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Effect of uniaxial compression on water retention, hydraulic conductivity and the penetration resistance of six Greek soils

K.P. Panayiotopoulos, E. Salonikiou, K. Siaga, V. Germanopoulou, and S. Skaperda*

Laboratory of Soil Science, School of Agriculture, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece

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A b s t r a c t. Undisturbed samples from three Entisols, two Alfisols and a Vertisol were compressed uniaxially by 0 (control), 100, 200 or 300 kPa and the changes in soil water retention characteristics, saturated hydraulic conductivity and penetration resistance were studied. Penetration resistance was determined on samples equilibrated, after compression, at soil water matric suctions of 1, 10, 100, 1000 and 100000 kPa.

The results obtained showed that uniaxial compression slight ly affected soil water retention characteristics only at low matric suctions while the influence of compression on saturated hydraulic conductivity was significant. Significant differences in penetration resistance between the controls and the compressed samples were found especially for samples equilibrated at soil water matric suctions higher than 100 kPa. The influence of both particle size distribution and structure development and stability on the response of the soils used to compression and on the consequent changes in saturated hydraulic conductivity and in penetration resistance is discussed.

K e y w o r d s: uniaxial compression, water characteristics, penetration resistance, Greek soil

INTRODUCTION

Although conservation tillage systems have been introduced in many parts of the world, compaction of field soils by agricultural traffic is still a problem of world-wide concern, because of the continuous development and use of heavier agricultural machinery and the intensification of agricultural practices (Soane and van Ouwerkerk, 1994). Compaction influences most of the properties and processes taking place in soils and is characterised as one of the most harmful and persistent of degradation phenomena. It also results in a decrease of both the quantity and the quality of agricultural products (Boone and Veen, 1994; Lipiec and Simota, 1994). Soil properties directly affected by compaction include bulk density (Hernanz and Sanchez-Giron, 2000), porosity, and pore size and continuity (Kooistra and Tovey, 1994) which determine water retention and flow (Horton *et al*., 1994), gas diffusion rate (Stępniewski *et al*., 1994), thermal properties and resistance to root growth (Gliński and Lipiec, 1991; Panayiotopoulos *et al*., 1994). Although the influence of compaction on the physical, chemical and biological properties of a variety of agricultural soils has been studied extensively (Soane and van Ouwerkerk, 1994; Horn *et al*., 2000), not much work has been done on Greek soils. Therefore, the objective of the present work was to study, under laboratory conditions, the consequences of uniaxial compression on soil water retention characteristics, hydraulic conductivity and penetration resistance of six Greek soils, differing in particle size distribution and structure development and stability.

MATERIALS AND METHODS

Undisturbed soil samples were taken by means of stainless steel cylinders (57 mm in diameter and 40 mm in length) from the A_p horizon from six areas of agricultural importance and representative of Greek soils. The soils were classified as Entisols (3 soils), Alfisols (2 soils) and Vertisol (Soil Survey Staff, 1975). Entisol-1 and Entisol-2 were under asparagus while Entisol-3 was under natural vegetation. Alfisol-1 and Vertisol used to be vineyards but they had not been cultivated for the last fifteen years while Alfisol-2 was under winter wheat. Both the Alfisols and the Vertisol used for this work were characterised by high aggregate stability (Panayiotopoulos and Kostopoulou, 1989) while all the Entisols studied were of low structure development and aggregate stability. In preliminary measurements it was

*Corresponding author's e-mail: kpp@agro.auth.gr

found that the pre-compression stress of Entisol-1, Alfisol-2 and Vertisol was less than 100 kPa, of Entisol-2 roughly equal to 100 kPa and of Entisol-3 and Alfisol-1 was approximately equal to 200 kPa. However, for comparison purposes all samples were handled and stressed in a similar manner. The samples taken were used for bulk density, soil water retention characteristics and to determine penetration resistance. In order to determine saturated hydraulic conductivity, the undisturbed samples were taken by means of brass cylinders 75 mm in diameter and 105 mm in length.

