The behaviour of sub-soils from the Po river embankments: an example of transitional behaviour in natural soils

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Summary

A series of triaxial and oedometer tests has been analysed on highly heterogeneous alluvial sediments from the flood plain of the River Po in Italy. It is shown that the framework applicable to behaviour of the soils may be correlated with the grading and that as the fines content reduces the mechanics change from a clay type of behaviour that follows the key assumptions of Critical State Soil Mechanics to a transitional mode in which many of these assumptions break down. This transitional behaviour has only previously been seen for a variety of reconstituted soils, including some taken from the same site, and even if the data are imperfect, they provide the first evidence of transitional behaviour in soils with their natural geological fabric.

Introduction

In recent years the behaviour of soils of intermediate grading has received increasing attention [e.g. Thevanayagam, Mohan, 2000], often demonstrating, for example, how basic properties change with some measurement of the grading or nature of the soil particles [e.g. Cola, Simonini, 2002]. Some progress has also been made by using granular void ratio in which the fines content is counted as part of the void space rather than the solid phase. The justification for this is that in a mixed graded soil with a relatively low fines content, the fines are inactive and simply occupy void space without contributing to the transmission of stress, which is concentrated in strong force chains running through the sand fraction. By this means it has been possible to define critical state lines in the v: lnp' plane (where v = specific volume; p' = mean normal effective stress) that are unique and independent of the initial grading, although Ni *et al.* [2006] found it necessary to modify the definition of granular void ratio to account for the plasticity of the fines.

Most of this work on soils of intermediate grading has assumed that the basic concepts of Critical State Soil Mechanics are applicable, i.e. there is a unique Critical State Line (CSL) in the v:lnp' and q:p' planes (where q is the deviatoric stress), a unique isotropic Normal Compression Line (NCL) in the v:lnp' plane and in general a unique State Boundary Surface (SBS) in the three dimensional space q:p':v. However, it has been found that for some soils this is not the case. Martins *et al.* [2002] found that for reconstituted samples of a gap graded residual soil no unique one-dimensional NCL could be defined in oedometer tests, the compression paths for different initial densities tending to remain parallel even to high stress levels. For the same soil Ferreira and Bica [2006] found that for reconstituted samples created with two different initial specific volumes, there were two distinct but unique CSLs in the v:lnp' plane. This mode of behaviour that was in disagreement with the basic assumptions of Critical State Soil Mechanics is termed "transitional" behaviour since it was believed to be a transitional mode between the critical state type of behaviour seen for clays and that for sands.

Martins *et al.* [2002] and Shipton *et al.* [2006] have shown that this transitional mode of behaviour can be seen even for simple gap graded mixes of quartz or carbonate sands with either kaolin or a crushed quartz silt, and that it was therefore a function of the grading rather than the complex mineralogy of the residual soil. Nocilla *et al.* [2006] then extended the work to demonstrate that transitional behaviour could also be seen for well graded silty soils and that since it was not restricted to gap-graded soils it might be much more widespread that had previously been suspected. Nocilla *et al.* tested reconstituted samples of soils from the flood plain of the River Po at Viadana in Italy, controlling the grading by sedimentation techniques so that samples of different clay contents were created. For the soils with high clay contents, samples reconstituted at different initial specific volumes converged towards a unique NCL in oedometer tests (Fig.1a) and a unique CSL could be found in triaxial tests. How-

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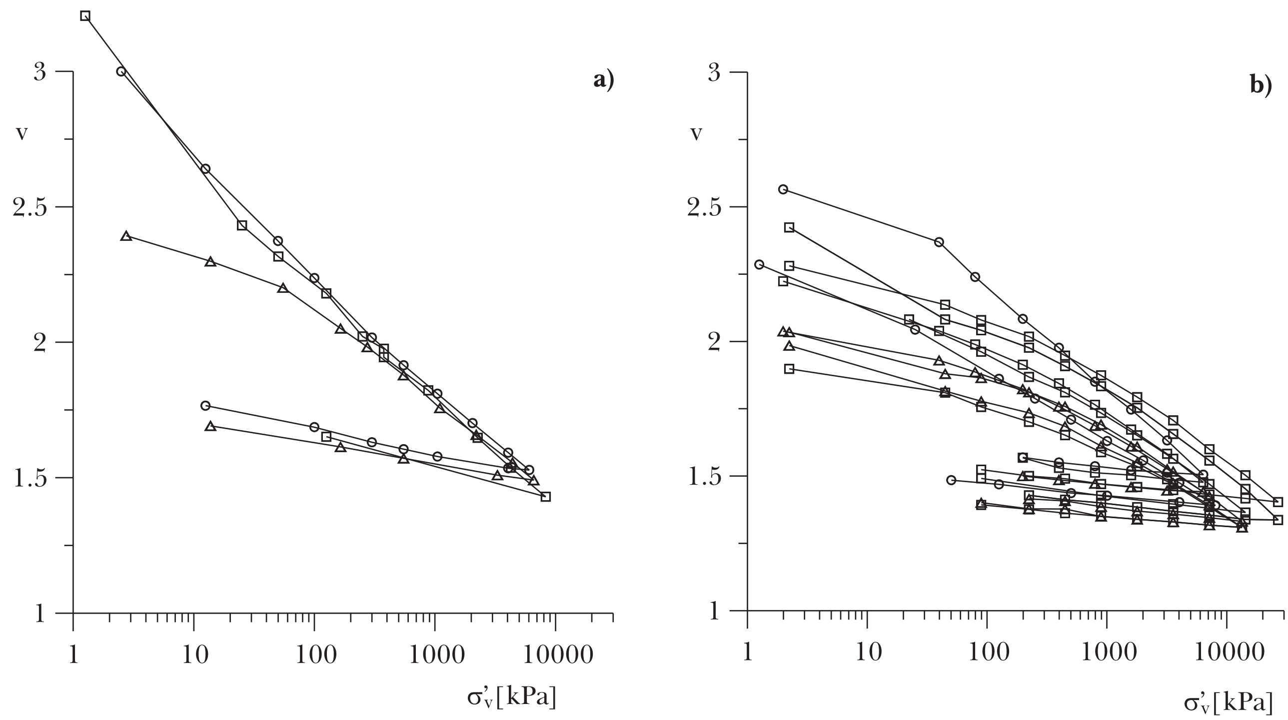

