger scatter in the results can be seen that could be a consequence of variability in the in-situ structure, but the data lie on the same trend and could indicate that the effect of the bonding on the intact samples is small.

Compression behaviour of the sandy silt (E)

- Slurry samples

Oedometer tests were carried out on slurry samples of the sandy silt (E). The slurries were created at different initial water contents, which varied from 1 to 1.5 times the liquid limit. The initial void ratio for each water content is shown in Table 2. The compression behaviour is shown in Fig. 10(a) together with previous results obtained by Radici (2006). Apart from tests E_S1 and E_S3, the compression lines do not show any tendency to converge onto a unique NCL despite being tested to stress levels in the range of 8 to 12MPa. The position of each compression line depends on the initial void ratio meaning that the initial structure could not be disturbed enough to reach a unique NCL during compression, even at high stresses, and therefore showing a clear transitional behaviour. In the case of a relatively small difference in the initial void ratio (e.g. E_S1 & E_S3), an apparent convergence could be found but this does not mean that for larger differences in initial void ratios there will be the same convergence, as shown with the other specimens. Consequently, it is important to create samples with larger differences in the initial void ratio in order to check the possible transitional behaviour of a soil, but paying attention to avoid any segregation of the soil at too high water contents.

Figure 11 shows a comparison of the compression response of the slurry samples of the two BRS materials. Only a few compression tests for the clayey silt (B) have been included for clarity. It can be clearly seen that while the compression lines of the clayey silt (B) converge onto a unique 1D-ICL* regardless of the initial structure, the response of the sandy silt (E) displays a transitional behaviour. The slope of the clayey silt compression lines is slightly higher that those of the sandy silt, possible due to its higher plasticity.

- Compacted samples

The details of each test conducted on compacted samples of the sandy silt (E) are shown in Table 2. Figure 10(b) shows the compression response together with the results of two more tests carried out by Radici (2006). It can be observed that, regardless of the compaction method, all the compression curves converge onto a unique NCL, with a compression index of C_c=0.29. This result contrasts with the behaviour of the slurry samples, where it is not possible to find a unique NCL during compression for the same range of applied stresses. Consequently, the sample preparation technique must have produced different initial structures which resulted in a non-convergence of the compression curves and therefore determined whether there is transitional behaviour of the Bormida sandy silt (E).

Influence of the initial structure on the compression behaviour of the BRS soils

- Clayey silt (B)

In order to evaluate the effects of the in-situ structure on the one-dimensional compression behaviour, the intact soil response is compared with its reconstituted state. In the case of the clayey silt (B), a unique intrinsic compression line 1D-ICL* is found for the slurry specimens and it has been taken as the reference line for comparison with the behaviour of the intact samples. The compression lines of the intact samples and the 1D-ICL* are normalized by volume using the void index (I_v) (Burland, 1990) and are plotted in Fig. 12(a), together with the sedimentary compression line (SCL) defined by Burland. The void index is calculated by using equations (5) and (6).

$$I_v = \frac{e - e^*_{100}}{C^*_c} \qquad (5)$$

$$C^*_c = e^*_{100} - e^*_{1000} \qquad (6)$$

where C^*_c is the intrinsic compression index determined on the 1D-ICL* and e^*_{100} and e^*_{1000} are the intrinsic void ratios corresponding to σ'v=100kPa and σ'v=1000kPa respectively.

The normalized compression lines of the intact specimens cross the 1D-ICL* and yielded at different stress levels in between the 1D-ICL* and the SCL. The ratio of the yield stress (σ'_y) to the equivalent effective stress on the intrinsic compression line (σ'_{ve}) was defined by Cotecchia & Chandler (2000) as the stress sensitivity ($S_\sigma=\sigma'_y/\sigma^*_{ve}$). For the clayey silt (B), the stress sensitivity varies from 1.2 to 2.5 with the lowest and highest values corresponding to the densest and loosest samples respectively. The post-yield behaviour shows a slow convergence towards the 1D-ICL*, displaying a robust effect of the initial structure during one-dimensional compression. Burland et al. (1996) suggested that in cases where the yielding stress is located between the 1D-ICL* and the SCL in a $\log\sigma'_v:I_v$ plane, the main difference in the compression behaviour between reconstituted and intact samples is due to different fabrics, with a small influence of bonding. It is believed that this is the case of the intact specimens of the Bormida clayey silt (B).

The normalised compression response of the compacted specimens is shown in Fig. 12(b). The compression lines also cross the estimated 1D-ICL* showing an effect of the initial structure created during compaction. This effect is more important as the initial density decreases. In fact, the samples with higher initial void ratios reach the SCL with stress sensitivity values of around 5, displaying a post-yield convergence towards the 1D-ICL*. At high stress levels the compression lines plot only slightly above the 1D-ICL*. The observed effect of the initial structure of the remoulded compacted samples when compared with the slurry behaviour proves that they should not be used as a reference for the analysis of the effects of the initial structure of the natural intact samples. In fact, the intact and compacted effects of structure are similar and that could lead to the conclusion that there is “no” structure effects at a meso-level if the compacted behaviour were used as a reference. In addition, as in the case of the intact samples, fabric must be the main part of the structure controlling the soil’s behaviour since there can be no bonding. This result emphasises how the quantification of the natural structure is critically dependent on the means of preparing the reference samples.