All cores were saturated slowly with de-aerated 0.005 M $CaSO_4$ solution under vacuum (2 – 3 kPa) over a period of twelve hours and allowed to equilibrate at a 10 kPa matric suction (field capacity). $CaSO_4$ solution was used in order to minimize clay dispersion and any consequent alteration to the structure. After equilibration, all samples were stressed uniaxially at 0 (control), 100, 200 or 300 kPa by static loading for 1 min. The compression of the samples was obtained by means of a compression test machine (Wykeham Farrance Eng. Ltd). The range of stresses applied was chosen to cover the stresses applied to field soils by agricultural machinery (Panayiotopoulos, 1989a) .

For the soil water retention characteristics, both the control and the compressed samples were saturated under vacuum with a 0.005 M $CaSO_4$ solution. After saturation, the samples were allowed to equilibrate at progressively increasing matric suctions from 1 to 10^5 kPa. The equilibration of the samples was obtained by means of i) a tension table (hanging column) for matric suctions of 1, 2, 4 and 10 kPa and ii) a pressure plate apparatus, for matric suctions of 33, 100 and 1000 kPa. After equilibration at a given suction, the samples were removed, weighed, put in the proper apparatus and the next higher matric suction was applied. Finally, the samples were allowed to equilibrate with the water-vapor tension of the atmosphere (air-drying), which is equivalent to a matric suction of 10^5 kPa. After air-drying, the samples were weighed, oven-dried and re-weighed and the dry mass of each sample was determined. The water content (on a dry mass basis) of any matric suction applied could then be calculated. Three replicates were used for each soil and compression level applied.

For determining penetration resistance, the control and the compressed samples were saturated as previously described and allowed to equilibrate at a matric suction of 10^0, 10^1, 10^2, 10^3 and 10^5 kPa. A metal probe (2.5 mm in diameter) with a conical end (60^0 cone angle and 3 mm base diameter) attached to a compression test machine (Wykeham Farrance Eng. Ltd) was used as a penetrometer. The rate of penetration was kept constant at 1.52 mm min^{-1}. Penetration resistance was calculated as the force exerted by the penetrometer divided by its cross-sectional area, when the conical tip reached a depth of 10 mm (Whiteley *et al*., 1981). Three penetrations were made on each sample (replicate) and three replicates were used for each soil, compression level and matric suction studied.

Saturated hydraulic conductivity was determined by means of a constant head permeameter. A 0.005 M $CaSO_4$ solution was used as a test fluid (Klute and Dirksen, 1986) and ten replicates were used for each soil and compression level studied.

Bulk density was determined by the core method (Blake and Hartge, 1986) while porosity was taken as the volumetric water content at saturation under vacuum.

In some cases the results of soil properties affected by uniaxial compression are given in relative values. These values are expressed as fractions of the controls (i.e., those under zero applied stress).

Particle size distribution, organic matter and $CaCO_3$ content, pH and electrical conductivity were also determined on disturbed and sieved (< 2 mm) soil samples, by standard methods (Page *et al*., 1982; Klute, 1986), in three replicates. The t-test was used for statistical analysis.

RESULTS AND DISCUSSION

As can be seen from Table 1, the soils used were of varying particle size distribution, organic matter and $CaCO_3$ content, electrical conductivity (E.C.), bulk density, aggregate size and stability and saturated hydraulic conductivity.

As expected (e.g., Campbell, 1994) uniaxial compression resulted in an increase of bulk density (Fig. 1) in all soils but any significant differences ($p<0.05$) between compression of 0 (control) and 300 kPa were observed only in Entisol-1 and in Vertisol. The significant increase of bulk density in these soils may be attributed to their low initial bulk density (Table 1) and pre-compression stress and the consequent increased compressibility.