Fig. 1 – Oedometric compression test data for reconstituted samples of Po River embankment silts (a) 45% clay content (b) 8% clay content [after NOCILLA *et al.*, 2006].

Fig. 1 – Dati ottenuti da prove di compressione edometrica per campioni ricostituiti di limo degli argini del fiume Po (a) 45% contenuto di argilla (b) 8% contenuto di argilla [da NOCILLA et al., *2006].*

ever, for the soils with a low clay content a pattern of approximately parallel compression paths, typical of a transitional soil was seen (Fig.1b). Triaxial tests showed that in the v:lnp' plane the isotropic compression paths and critical states were also dependent on the initial specific volume.

As observed by NOCILLA *et al.* [2006], transitional soils, like sands, have an initial specific volume in situ that is determined by the nature of the soil, particularly its grading, and by the density at which it was deposited. Clays are typically deposited at such high specific volumes that they reach their NCL at a few centimetres burial depth [SKEMPTON, 1970], so that even when a sedimentation structure is developed, the yield stress in a laboratory compression test may still be associated with the past maximum applied stress [COTECCHIA and CHANDLER, 2000]. The initial specific volume of a clay in situ is then strongly related to the stress history. In contrast, sands only reach a yield stress in compression when the particles break [COOP and LEE, 1993; PESTANA and WHITTLE, 1995; MCDOWELL and BOLTON, 1998], which for most sands does not occur within the range of typical in-situ stresses encountered in civil engineering environments. In this case, a yield stress seen in a laboratory compression test on a natural sand sample would not be expected to correlate with any past maximum stress experienced [e.g. VENTOURAS and COOP, 2008].

For the 40% clay content samples in figure 1a, the samples follow a NCL almost from the lowest stresses applied, while for the transitional behaviour seen for the 8% clay content soil each sample shows a gradual yield at a few hundred kPa, which, as for sands, is not associated with any past stress, since in this case the samples are reconstituted. However, in contrast to sands, the yield is less clear, and the compression paths are initially much steeper than for sands, so that the paths tend to approach the limiting specific volume of unity faster than any convergence between them, as illustrated schematically in figure 2. This yielding behaviour of the 8% clay content soil is also not associated with any significant particle breakage for the Viadana soils [NOCILLA *et al.*, 2006] although SHIPTON *et al.* [2006] found that particle breakage does occur in some transitional soils.

The present paper describes an analysis of tests on intact samples taken from the same site at Viadana, to determine whether transitional behaviour could be seen in the natural soils as well as the reconstituted. For their residual soil, FERREIRA and BICA [2006] had found that while the reconstituted samples had a clear transitional mode of behaviour,

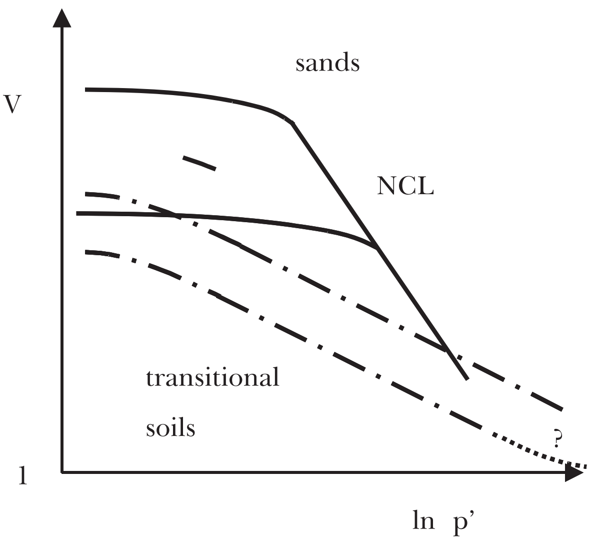

Fig. 2 – Schematic illustration of the compression of sands and "transitional" soils [after Nocilla *et al.*, 2006].
Fig. 2 – Rappresentazione schematica del comportamento a compressione per le sabbie e per i terreni di transizione [da Nocilla et al.*, 2006].*

the intact samples did follow a classical Critical State type of behaviour.

