

# Ahead of his time: Terzaghi's first oedometer tests through the lens of modern compression frameworks

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## 1 Introduction

The first oedometer apparatus was developed by Terzaghi in the late 1910s. The oedometer was used to obtain test results for five clays, forming the basis for the development of the theory of one-dimensional consolidation – which is still widely adopted in everyday practice by geotechnical engineers today, more than a century later. The test results and the earliest version of consolidation theory were published in German in a technical paper (Terzaghi, 1923) and in the seminal work *Erdbaumechanik* (Terzaghi, 1925), which is widely considered to have marked the birth of soil mechanics and geotechnical engineering. Remarkably, a clear understanding of the principle of effective stress was displayed in these publications, although effective stress was only formally defined more than a decade later. It is perhaps not as widely known that oedometer test results for a quartz sand were also reported in *Erdbaumechanik*. This paper revisits these test results and Terzaghi's discussions within the context of modern compression frameworks for clays and sands.

## 2 Modern compression models

One of the key assumptions of Terzaghi's consolidation theory was that a unique normal consolidation line (NCL) exists for a given soil. This was proven true for a remoulded clay by Rendulic (1937) using an early triaxial apparatus in Terzaghi's laboratory in Wien. Further experimental evidence after Skempton (1944) and Henkel (1960) allowed for a unique NCL as part of a state boundary surface to be proposed for remoulded clays, which formed a key component of critical state soil mechanics (CSSM)-based constitutive models (e.g. Schofield & Wroth, 1968). The framework proposed by Burland (1990) suggested a unique intrinsic normal consolidation line (ICL) for a reconstituted clay. States plotted beyond the ICL are only attainable due to effects of soil structure (Leroueil & Vaughan, 1990).

However, the appropriateness of this assumption is dependent on material type. Today it is known that remoulded non-plastic sands do not necessarily exhibit a unique NCL, and that the compression path of a normally consolidated sand may depend on the initial void ratio. There would thus be no unique normal consolidation line acting as a state boundary surface. A state boundary surface called the limiting compression curve (LCC), governed by particle crushing, was proposed by Pestana & Whittle (1995). A limitation of their model was that the behaviour of sands at any state beneath the LCC was assumed to be linear-elastic. Jefferies & Been (2000) conducted oedometer tests on a clean sand prepared over a range of initial void ratios without imposing any stress history. They proposed that an infinite number of NCLs exist for a given clean sand, all of which are parallel at low to moderate stresses. In idealised form, when unloading and reloading from any one of these elastoplastic NCLs, an infinite number of parallel elastic swelling lines exist. If the two aforementioned models are combined, it is suggested that each of the infinite NCLs would eventually converge onto the LCC due to particle crushing under high stresses. The idealised compression models for clays and sands are illustrated in Fig. 1.

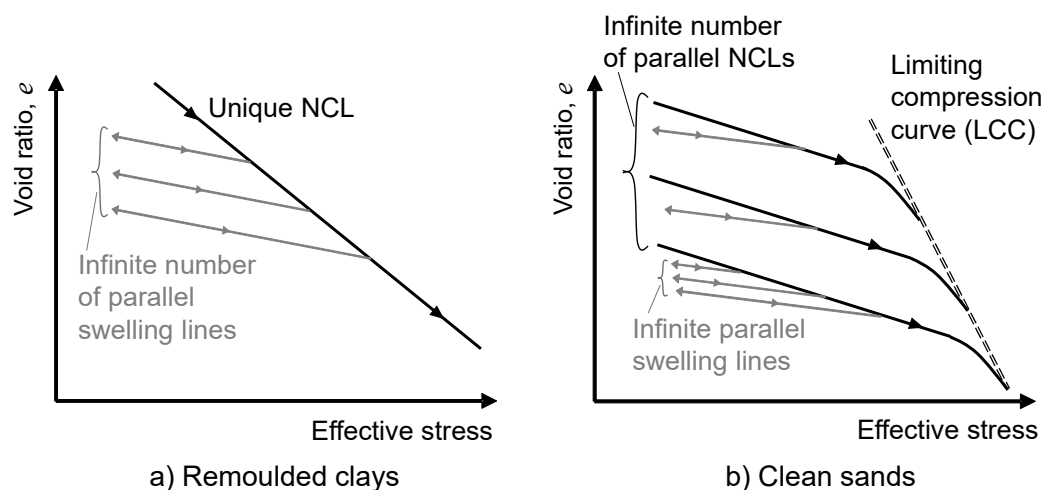


Fig. 1: Modern idealised compression frameworks compatible with CSSM

### 3 Terzaghi's tests

Although the oedometer tests on clay reported by Terzaghi (1923, 1925) did not explicitly investigate his assumption of a unique NCL, they did allow for the widely accepted form consisting of an elastoplastic NCL with elastic unload-reload 'swelling' lines (as illustrated in Fig. 1a) to be established. These results were originally plotted using a linear applied stress axis. Results for two of the clays have been reproduced and plotted using a logarithmic scale on the effective stress axis, as is common practice today, in Fig. 2.

The lesser-known oedometer tests on a fine quartz sand (0.25 to 1.00 mm) reported by Terzaghi (1925) have been reproduced and plotted in Fig. 3.

