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Compaction of restored soil by heavy agricultural machinery—Soil physical and mechanical aspects

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Abstract

As construction and open-cast mining activities continue to expand on fertile agricultural land, the removal and subsequent restoration of soil to be re-used for plant growth has become an increasingly important issue in soil protection. A key factor for the success of soil restoration is that the soil is allowed to develop sufficient mechanical strength to withstand the stresses involved in the intended type of land use. The objective of this study was to investigate the effects of the first use of heavy agricultural machinery on the physical and mechanical properties of a restored soil after the period of restricted cultivation (as prescribed by current guidelines), when the soil is re-submitted to normal agricultural management. We performed two traffic experiments on a soil which had been restored according to current guidelines 4 years before the beginning of the study. In the first year of the study, a combine harvester passed two times across the wetted experimental area, and in the following year 10 times. Two passes along the same tracks caused only weak compaction effects, mainly reducing coarse porosity. In contrast, after 10 passes, deep ruts had formed, and coarse porosity was drastically reduced down to the subsoil. Confined uniaxial compression tests revealed an increase in precompression stress and a decrease in the slope of the virgin compression line, i.e. the compression index, after 10 passes. However, precompression stress was still much lower than the exerted soil stresses at the corresponding soil depths, indicating that due to the short duration of the wheel loadings equilibrium conditions were not reached in the traffic experiments and that further compaction would have occurred with additional passes. The decrease in compression index found after 10 passes may be due to the practice that samples are pre-conditioned to a specified water tension for the oedometer tests. The results show that loads may exceed precompression stress for short durations even in a restored soil which is still far from having re-gained normal strength without serious damage. Thus, the use of precompression stress as a criterion for trafficability was on the safe side in preventing damage to the ecological quality of the soil by compaction, even if the concept did not fully apply to the field reality of the mechanical stress conditions.

Keywords: Soil restoration; Soil compaction; Precompression stress; Compression index; Bolling probe pressure

1. Introduction

Large areas of fertile land are temporarily used for construction and open-cast mining purposes or permanently destroyed by building. In the course of these activities, large quantities of soils are excavated. In many cases these soils are later restored at the original site as in many open-cast tunnelling, pipeline construction and gravel exploitation projects or used for soil restoration at a new site. In the Canton of Zurich (Switzerland), for instance, 50–60 ha of agricultural land are presently restored per year for re-cultivation of closed gravel pits and other landscaping activities. This corresponds to 0.07–0.08% of the total agricultural area of the canton (about 75 000 ha). Thus, restoration of soil to be re-used for plant growth has become an increasingly important issue in soil protection.

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Excavation, transport and repacking disrupt the structure of a soil and cause a rearrangement of clods, aggregates and particles. This leads to mechanical destabilization and an increased risk of soil compaction. The risk depends on many factors, including soil wetness, texture and stabilization by plant roots, as well as on the care with which the soil is handled (Schröder et al., 1985). The increased risk of compaction does not end with the rebuilding of the soil. Freshly restored soils have a low degree of aggregation and are very susceptible to compaction (Lebert and Springob, 1994). Over the years, strength will redevelop (Schneider and Schröder, 1991) due to physical (Voorhees, 1983; Bullock et al., 1985), chemical (Dexter et al., 1988) and biological (Von Albertini et al., 1995) regeneration processes. The formation of aggregates is considered to play a key role in this process (Horn, 1983, 1988; Baumgartl and Horn, 1991; Lebert and Horn, 1991).

It is important for the success of a soil restoration that the soil is allowed to regain sufficient mechanical stability before it is used again for agriculture. Undue handling during cultivation operations within the first years after restoration may easily damage or even completely destroy the weak soil structure and thus reduce water conductivity (Logsdon et al., 1992; Arvidsson, 2001) and air permeability (Horn, 1986; Gysi et al., 1999). This in turn may have negative ecological (Soane and van Ouwerkerk, 1995) and economical (e.g. yield losses: Håkansson and Reeder, 1994) consequences. On the other hand, economic interest in the re-use of restored soil for crop production creates pressure to minimize the time of restricted cultivation. Responding to this conflict between economic interests and the imperative of sustainability, guidelines like those of Zwölfer et al. (1991), VSS (2000), BUWAL (2001) and FSK (2001) have been issued. These guidelines only allow very restricted land use for at least three to four years after restoration in order to avoid compaction by excessive mechanical stresses. The guidelines are based on practical experience and to some degree represent a compromise between land use and soil protection interests.

The high compaction risk of restored soils calls for preventive measures. The regeneration of mechanical stability after disturbance depends on soil properties and on the way how the soil is repacked and subsequently cultivated (Lebert, 1991; Davies and Younger, 1994). Therefore a stability criterion is needed that is directly related to the mechanical properties of restored soils. The concept of precompression stress has been applied to agricultural soil mechanics e.g. by Horn (1981) and Kirby (1991a). Precompression stress is determined from compression curves (void ratio versus logarithm of normal stress) obtained by confined uniaxial compression tests (Koolen, 1974). Conceptually, it indicates the maximum stress a soil has been submitted to before under given conditions (Kirby, 1991a; Veenhof and McBride, 1996). According to the conventional concept of precompression stress, deformation is elastic (reversible) at stresses below and plastic (irreversible) above precompression stress. Compression above precompression stress occurs along the virgin compression line (VCL). The slope of the VCL, i.e. the ‘‘compression index’’ (CI) according to Larson et al. (1980), is inversely related to soil stiffness. Upon unloading, the maximum applied stress becomes the new precompression stress, and upon reloading, the soil is further compressed along the original VCL when the applied stress exceeds this new precompression stress. Thus, the concept implies that precompression stress increases during compaction, whereas CI remains unaffected.

Its conceptual features make precompression stress attractive as a criterion for the limit up to which a soil may be loaded without irreversible damage to its ecological functions, i.e. as an indicator of ‘‘ecological’’ trafficability. The latter should be distinguished from what may be called ‘‘technical’’ trafficability, for which e.g. the empirical ‘‘California Bearing Ratio’’ (CBR, see e.g. Porter, 1950), which is an index of the shear strength of a soil (Turnbull, 1950), is widely used.

Despite the advantage of the precompression stress concept that it directly relates soil stress to strength, there are a number of uncertainties when using precompression stress determined by laboratory tests as an indicator of the maximum stress experienced by the soil in situ. First, the concept presupposes that stress–strain conditions in soil samples during uniaxial compression tests are comparable to those in undisturbed soil subjected to mechanical load in the field. In particular, the concept relates to equilibrium conditions (i.e. sufficiently long exposure to a load, slow increase in load) and laterally confined expansion. These conditions may often not be sufficiently fulfilled in field situations. As a consequence, the (time-dependent) stress tensors describing the stress distribution below a moving wheel (e.g. Abu-Hamdeh and Reeder, 2003) and in an uniaxial compression test (Koolen, 1974) can be quite different.

Second, precompression stress is conditional on the soil moisture status and the drainage conditions, which are usually not the same in laboratory tests and the field. Third, the concept refers to conditions with no changes in the structural arrangement of soil particles (i.e.