Uniaxial compression up to 300 kPa resulted in a significant ($p<0.05$) decrease of water retention at low soil water matric suctions, especially at matric suctions smaller than field capacity (=10 kPa; Fig. 2) for all soils except the two Alfisols studied. These two soils retained the least water at saturation (≈ porosity; 0.511 and 0.588, respectively) as compared to the other soils. For the same soils, the increase in bulk density due to compression was not significant ($p<0.05$). Therefore, uniaxial compression of 300 kPa resulted in a relatively small decrease in porosity and to a non significant alteration of pore size reduction which caused a non significant decrease in water retention at matric suctions ≤ 10 kPa.

For matric suctions >100 kPa, no clear trend of water retention was found between control and compressed samples. In some cases more water was retained by compressed samples as found and by other researchers (Reicosky *et al*., 1981), and in other cases less retained water was found, as compared to unstressed samples. However, in any case, no significant difference ($p<0.05$) in water retention was observed between the control and the compressed samples.

The saturated hydraulic conductivity (K_s) of non-compressed samples (control) was increased in the order

T a b l e 1. Basic physical and chemical properties of the soils used

Soil property	Entisol-1	Entisol-2	Entisol-3	Alfisol-1	Alfisol-2	Vertisol
Sand content (g kg^{-1})	774	562	80	566	577	247
Silt content (g kg^{-1})	151	321	688	136	290	371
Clay content (g kg^{-1})	75	117	232	298	133	382
Texture	loamy sand	sandy loam	silty loam	sandy clay loam	sandy loam	clay loam
pH	7.5	7.4	7.5	7.25	5.8	7.5
Organic matter content (g kg^{-1})	10.9	6.6	21.0	11.7	14.8	24.0
$CaCO_3$ (g kg^{-1})	15.8	30.8	6.0	5.7	0.0	7.0
E. C. (dS m^{-1})	ND	ND	0.63	0.155	0.177	0.702
Bulk density (Mg m^{-1})	1.16	1.36	1.15	1.42	1.11	1.08
MWAD* (mm)	ND	ND	0.94	2.56	1.83	1.97
Aggregate stability (%)	ND	ND	37	80	84	64
Saturated hydraulic conductivity (m s^{-1})	3.067	17.995	1.112	2.493	27.64	2.827

*Mean Weighed Aggregate Diameter after wet sieving, ND – not determined.

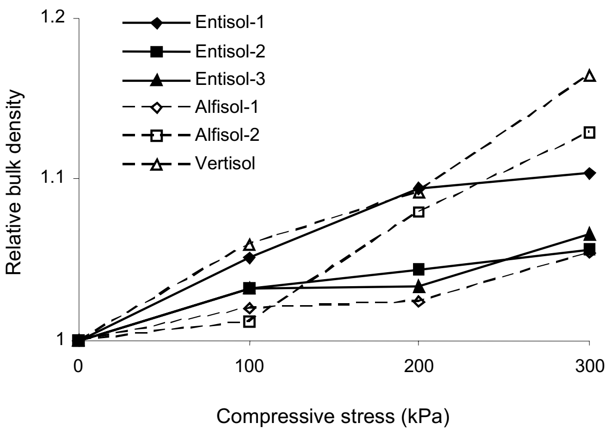

Fig. 1. Relative increase of bulk density after uniaxial compression at different compression levels.

Entisol-3, Alfisol-1, Vertisol, Entisol-1, Entisol-2 and Alfisol-2 (Table 1) and the differences between the soils were in most cases significant. The low K_S of Entisol-3 can be attributed to its low sand and very high silt content which resulted in low macroporosity. In addition, the low aggregate stability of this soil leads to a breaking of the aggregate, particle movement by flowing water and pore clogging. The high K_S of Alfisol-2 (sandy loam) may be due to its high sand content and aggregate stability (Table 1).