Site investigation

The embankments of the Po River at Viadana were constructed from borrow pits that were on the flood plain, above the usual high water level but within the flood channel bounded by the embankments. While the work on reconstituted samples by Nocilla *et al.* [2006] used bulk samples taken from the same borrow pits, the research described in this paper used intact natural samples of the flood plain soils taken from the sub-soils between the embankment and the river. These samples were taken as part of a site investigation associated with a trial embankment, which was constructed to form a pond adjacent to the existing embankment so that the seepage flow through the river embankments could be measured [A.I.P.O., 2004]; the locations of the boreholes are indicated on figure 3. A piston sampler was used, which from experience in other soft silty soils may have caused some disturbance to the natural structure of the soils [Hight *et al.*, 1992], but the tests discussed in this paper involve the behaviour at large strains, for which any effects of disturbance should not be significant. Basic properties of each sample are reported in tables I and II for the oedometer tests and triaxial tests that were carried out at the University of Rome [A.I.P.O., 2004], and their gradings are given in figure 4. The gradings are very similar to those of the reconstituted soils tested by Nocilla *et al.* [2006] and it is evident that the soils are highly heterogeneous, as is typical of flood plain deposits [e.g. Coop and Cotecchia, 1995], with very little correlation of soil properties with depth.

For transitional soils it is important to calculate the initial specific volume with the greatest accuracy and avoiding unnecessary assumptions, so that any real tendency to have non-unique CSLs or NCLs in the v:lnp' plane can be separated from simple data scatter arising from inaccuracies in the calculations of specific volume. Fortunately, for all the tests, the initial water contents and the bulk unit weights were measured independently along with the specific gravities, thereby allowing the calculation of the initial specific volume without the need to assume full saturation of the samples, even if the values of S that were also calculated are mostly fairly close to unity.

If the samples were undisturbed by sampling, the initial specific volumes reported in Tables I and II would correspond to those in situ. Any large

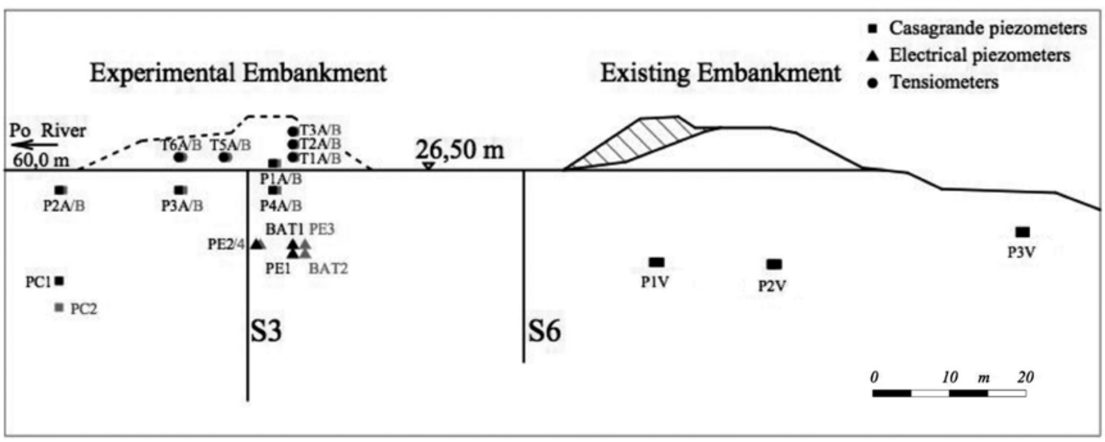

Fig. 3 – Schematic section illustrating borehole and instrumentation locations.
Fig. 3 – Sezione schematica con ubicazione dei sondaggi e della strumentazione.

Tab. I – Details of the oedometer tests.
Tab. I – Sintesi delle prove edometriche.

Test	Specimen	z (m)	Sand (%)	Silt (%)	Clay (%)	PI	γ (kN/m^3)	G_s	v_0	S	σ'_{v0} (kPa)	σ'_c (kPa)	YSR
O1	S3/Ab	2	17,2	62,8	20	7,7	18,92	2,72	1,791	0,93	47,3	300	6,34
O2	S3/B	3,3	4	66	30	14,3	18,18	2,73	1,953	0,94	71,6	273	3,81
O3	S3/C	4,8	10	74	16	-	19,31	2,74	1,799	1,00	92,6	480	5,19
O4	S3/Da	6,1	1,7	45	53,3	-	17,73	2,74	2,119	0,97	109,9	176	1,6
O5	S3/Ea	7,8	4,4	74,5	21,1	13,1	19,06	2,74	1,852	1,00	125,5	329	2,62
O6	S3/Fa	9,1	10	77	13	-	17,97	2,72	2,012	0,95	137,4	296	2,16
O7	S6/A	3,15	1	60	39	-	18,3	2,74	1,946	0,94	68,8	423	6,15
O8	S6/B	4,75	4	67	29	-	18,47	2,72	1,852	0,96	91,2	317	3,48

Tab. II – Details of the triaxial tests.
Tab. II – Sintesi delle prove triassiali.