- sandy silt (BRS-E)

In the case of the Bormida sandy silt (E), only slurry and compacted samples were tested with no intact specimens available. As shown in Fig. 13 for the slurry samples it is found that a different NCL is obtained for each initial water content, showing a clear transitional behaviour. The slope of each NCL defined at high stresses is essentially the same. This lack of uniqueness of the NCL would make any comparison between natural intact samples and slurry samples to determine the effects of structure impossible, and the concept of intrinsic compression line as a reference framework can not be used for this more coarse-grained material. On the other hand, a unique NCL is identified for the compacted samples, that has a very similar slope to the compression lines of the slurry samples. Consequently, for the Bormida sandy silt (E), the sample preparation technique has an important effect on the presence of transitional behaviour in one-dimensional compression.

CONCLUSIONS

The one-dimensional compression behaviour of young alluvial soils, the Bormida silty soils (BRS) has been investigated. Two different soil gradings were tested; the Bormida clayey silt (B) classified as ML and the sandy silt (E) classified as CL-ML. The main important features of their behaviour are summarised in the following paragraphs:

- A unique normal compression line is found for the slurry samples of the clayey silt (B) regardless of the initial water content. This 1D-ICL* has been used as a reference for analysing the effect of the initial structure of the compacted and the intact specimens.
- The normalized compression lines of the compacted samples of the clayey silt (B) are located to the right of the 1D-ICL* and below the SCL, showing the effect of the initial structure created during compaction. The specimens with the highest initial void ratios reached the SCL, exhibiting a post-yield convergence towards the 1D-ICL*. In the case of the densest samples, the effect of the initial structure was less pronounced. At high stress levels, and although the initial structure of each sample is expected to be different, the deformation induced during compression was enough to

ensure that any differences of structure were not sufficient to affect the meso-scale behaviour of the soil significantly as they tended to converge onto the unique 1D-ICL*. The NCL at high stress levels is very robust, regardless of the compaction method, the number and heterogeneity of soil layers created during compaction and the presence of holes. This does not mean that the structure of each sample became the same for the range of stress applied.

- The effect of the in-situ structure of the intact block material is clear as the normalized compression curves cross the 1D-ICL* and yield at different stress levels in between the 1D-ICL* and the SCL. The stress sensitivity varies from 1.2 to 2.5 with the lowest and highest values corresponding to the densest and loosest samples respectively. The post-yield behaviour shows a slow convergence towards the 1D-ICL*, displaying a robust effect of the initial structure during one-dimensional compression and at high stress levels the stress sensitivity is still higher than unity. The absence of a clear and abrupt change in the slope of the compression lines after yield could be associated to there being only a small effect of the initial bonding on the soil behaviour. It appears that the in-situ fabric of the Bormida clayey silt has the major effect on the compression behaviour.
- The intact and compacted effects of structure are similar and that could lead to the conclusion that there are “no” structure effects at a meso-scale if the compacted behaviour were used as a reference. This justifies that the remoulded/compacted behaviour can not be used as a reference for assessing the effect of structure of intact samples.
- The compression lines of the slurry specimens of the sandy silt (E) do not show any sign of convergence towards a unique NCL for the range of stresses applied. In fact, the lines run parallel to each other and the locations appear to depend on the initial

fabric of each sample. This behaviour means that the soil “remembers” its initial fabric during compression even at large stresses displaying a clear transitional behaviour. This lack of uniqueness of the NCL would make impossible any analysis of the effect structure using the slurry behaviour as a reference and shows the lack of meaning of the term “intrinsic” behaviour as a reference framework. A unique NCL could be identified for the remoulded compacted specimens regardless the compaction method and the initial fabric. The slope of the unique NCL defined by the compacted specimens is the same as those of the slurries. This result shows that contrary to what is often stated in the literature, sample preparation technique can affect whether a transitional mode of behaviour is seen or not.

- Fabric seems to be the most import part of the structure in controlling the behaviour of the young alluvial silts from the Bormida River. Similar behaviour has been seen in other young alluvial materials such as the Pisa clayey silt (e.g. Rampello & Callisto, 1998)
- The results emphasise how the quantification of the natural structure is critically dependent on the means of preparing the reference samples.

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Table 1. Index properties

Soil	Clay-size: %	Silt: %	Sand: %	LL	PI	USCS	A	OM: %	CaCO$_3$: %
Intact block (B)	22	60	18	35.2	10.3	ML	0.47	1.1	10.4
Remoulded (E)	13	50	37	25.3	4.2	CL-ML	0.33	-	12

Table 2. Summary of the oedometer tests carried out on samples of the clayey silt (B) and sandy silt (E)

test	Preparation method	Sample diameter (mm)	Initial void ratio e_0	Yield stress σ'_y: kPa	σ_v: kPa[a]	Comments
B_S1	Slurry	50	1.050	-	-	
B_S2	Slurry	50	1.105	-	-	
B_S3	Slurry	38	0.993	-	-	
B_S4	Slurry	38	1.077	-	-	
B_S5	Slurry	38	1.274	-	-	
B_DC1	DC_W	38	0.590	840	-	
B_DC2	DC_W	50	0.826	130	-	
B_SC3	SC_W	50	1.132	20	86.6	1 layer
B_SC4	SC_W	50	0.849	70	407.5	1 layer
B_SC5	SC_W	50	0.790	160	-	1 layer
B_SC_L1	SC_W	50	0.828	170	-	2 layers; $e_1 \cong 0.6$, $e_2 \cong 1$
B_SC_L2	SC_W	50	0.853	120	-	3 layers; $e_1 \cong 0.6$, $e_2 \cong 0.8$, $e_3 \cong 1$
B_SC_H1	SC_W	50	0.867	145	-	3 drilled holes
B_SC_H2	SC_W	50	0.828	160	-	3 pushed holes
B_SC_H3	SC_W	50	0.878	120	407.5	17 drilled holes
B_SC_H4	SC_W	50	1.102	30	204	10 drilled holes
B_SC_H5	SC_W	50	1.140	24	86.6	14 pushed holes
B_I1	Intact	50	0.808	300	-	
B_I2	Intact	50	0.765	300	-	
B_I4	Intact	50	0.713	345	-	
B_I5	Intact	50	0.748	230	-	