The application of increasing uniaxial compression to the soils resulted in the progressive decrease of K_S (Fig. 3). Although uniaxial compression resulted in significant increase ($p<0.05$) in bulk density only for Entisol-1 and Vertisol, the same treatment resulted in a significant reduction ($p<0.05$) in K_S for all soils. These results are in agreement with the findings of Dawidowski and Lerink (1990). However, the decrease in K_S with compression was not similar in all the soils used. For Entisol-1, Entisol-3, Alfisol-2 and Vertisol significant differences ($p<0.05$) in K_S were observed between the control and the samples compressed at any stress applied. For Entisol-2 and Alfisol-1 significant differences ($p<0.05$) in K_S were obtained between the control and the samples compressed at 200 or 300 kPa. Furthermore, the trend of decreasing K_S with increasing compressive stress was not similar for all soils used.

In Entisol-1, Alfisol-2 and Vertisol a sudden decrease of K_S was observed after compression of 100 kPa while further compression by 200 or 300 kPa resulted in a negligible extra decrease of K_S (Fig. 3). These soils are characterized by low (<100 kPa) pre-compression stress and low initial bulk density (Table 1) which resulted in high compressibility (Panayiotopoulos, 1989a) and an increased pore size reduction even after relatively low compression (100 kPa). For Entisol-1 and Vertisol significant increases ($p<0.05$) in bulk density and significant decreases ($p<0.05$) in water retention were also observed.

In Entisol-2, compression by 100, 200 or 300 kPa resulted in a gradual and almost linear decrease of K_S (Fig. 3). The compression of this soil, which had an intermediate pre-compression stress ($\approx$100 kPa) and initial bulk density (1.36 Mg m^{-3}), resulted in an insignificant ($p<0.05$) increase of bulk density.

In Entisol-3 and Alfisol-1 a sudden and large decrease of K_S was observed up to 200 kPa uniaxial compression while a 300 kPa compression resulted in a negligible further decrease of K_S (Fig. 3). These two soils had the largest pre-compression stress ($\approx$200 kPa) and their compression up to 300 kPa resulted in an insignificant ($p<0.05$) increase