Test	Specimen	z (m)	Sand (%)	Silt (%)	Clay (%)	PI	γ (kN/m^3)	G_s	p' (kPa)	v_0	S	Shearing
T1	S6/A	3,15	1	60	39	29,8	18,4	2,74	588	1,910	0,95	Drained
T2	S6/A	3,15	1	60	39	29,8	18,4	2,74	880	1,944	0,94	Drained
T3	S6/A	3,15	1	60	39	29,8	18,4	2,74	1176	1,965	0,98	Drained
T4	S3/B	3,3	4	66	30	-	18,53	2,73	50	1,906	0,96	Undrained
T5	S3/B	3,3	4	66	30	-	18,53	2,73	100	1,935	1,00	Undrained
T6	S3/B	3,3	4	66	30	-	18,53	2,73	200	1,920	0,98	Undrained
T7	S3/C	4,8	10	74	16	-	19,4	2,74	50	1,754	0,99	Undrained
T8	S3/C	4,8	10	74	16	-	19,4	2,74	100	1,777	0,99	Undrained
T9	S3/C	4,8	10	74	16	-	19,4	2,74	200	1,781	0,97	Undrained
T10	S3/Dc	6,3	28	46,5	25,5	16,2	19,41	2,74	50	1,746	0,95	Undrained
T11	S3/Dc	6,3	28	46,5	25,5	16,2	19,41	2,74	100	1,738	0,96	Undrained
T12	S3/Dc	6,3	28	46,5	25,5	16,2	19,41	2,74	200	1,732	0,94	Undrained
T13	S3/Ea	7,75	4,4	74,5	21,1	13,1	18,85	2,74	50	1,884	1,00	Undrained
T14	S3/Ea	7,75	4,4	74,5	21,1	13,1	18,85	2,74	100	1,893	0,99	Undrained
T15	S3/Ea	7,75	4,4	74,5	21,1	13,1	18,85	2,74	200	1,888	0,99	Undrained
T16	S6/B	4,75	4	67	29	14	19,27	2,72	50	1,778	0,96	Undrained
T17	S6/B	4,75	4	67	29	14	19,27	2,72	100	1,750	0,96	Undrained
T18	S6/B	4,75	4	67	29	14	19,27	2,72	200	1,744	0,97	Undrained
T19	S6/Cb	6,45	12	68	20	20,4	19,03	2,73	50	1,854	1,00	Undrained
T20	S6/Cb	6,45	12	68	20	20,4	19,03	2,73	100	1,842	0,99	Undrained
T21	S6/Cb	6,45	12	68	20	20,4	19,03	2,73	200	1,808	0,99	Undrained

disturbance that had occurred would, however, cause larger than expected volumetric strains at the start of the oedometer tests, and this is not evident in any of the tests. Although the complete isotropic compression data are not available for the triaxial tests, it is also clear that triaxial samples that have been compressed to small stress levels have undergone small volumetric strains, which is again an indication that the sample disturbance has not been large.

In order to calculate the vertical effective stresses at the sample locations, the vertical total stresses have been based on a mean bulk unit weight, γ, of 18.7kN/m^3 for the soils above the water table and 19.0kN/m^3 for the soils below. For the in-situ pore pressures, piezometers of both electrical and Casagrande types were installed at various locations along two instrumentation lines, A and B that were 60m apart, through the existing and new embankments (Fig. 3). Borehole S3 was on instrumen-

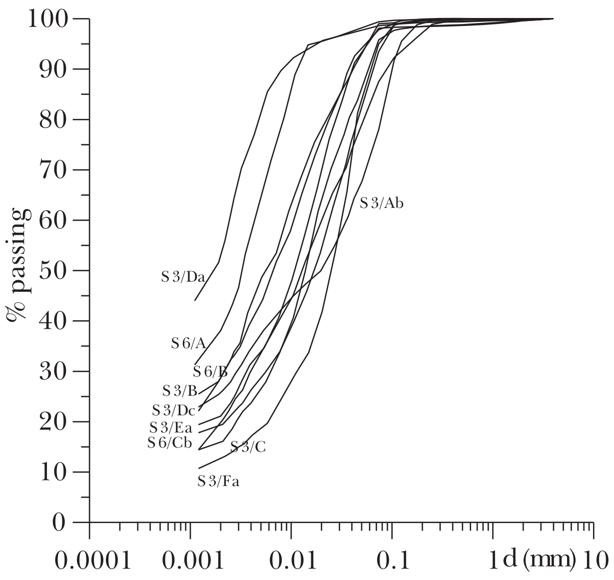

Fig. 4 – Grading curves for the soils (data from A.I.P.O., 2004).
Fig. 4 – Curve granulometriche dei terreni (dati da A.I.P.O., 2004).

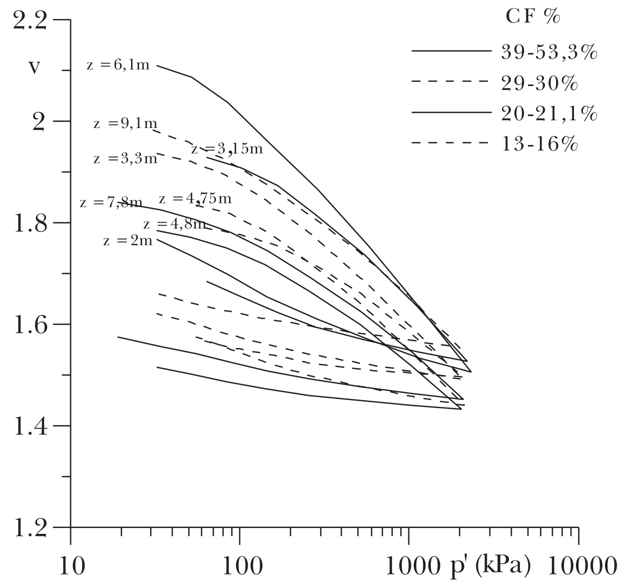

Fig. 5 – Summary of the oedometer tests.
Fig. 5 – Sintesi delle prove edometriche.

tation line B, but was made before the experimental embankment was constructed and borehole S6 was mid-way between the two lines. Measurements made over a three month period before the pond was filled for the seepage tests indicated that, if hydrostatic conditions are assumed, the water table would be at about 5.5m depth and that there was a change of only around ±0.2m from the average for the maximum and minimum river levels during that period. The piezometers above the water table were not able to register negative pore pressures, but a series of ten suction probes was installed by Geotechnical Observations within the new embankment along lines A and B. Prior to the filling of the pond these measured very small suctions, with maximum values of around 10kPa. The embankment materials are very similar in nature to the sub-soil and so a maximum suction of 10kPa has been assumed also for the sub-soil. Hydrostatic pore pressures have then been assumed below the water table, and for 1m above the water table.