B_I6	Intact	50	0.778	365	-	
B_I7	Intact	50	0.721	300	-	
B_I8	Intact	38	0.723	400	-	
E_S1	Slurry	50	0.807	-	-	
E_S2	Slurry	38	1.031	-	-	
E_S3	Slurry	38	0.703	-	-	
E_DC1	DC_W	50	0.635	900	-	
E_DC2	DC_A	50	0.793	250	-	

Note: B clayey silt; E sandy silt; S slurry; I intact; DC dynamic compaction; SC static compaction; DC_W dynamic wet compaction; SC_W static wet compaction; DC_A dynamic air-dry compaction; [a] Maximum vertical stress applied during static compaction

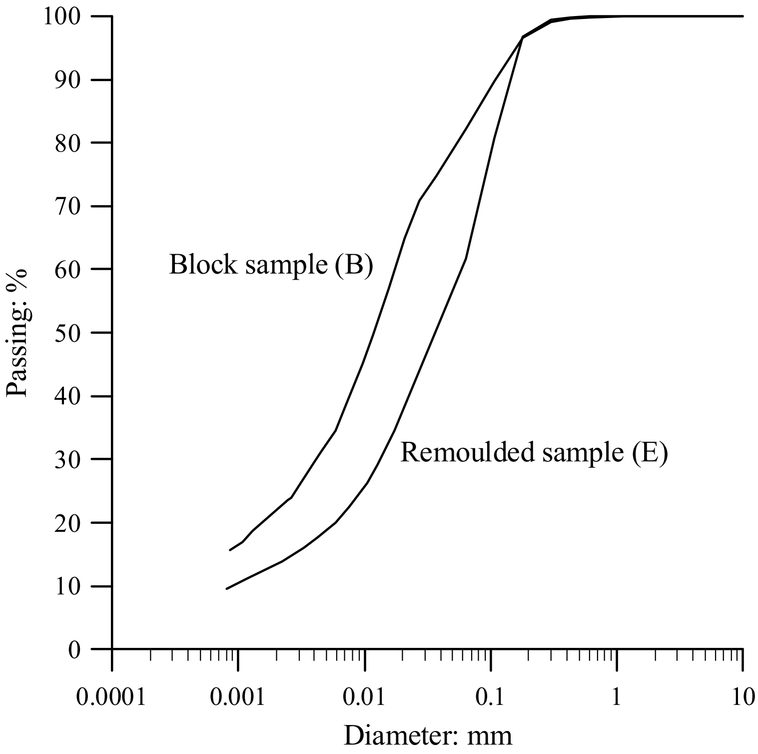


Fig. 1. Particle size distributions of the Bormida River silts (BRS)

Fig. 2. Plant root in an intact sample of the clayey silt (B)

(a)

(b)

Fig. 3. (a) Equipment used for static compaction and (b) oedometer compacted sample with drilled holes in a specimen of the clayey silt (B)