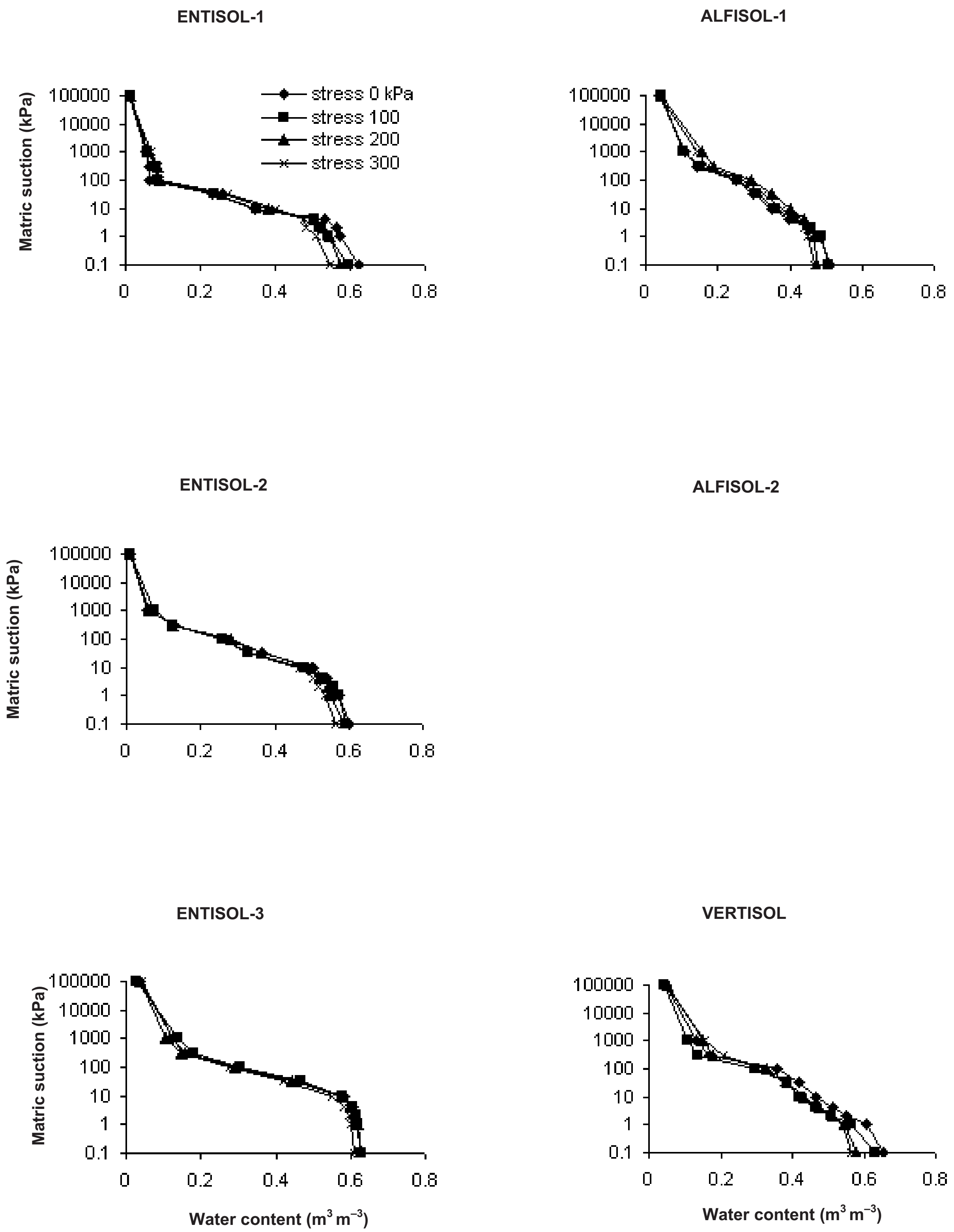

Fig. 2. Soil water retention characteristics of the soils used after uniaxial compression at different compression levels.

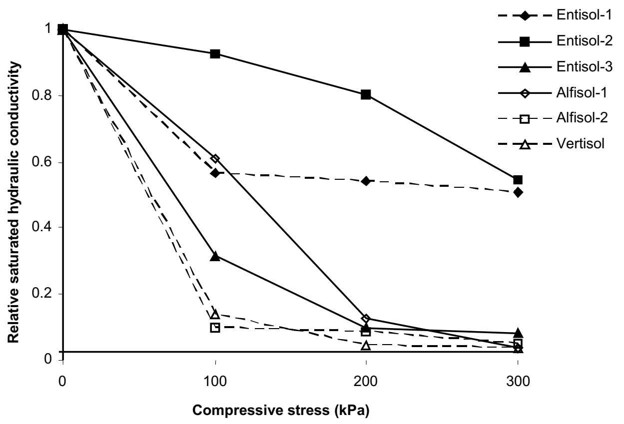

Fig. 3. Relative saturated hydraulic conductivity of the soils used after uniaxial compression at different compression levels.

of bulk density. It is expected therefore that these soils would have a lower compressibility and pore size reduction compared to the other soils used at the same compression level. In addition, Alfisol-1 is characterized by a high aggregate stability (Table 1) and compressive strength (Panayiotopoulos, 1989b) both of which resulted in a low compressibility and K_S reduction.