Analysis of laboratory test data

A summary of the oedometer test data is given in Figure 5. There is a large amount of scatter in both the values of v_0 and the compression paths, which arises from the heterogeneous nature of the sediments, so that the values of v_0 do not correlate at all with depth, as COOP and COTECCHIA [1995] found for the alluvial sediments of the Sibari plain in southern Italy. Using a Casagrande construction, yield stresses, σ'_c, have been estimated and then yield stress ratios, YSR, have been calculated from the estimates of the in-situ effective vertical stress, σ'_{v0}, in Table I, where:

$$YSR = \frac{\sigma'_c}{\sigma'_{v0}} \qquad (1)$$

The resulting values of YSR are shown in Figure 6, which gives the typical pattern of decreasing values with depth as the value of σ'_{v0} increases,

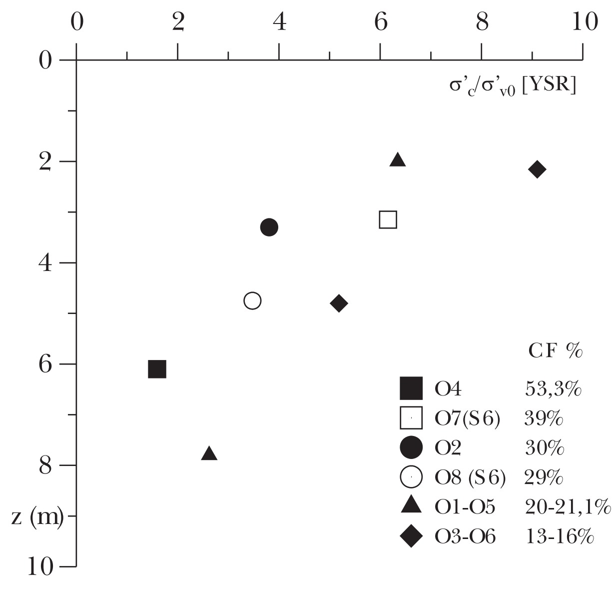

Fig. 6 – Yield stress ratios.
Fig. 6 – Rapporto tra tensione di snervamento e tensione insita.