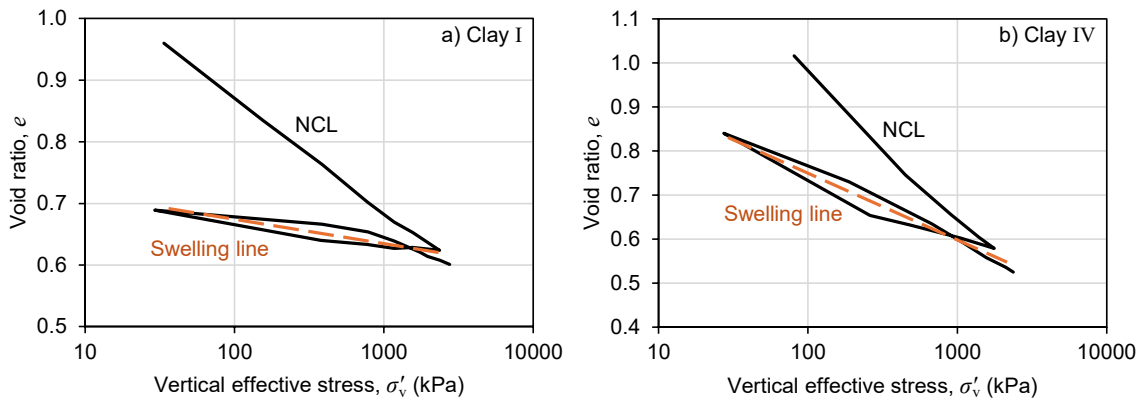


Fig. 2: Earliest oedometer tests on remoulded clays (after Terzaghi, 1925)

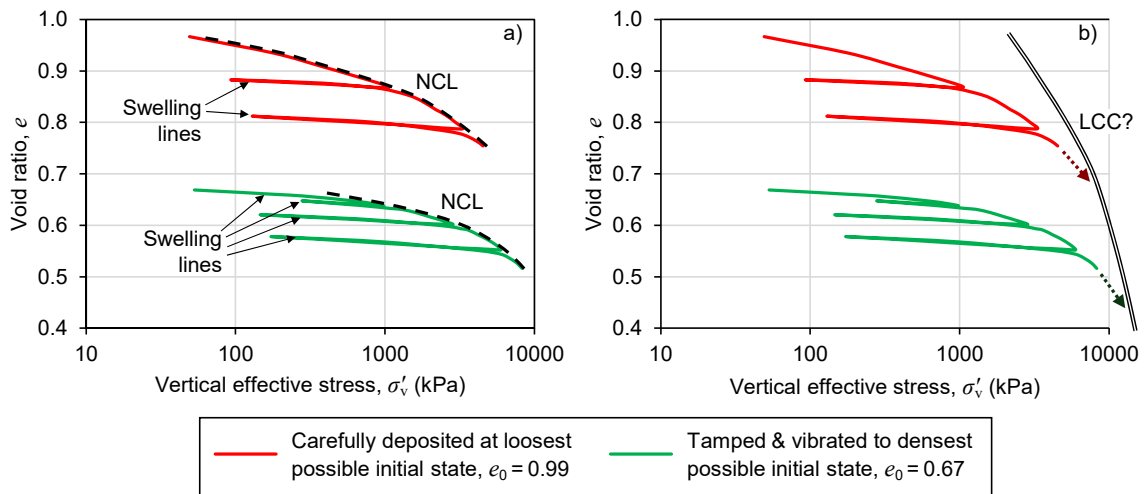


Fig. 3: Earliest oedometer tests on a clean sand (after Terzaghi, 1925)

The two samples were loaded to high stresses, with multiple unload-reload stages. The first was deposited at its loosest possible state prior to testing, and was thus normally consolidated from the onset of loading. The second was subjected to moderate tamping, followed by vibration to the densest possible state, prior to loading. Although initially overconsolidated, this sample was loaded to significantly greater stresses than what was applied during compaction. The annotations added to Fig. 3a highlight the immediately evident similarities to the idealised framework in Fig 1b. Terzaghi (1925) noted that each sand result took on the same form as his clay results, with logarithmic “main branches” (referring to NCLs) as well as parallel logarithmic elastic “swell curves” measured during unloading and reloading. This agrees with the observations of Jefferies & Been (2000). Terzaghi proposed that the sets of swelling lines for the loose and dense samples were also parallel to each other, but that the “main branch” for the loose test was steeper than that of the dense test, without further comment. Upon further inspection, one can see that the initial loading path for the dense test follows a swelling line, due to the fact that it was initially overconsolidated. After yielding, this path had seemingly converged onto an NCL parallel to that of the loose test, once more conforming with the results of Jefferies & Been (2000). When commenting on the observed loading paths for the sand, Terzaghi stated:

“...the permanent densification of the originally loose material caused by applied stress was significantly less than that achieved prior to [the dense] test by vibration and light tamping without significant effort. This phenomenon shows that unlike the clays, sands retain their original structure even under high pressure.” (Terzaghi, 1925; translated from German). This displays a clear appreciation of stress history, as well as the fundamental reasons for the non-uniqueness of compression paths for normally consolidated sands. Fig. 3b graphically hypothesises that the increasing compressibility of both samples at stresses of several MPa may have been a sign of a tendency toward a limiting compression curve. Remarkably, Terzaghi (1925) discussed how greater deformation would take place due to breakage of individual sand grains at high stresses, and that the reduction in void ratio due to grain crushing would increase linearly with applied stress. He conducted sieve analyses on a sample of the quartz sand before and after applying a mechanical load of 5 MPa, and found that the fines content increased from 0% to 4.6% due to particle crushing. The appreciation for elastoplastic behaviour, non-unique NCLs, and the phenomenon of particle crushing all show that Terzaghi’s results and analyses reflected several aspects of the modern understanding of compression behaviour of sands, three quarters of a century prior to the introduction of the frameworks that conclusively described them.

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