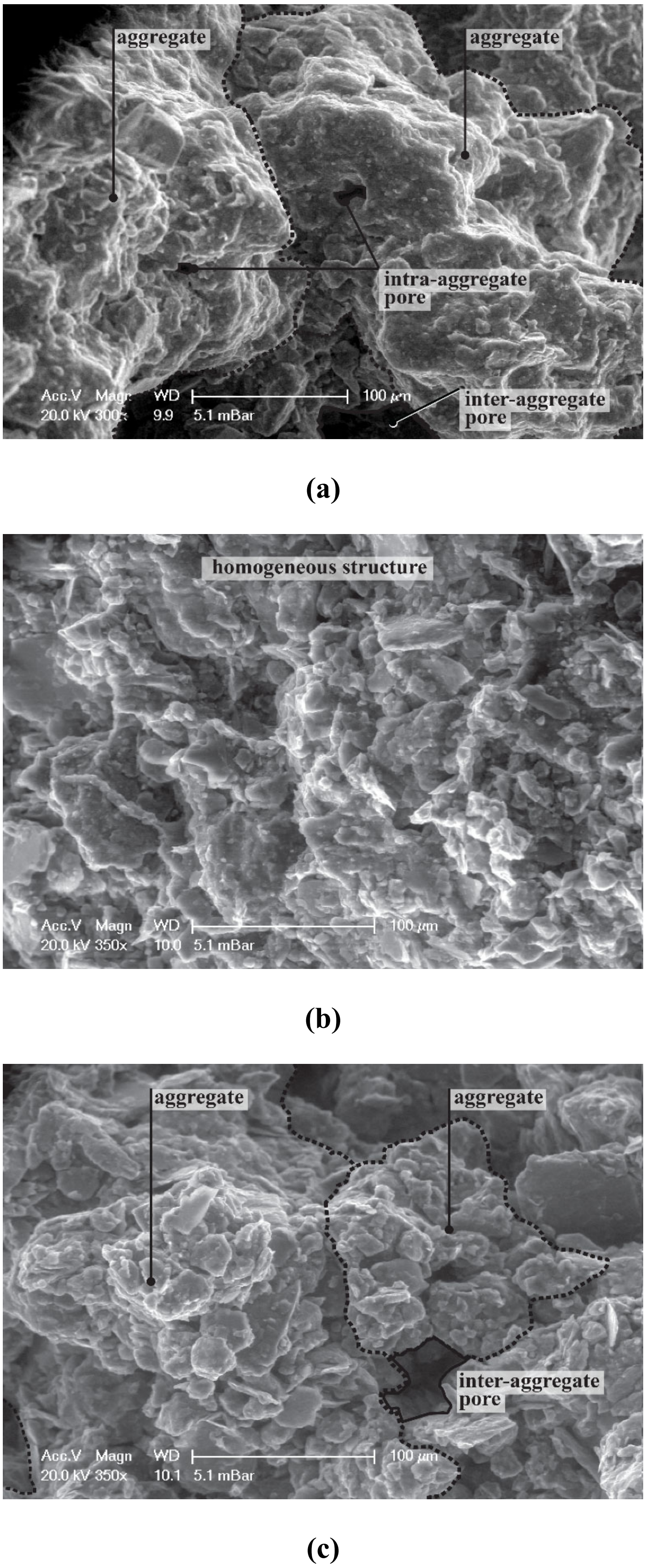


Fig. 4. Scanning electron microscopy images of: (a) intact; (b) slurry; and (c) compacted samples of the clayey silt (B)