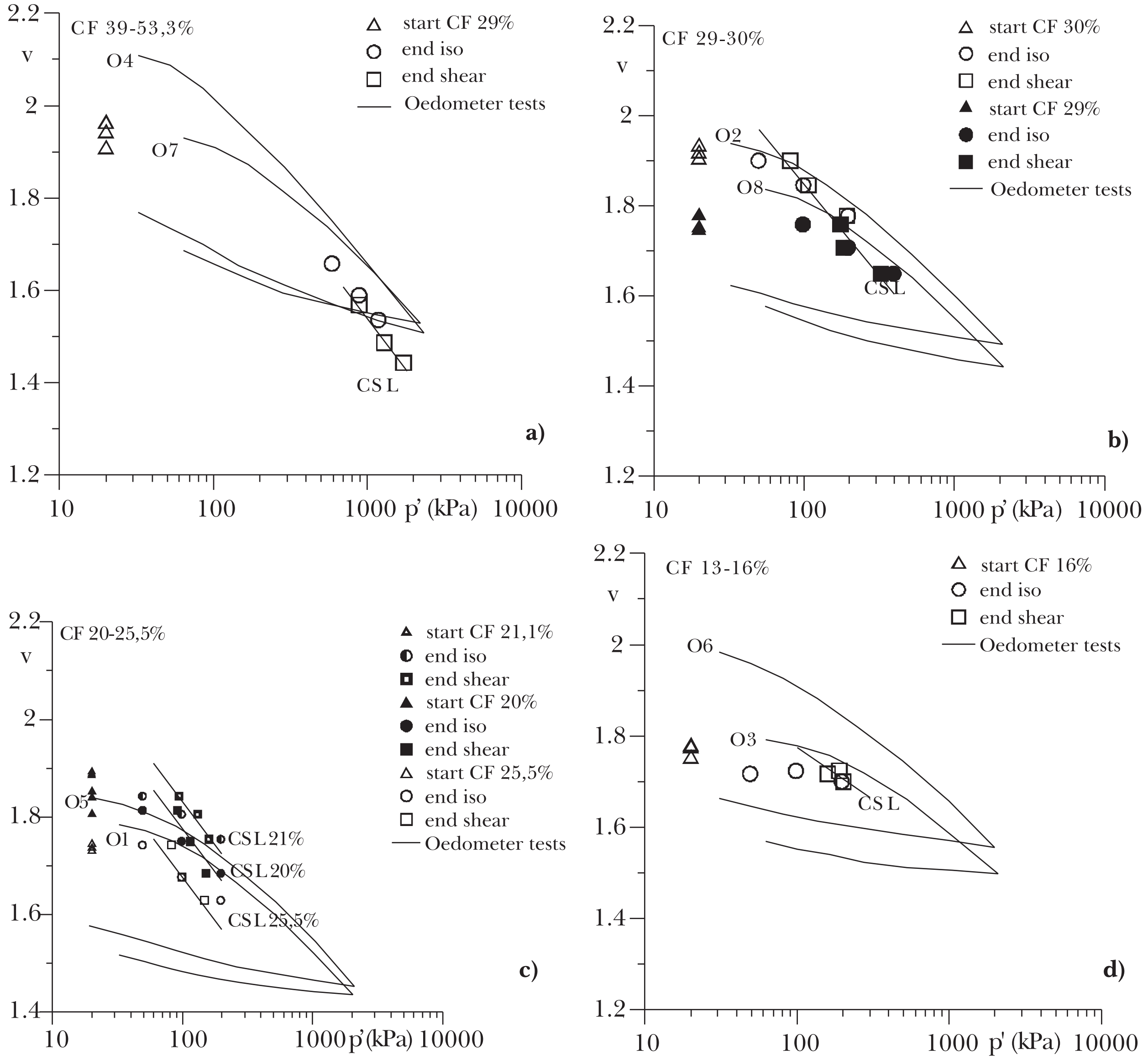

Fig. 7 – Triaxial and oedometer data. (a) 39-53.3% clay content (b) 29-30% clay content (c) 20-25.5% clay content (d) 13-16% clay content.

Fig. 7 – Dati ottenuti da prove edometriche e prove triassiali (a) 39-53.3% contenuto di argilla (b) 29-30% contenuto di argilla (c) 20-25.5% contenuto di argilla (d) 13-16% contenuto di argilla.

while there is no consistent change in σ'_c. However, for these soils, many of which will be shown to be transitional in behaviour, it must be doubtful whether the yield stresses correlate with the maximum past stress, so that the high YSR values at shallow depths would not be the overconsolidation ratios, OCR. It is possible but unlikely that in this geological environment there could have been sufficient erosion for that to account for the high σ'_c values. The suction measurements in the embankment materials also indicate that desiccation is unlikely to be the cause.

Figure 7 shows the compression curves along with the triaxial test data, grouping the tests according to the clay fraction, CF, as measured by sedimentation and shown in Figure 4, which was found to be a better indicator of behaviour than plasticity index, PI. For the oedometer tests p' has been calculated assuming values of K_0 that have been estimated from:

$$K_0=(1-\sin\phi')OCR^{\alpha} \tag{2}$$

where a value of 0.42 has been assumed for α for these low plasticity soils [LADD *et al.*, 1977]. The OCR has been assumed equal to the YSR, which may be justified because the difference between YSR and OCR was not appreciated when these relationships were published. It is also possible that for the samples from borehole S6 there are inaccuracies in the calculations of σ'_c, YSR and K_0 because of the proximity of the existing embankment, which would cause an inclination of the principal stresses. However, this would not be a problem at the higher stresses reached towards the end of the oedometer tests. For the triaxial tests the initial state is indicated, along with that after isotropic compression (unfortunately there are no intermediate data during isotropic compression), and then the critical states from the shearing stages.

For the high clay fraction data (Fig. 7a), there is a unique one-dimensional NCL defined by the two oedometer tests, and a unique CSL for the three triaxial tests. The two lines are parallel, but there is some uncertainty in this observation because of inaccuracies in the assumption of a constant K_0 on the NCL or from the small number of triaxial tests not allowing the CSL to be defined with certainty. The uniqueness of the CSL is also uncertain because all of the triaxial tests started from very similar values of v_0. The volumetric strains during isotropic compression should have been large enough to place the final points on an isotropic NCL, but although these plot parallel to the CSL, they are only slightly above it and are below the one-dimensional NCL. This might conceivably indicate a very highly skewed State Boundary Surface due to anisotropy. Otherwise the data seem to conform well to the basic features of Critical State Soil Mechanics.

The test data for 29-30% clay content (Fig. 7b) again seem to follow a Critical State framework, with a well defined CSL in the v:lnp' plane from six tests on samples from two depths. In this case the samples start with two distinct values of v_0, and yet the CSL is still unique. There is a small difference between the two oedometer curves, but this could arise from inaccuracies in the values of v_0. For the triaxial tests the isotropic loading has not been taken far enough to bring the initial states onto the isotropic NCL, as can be seen from the fact that the initial states at different stress levels for the two initial v_0 values lie on curved paths crossing the CSL. By comparison with Figure 7a, this shows that the yielding behaviour in compression is more associated with the nature of the soil than it is with the depth or any possible past maximum stress.

For the 20-25.5% clay data in Figure 7c there is a clear change to a more transitional mode of behaviour. The initial states of the various triaxial tests from each sample were similar, and as FERREIRA and BICA [2006] found for their residual soil, each v_0 gives a unique but distinct CSL, which are parallel in the v:lnp' plane. It is unlikely that the different CSL locations are the result of the slight variation in clay content, since there is no consistent trend, but as is seen with other transitional soils, there is a good correlation between v_0 and the CSL location. The isotropic compression points are again not at sufficiently high stress levels to have reached an isotropic NCL, and the two oedometer tests are at too similar values of v_0 to be able to see whether they are convergent or not.