The penetration resistance (PR) of both the control and the compressed samples of all soils used increased with the increasing soil water matric suction with which the samples were equilibrated before testing (Fig. 4). For any of the compressive stresses applied and for any one of Entisol-2, Entisol-3, Alfisol-2 and Vertisol, significant differences ($p<0.05$) in PR were obtained between soil water matric suctions equal to or greater than 100 kPa. For Alfisol-1, significant differences ($p<0.05$) in PR were found between suctions equal to or greater than 10 kPa. Finally, for Entisol-1 significant differences ($p<0.05$) in PR were observed between any of the matric suctions applied. The important role of soil water on the PR of the soils used can also be shown by the highly significant regression equations found between PR and water content, on a mass basis, for any single soil separately and irrespective of the compression level. The regression equations were all of the form $y = ax^{-b}$, where y and x stand for PR and water content on a mass basis, respectively and a and b are constants. The r-values obtained were always >0.85. Similar results were also obtained by others (Shafiq *et al*., 1994; Vaz *et al*., 2001).

Significant differences ($p<0.05$) of PR, irrespective of soil water matric suction at which the samples were equilibrated before testing, were found between unstressed samples (controls) of the soils used. This reflects the different mechanical behaviour of the soils used which depends on their different particle size distribution, structural properties (Table 1) and pre-compression stress. The mean PR of the controls was increased in the order Alfisol-2 (0.572), Vertisol (0.739), Entisol-1 (1.054), Entisol-2 (1.420), Entisol-3 (2.037), Alfisol-1 (7.347 MPa). With the exception of Entisol-2, the mean PR of the soils used followed the same trend as initial soil bulk density (Table 1).

Compression of samples by 100, 200 or 300 kPa resulted in significant increases ($p<0.05$) of PR (Fig. 4) of all soils used. However, as expected, the increase of PR with compressive stress was not similar in all soils. For Alfisol-1 and Vertisol, compression by 100, 200 or 300 kPa resulted in a significant increase ($p<0.05$) of PR for any soil water matric suction with which the samples were equilibrated before testing. These two soils differ in particle size distribution, pre-compression stress and initial bulk density but they have the highest mean weighed aggregate diameter (Table 1). For Entisol-2, Entisol-3 and Alfisol-2 compressed at 100, 200 or 300 kPa, significant increases ($p<0.05$) of PR were observed at matric suctions $\geq$100 kPa. Both Entisol-2 and Alfisol-2 are sandy loams while Entisol-3 is classified as silty loam (Table 1). Both Entisol-3 and Alfisol-2 had a low initial bulk density (1.15 and 1.11 Mg m^{-3}, respectively; Table 1) while, for all three soils, compression resulted in an insignificant ($p<0.05$) increase in bulk density. The latter may mean that it is necessary for the matric suction to be increased before a significant increase in PR is observed. Finally, for Entisol-1, significant increases ($p<0.05$) of PR due to compression were found only when the samples were equilibrated at matric suctions $\geq$1000 kPa. This soil is classified as a loamy sand with low pre-compression stress and initial bulk density. Compression however, of this soil resulted in a significant ($p<0.05$) increase of bulk density. It seems that for this soil (with a very high sand and a very low clay content, Table 1) the increased bulk density, due to compression is not sufficient *per se* to result in a significant increase of PR.

It is worth noting that Alfisol-1 presented the highest PR under any compressive stress applied and matric suction tested. For the rest of the soils used, however, compression by 300 kPa resulted in a more or less similar PR.

CONCLUSIONS

As a conclusion it can be stated that: i) uniaxial compression affected soil water retention characteristics slightly and saturated hydraulic conductivity strongly and ii) uniaxial compression resulted in a large increase of penetration resistance. The different response of the soils used to compression, which resulted in a differentiation of their saturated hydraulic conductivity and penetration resistance, may be attributed to their differences in particle size distribution and structure development and stability. Other factors which may play an important role are particle shape and orientation, clay mineralogy and the presence of cementing materials, which affect the stability, strength and compressibility of a soil's structure. All these soil properties were not determined and will be the subject of future work.