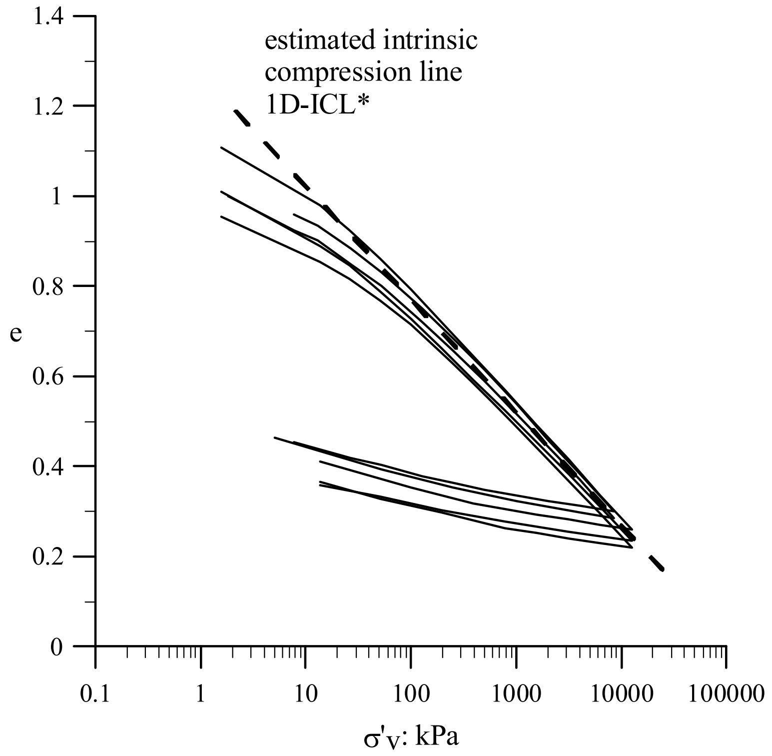
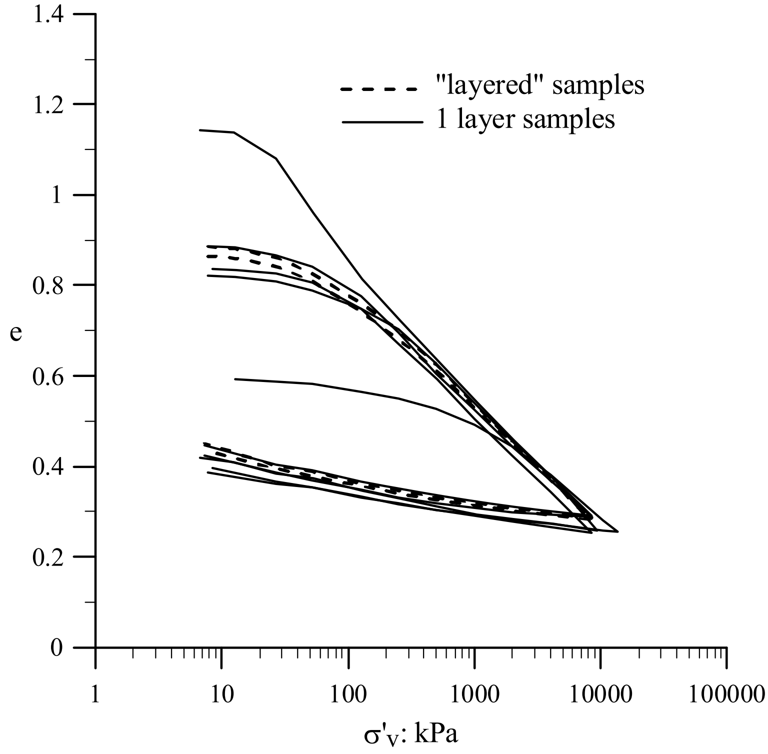
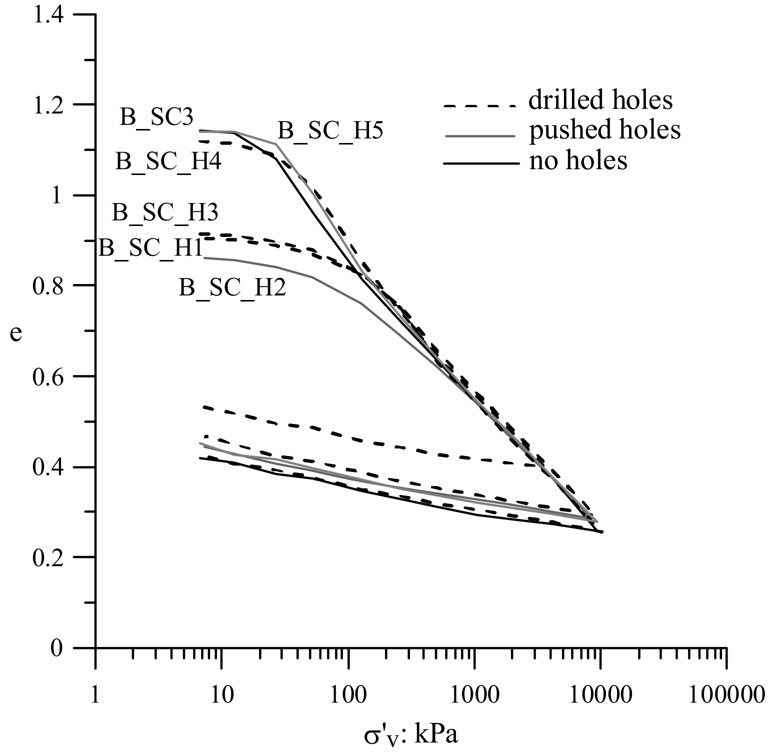