Figure 7d shows the test data for the lowest clay contents (13-16%). The two oedometer tests are non-convergent, whilst being much steeper than is seen for poorly graded sands [e.g. COOP, 2003], indicating transitional behaviour. Unfortunately the triaxial tests were only conducted on samples with very similar v_0 values and over too narrow a range

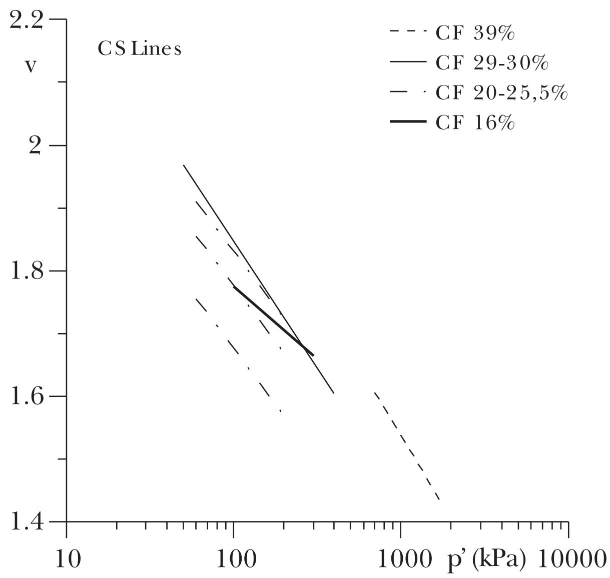

Fig. 8 – Summary plot of Critical State Line Locations.
Fig. 8 – Grafico di sintesi delle Linee di Stato Critico.

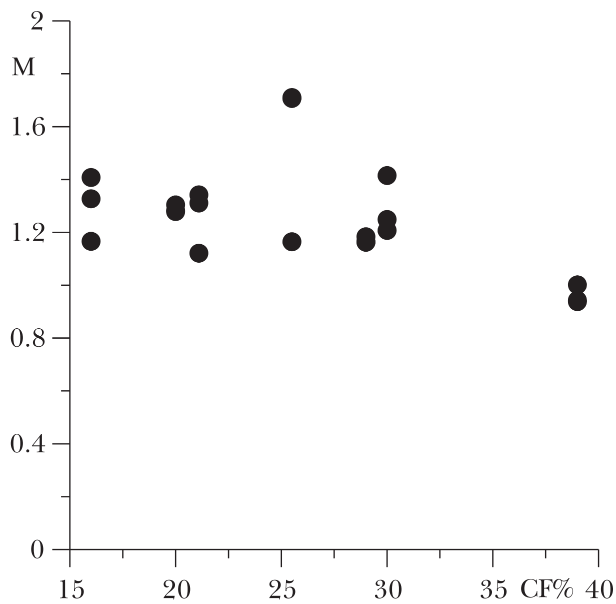

Fig. 9 – The influence of clay fraction on the Critical Stare Line gradient, M.
Fig. 9 – Influenza della frazione argilla sul gradiente M della Linea di Stato Critico.

of initial p' so the Critical State points are also too close together to be able to identify whether the CSL is unique or not. Again the isotropic compression points are not at sufficiently high stress levels to have reached any possible NCL.

A summary plot of the CSL locations is given in Figure 8. As the grading becomes coarser the gradient of the CSL reduces from 0.19 to 0.1. Generally the position of the CSL also moves to the left/down in the v:lnp' plane, although for the 20-25% clay