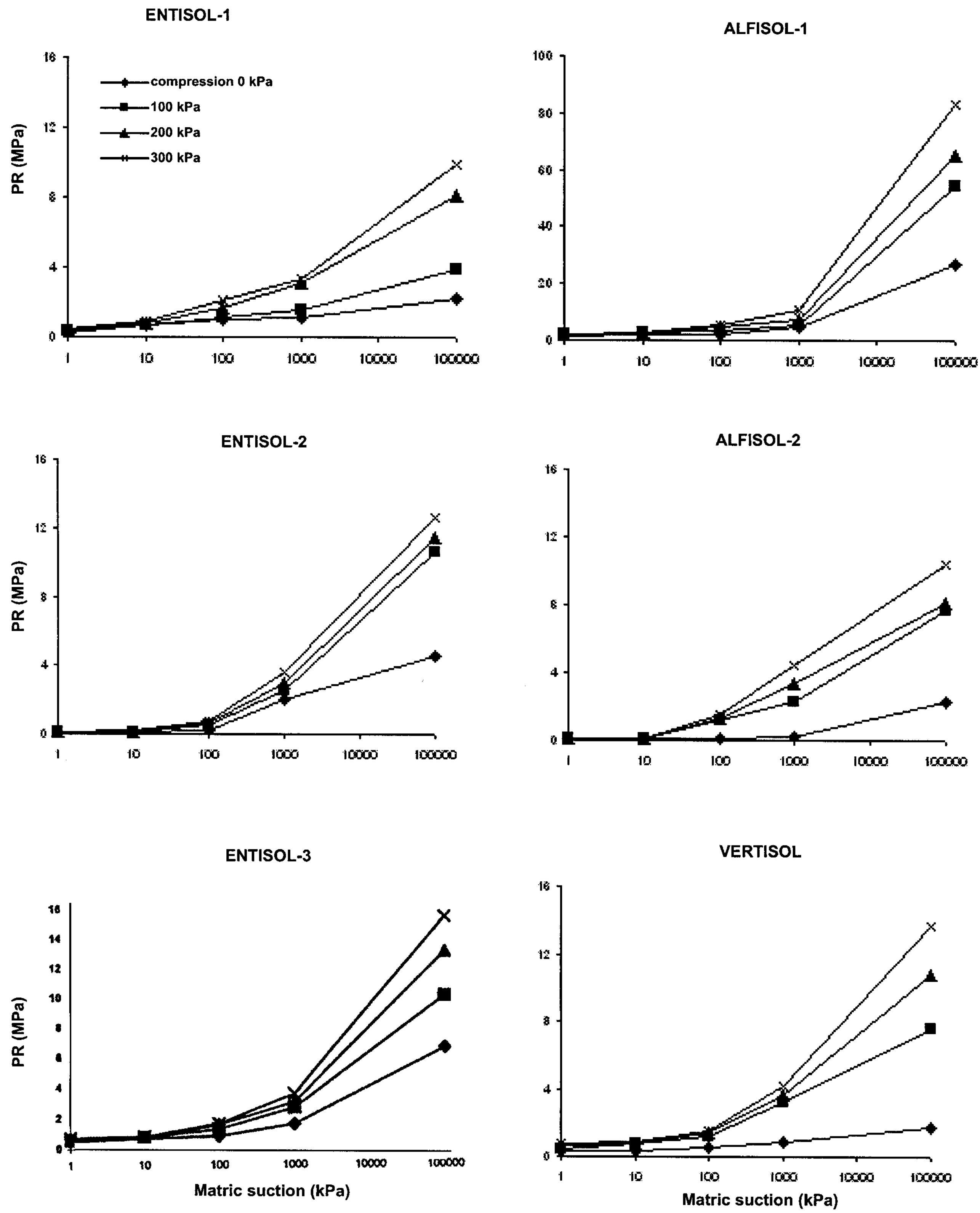

Fig. 4. Penetration resistance (PR) of the soils used after uniaxial compression at different compression levels and soil water matric suctions (Note the larger scale of the y-axis in Alfisol-1).

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