Fig. 5. Oedometer compression lines of the slurry samples of the clayey silt (B)



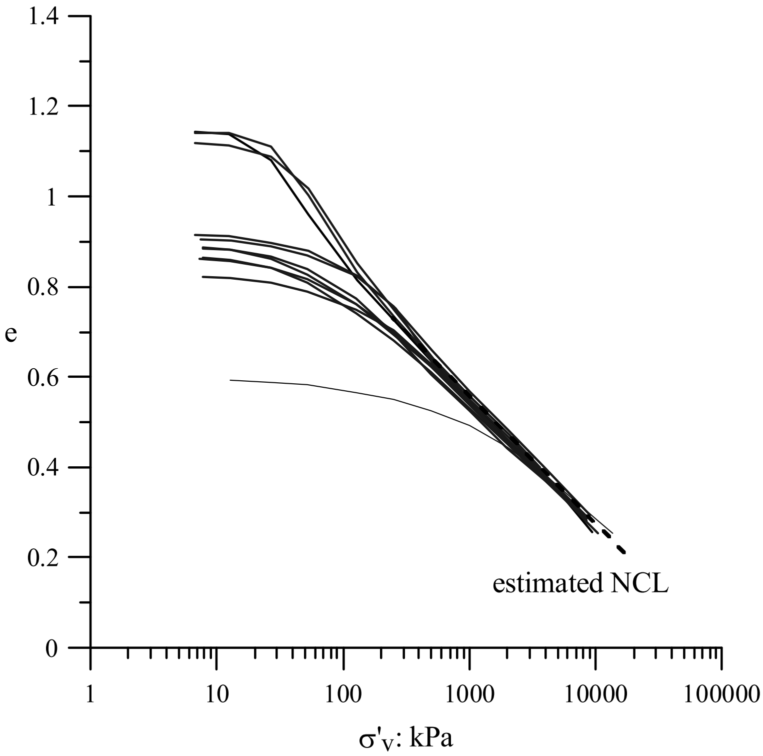
"layered" samples
1 layer samples
e
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
100
1000
10000
100000
σ'V: kPa

(a)



drilled holes
pushed holes
no holes
B_SC3
B_SC_H5
B_SC_H4
B_SC_H3
B_SC_H1
B_SC_H2
e
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
100
1000
10000
100000
σ'V: kPa

(b)



(c)

Fig. 6. Oedometer compression lines of the compacted samples of the clayey silt (B): (a) layered; (b) holes and (c) all samples

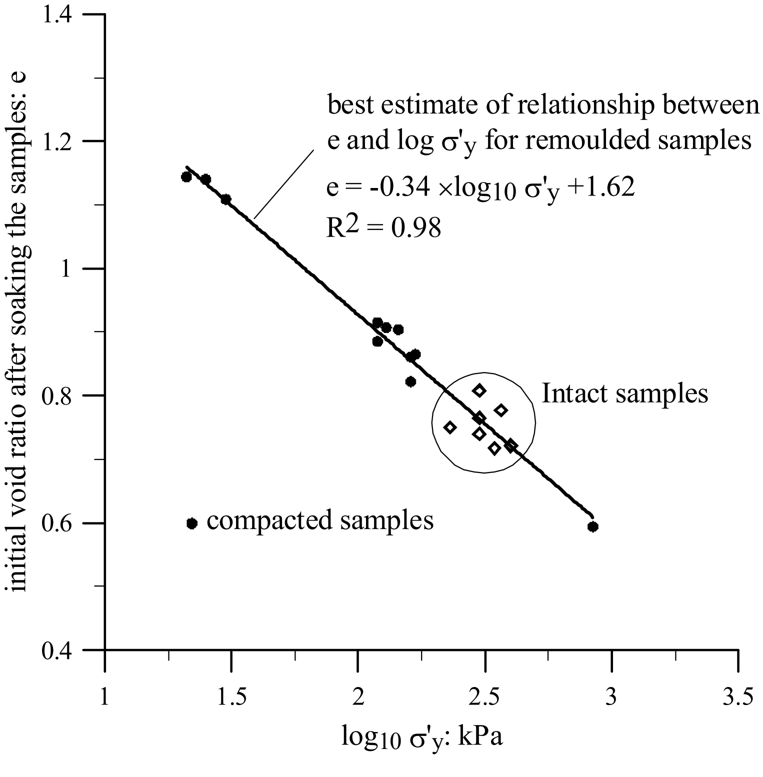


Fig. 7. Correlation between initial void ratio after soaking and yield stress for the compacted and intact samples of the clayey silt (B)