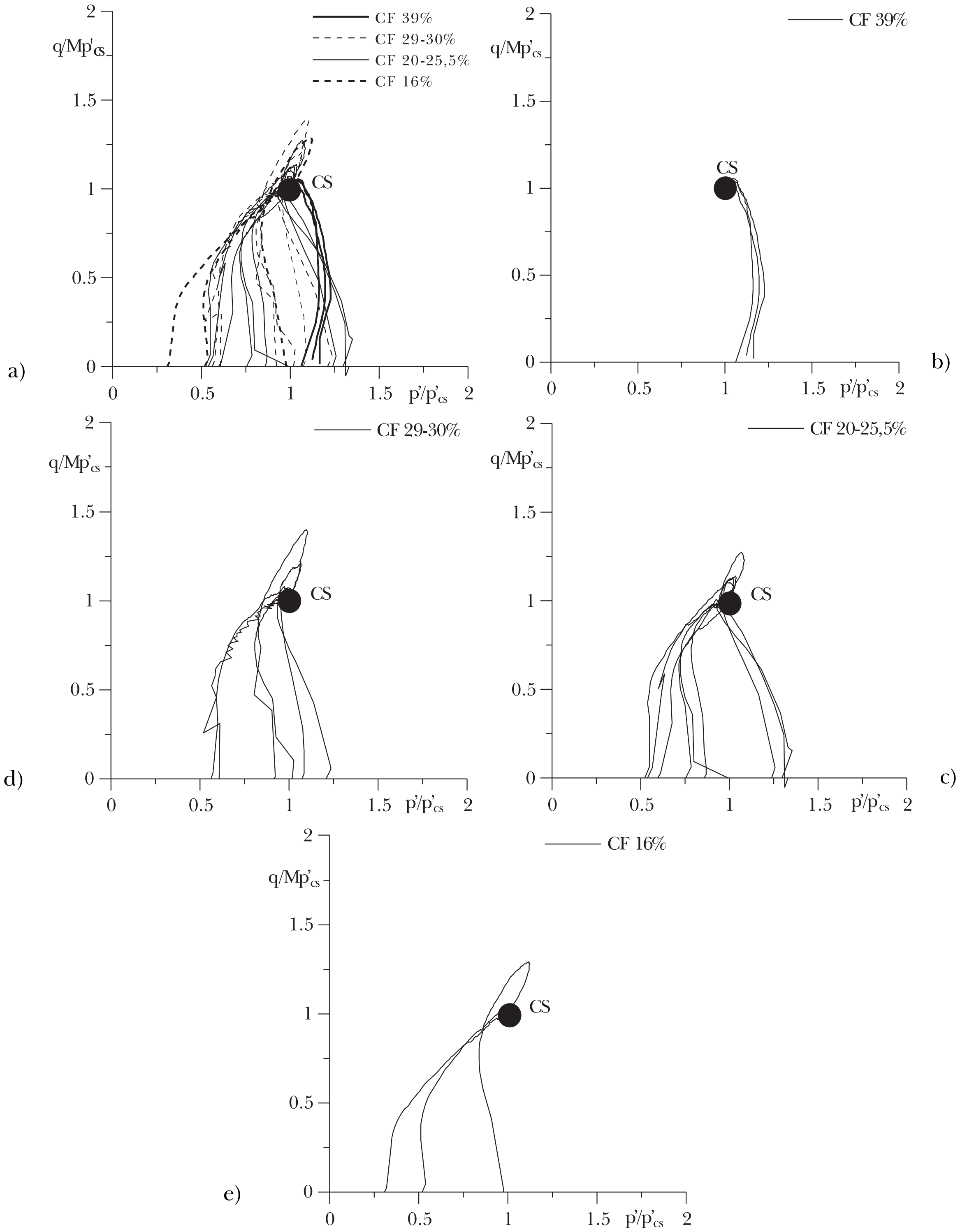

Fig. 10 – Normalised shearing paths for the triaxial tests. (a) Summary Plot; (b) 39% clay content; (c) 29-30% clay content; (d) 20-25.5% clay content; (e) 16% clay content.

Fig. 10 – Percorsi normalizzati delle prove triassiali; (a) Grafico di sintesi; (b) 39% contenuto di argilla; (c) 29-30% contenuto di argilla; (d) 20-25.5 contenuto di argilla; (e) 16% contenuto di argilla.

content soil there is no unique line. For the 16% clay content the CSL location apparently starts to move back upwards, but it must be remembered that since this grading is also transitional, this is only one of an infinite number of possible CSLs.

The Critical State friction angle from the shearing stages or M (q/p' at the Critical State) varies between the various samples. Figure 9 shows some correlation with the clay fraction, although there is scatter in the data because of the variation in the silt and sand contents. In figure 10 the shearing data from the triaxial tests have then been normalised with respect to equivalent pressures, p'_{cs}, taken on the CSL at the current specific volume:

$$p'_{cs} = \exp\left(\frac{\Gamma - v}{\lambda}\right) \quad (3)$$

Because of the variation of the value of M, the q/p'_{cs} axis has been further normalised with respect to this parameter. For the 20-25.5% clay content soil three different CSLs have been assumed as indicated on Figure 7c, and for the 16% clay content soil a single CSL has been chosen that is parallel to the compression curves for this soil.

The data for 39% clay content (Fig. 10a) are unusual in that the stress levels applied should have brought the initial state onto the isotropic NCL, but this is clearly not the case from the data, since the starting point lies almost directly below the CSL, and yet there is no evidence of any strongly anisotropic behaviour from the shape of the normalised stress paths. Otherwise, the normalised plots show that as the clay content reduces the paths tend to develop a more distinctive S-shape with a dilative tail and a loop back to the Critical State at the end of shearing, which NOCILLA *et al.* [2006] observed for the reconstituted soil of transitional behaviour, and which is also typical of sands [e.g. COOP, 2003]. NOCILLA *et al.* [2006] found that as the soils changed to a transitional mode of behaviour Rendulic's principle broke down and the normalised stress paths of the drained and undrained tests did not define the same boundary surfaces. Unfortunately, here there were only drained tests on the 39% clay content samples and only undrained tests on the other soils.

Conclusions

For such highly heterogeneous soils as these, that are typical of alluvial environments, the large scatter in the data can hide important differences of behaviour. Although there are also imperfections in the data because the tests were not specifically designed to investigate the aspects of behaviour investigated here, through careful examination of the data it has been possible to identify clear trends. In particular, there is an evolution from a clay mode of behaviour for the more plastic soils to a transitional mode for the less plastic ones. This change of behaviour with the nature of the soils is very similar to that observed by NOCILLA *et al.* [2006] for reconstituted samples from the same site. However, this is the first time that transitional behaviour has been identified for any intact natural soil and shows that it is not simply an artefact of laboratory created soils with reconstituted fabrics, but can also be seen for a soil with a fabric created by geological deposition. As for the reconstituted samples, none of the samples tested had a fines content that was sufficiently low so that a sand mode of behaviour could be reached, with a clear yield due to particle breakage. This indicates that sands must be very poorly graded to give this type of behaviour and that relatively small fines contents give rise to transitional behaviour, which is therefore likely to be widespread in natural soils.

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I terreni di fondazione degli argini del Po: un esempio di comportamento di transizione in terreni naturali.

Sommario

Vengono presentati e analizzati i risultati di prove di compressione edometrica e triassiale eseguite su campioni dei depositi alluvionali del fiume Po caratterizzati da un'ampia composizione granulometrica. I risultati sperimentali, correlabili con la dimensione dei grani, evidenziano, al diminuire della frazione fine, il passaggio dal comportamento tipico delle argille, nel quale vengono rispettate le ipotesi della meccanica dello stato critico, ad un comportamento di transizione, nel quale molte di queste assunzioni non sono più valide. Tale comportamento era stato già osservato su numerosi provini ricostituiti in laboratorio di terreni diversi, compresi quelli del sito in esame. Sebbene preliminari, i risultati ottenuti forniscono la prima evidenza sperimentale del comportamento di transizione anche nei terreni che presentano la loro struttura geologica naturale