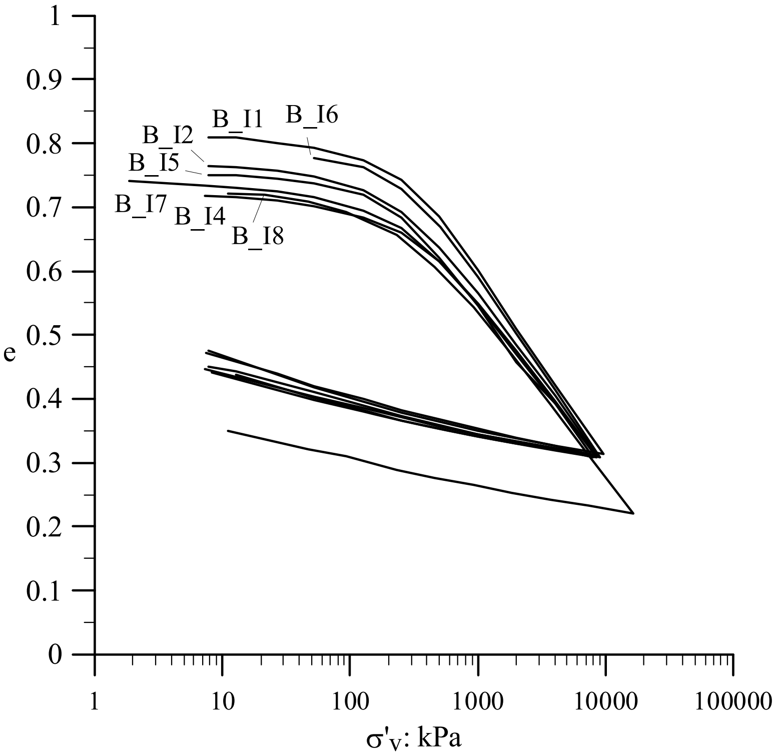


Fig. 8. Oedometer compression lines of the intact samples of the clayey silt (B)

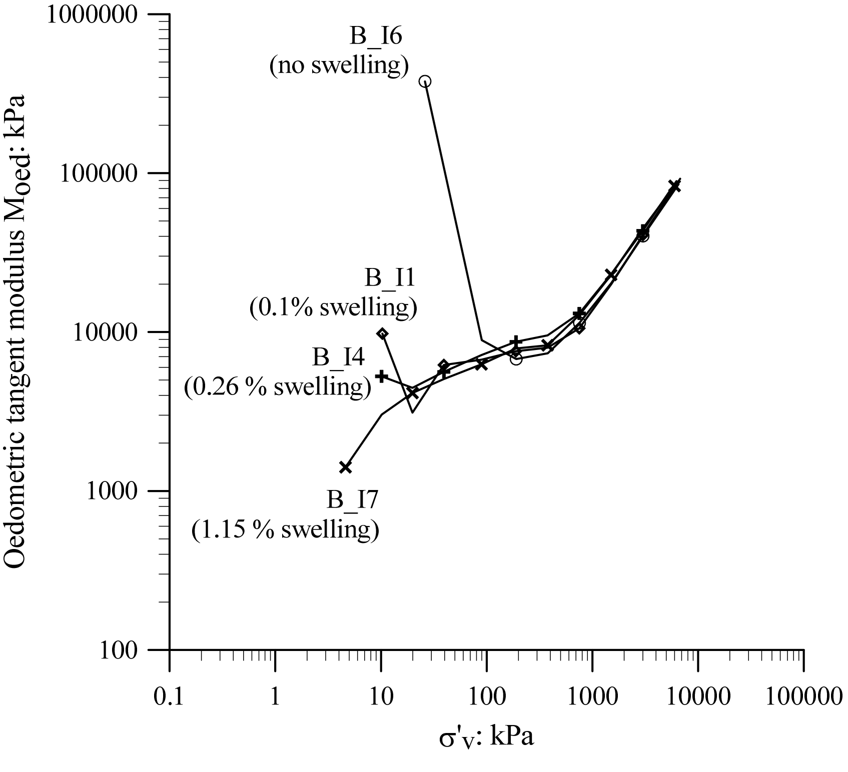
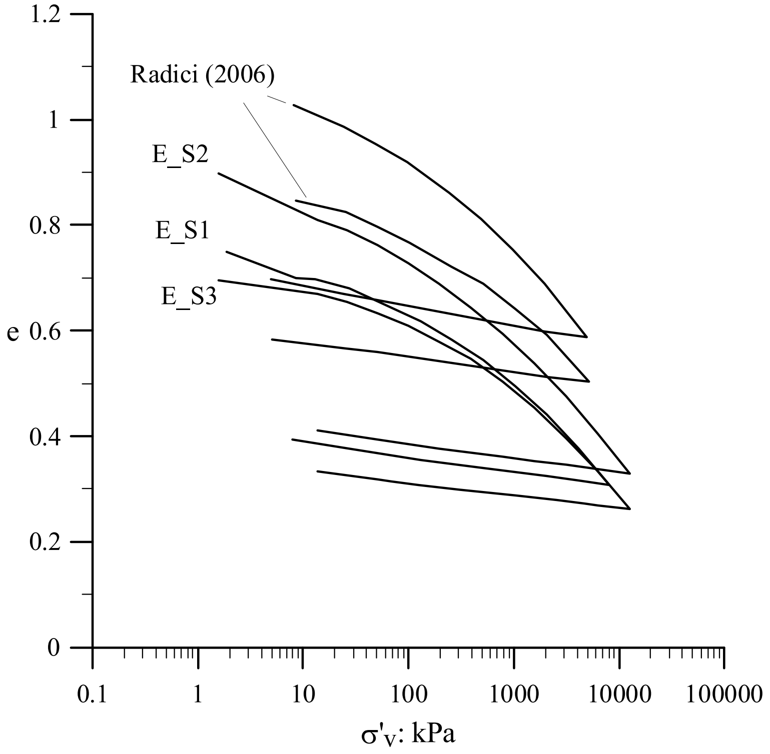
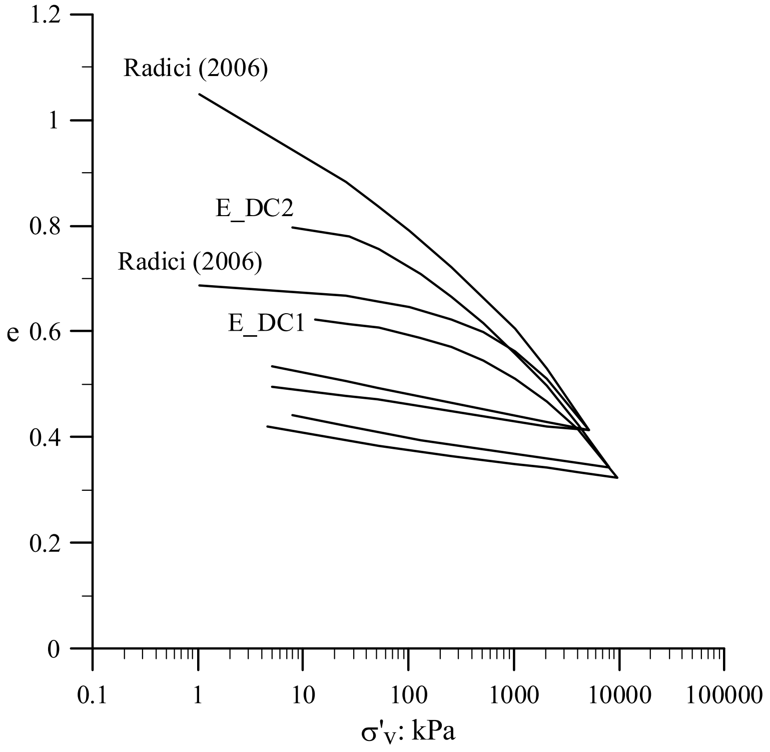


Fig. 9. Oedometer tangent moduli (M_{oed}) of the intact samples of clayey silt (B). Effect of initial swelling on the compression behaviour



(a)



(b)

Fig. 10. Oedometer compression lines of: (a) the slurry and (b) compacted samples of the sandy silt (E)

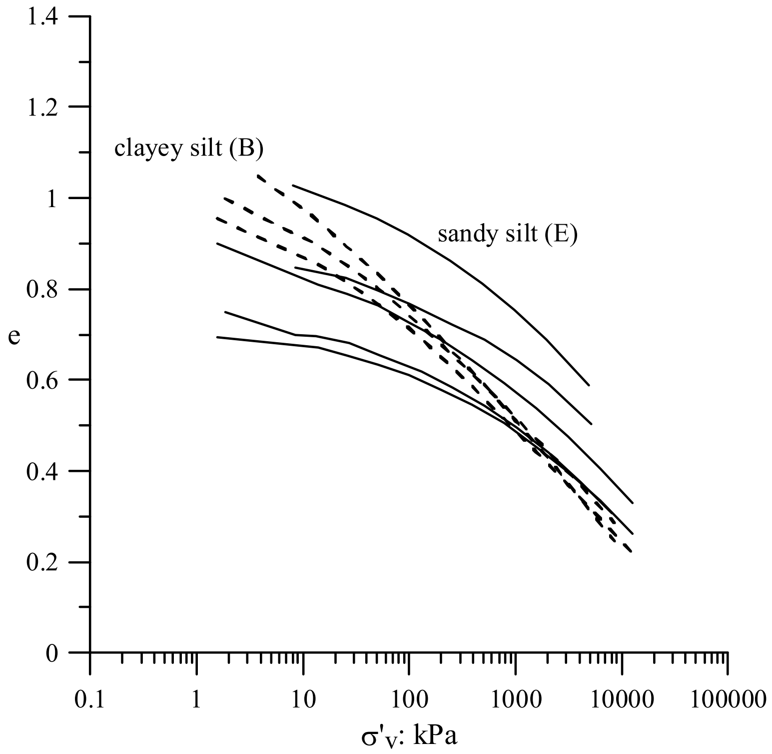
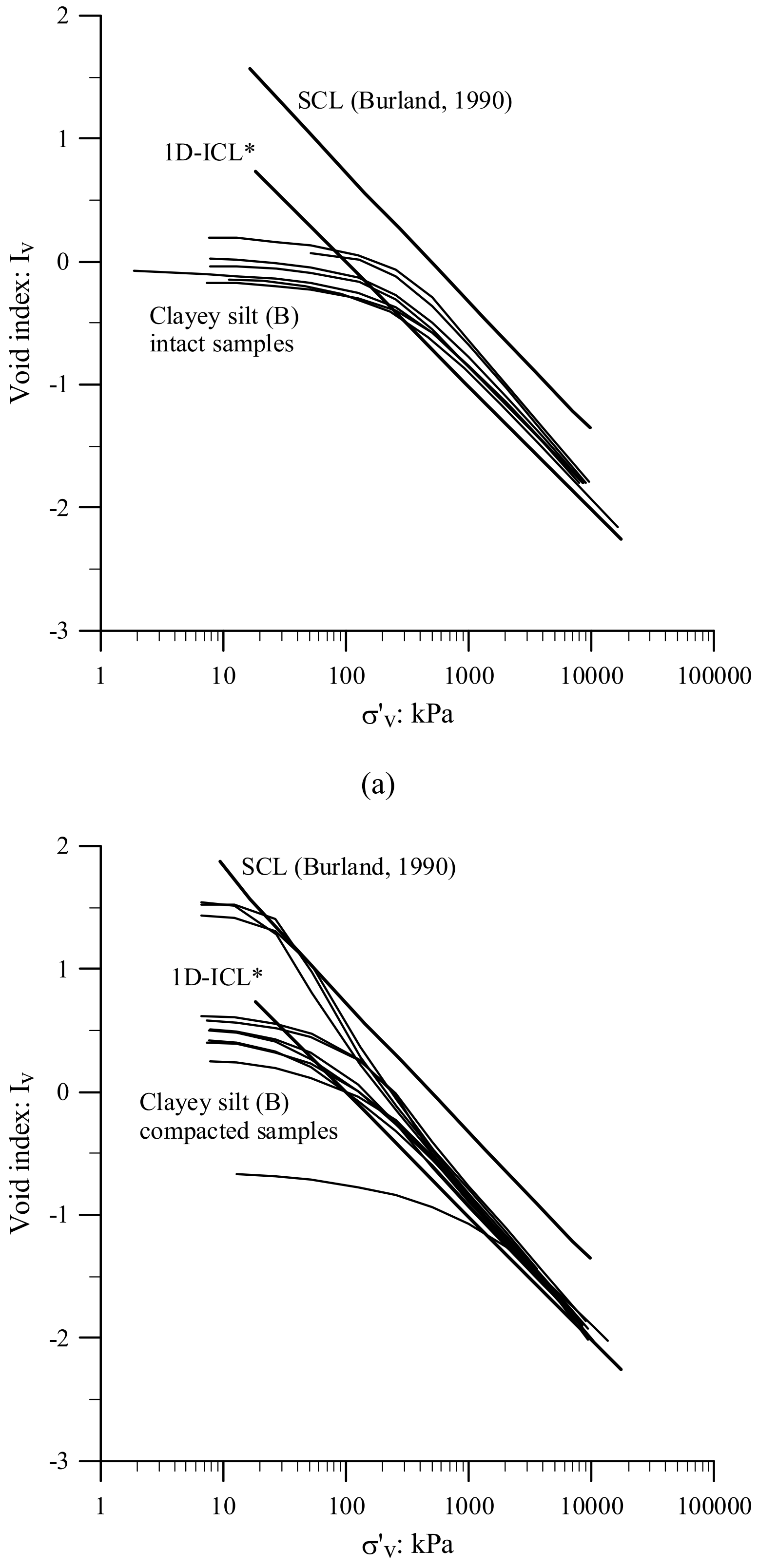


Fig. 11. Comparison of the oedometer compression lines of the slurry samples of the clayey silt (B) and sandy silt (E)



(b)

Fig. 12. Comparison between the normalized compression lines, the measured 1D-ICL* and the SCL of the clayey silt (B): (a) intact samples and (b) compacted samples

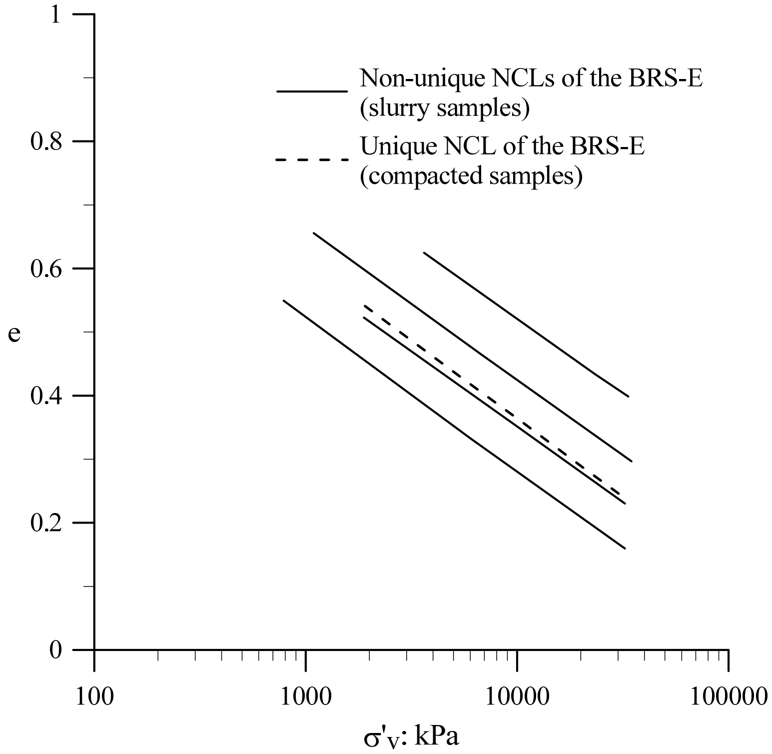


Fig. 13. Effect of the sample preparation method on the uniqueness of the normal compression lines of the sandy silt (E)