

## Practical guidelines on the determination of one-dimensional swell properties of highly expansive clays

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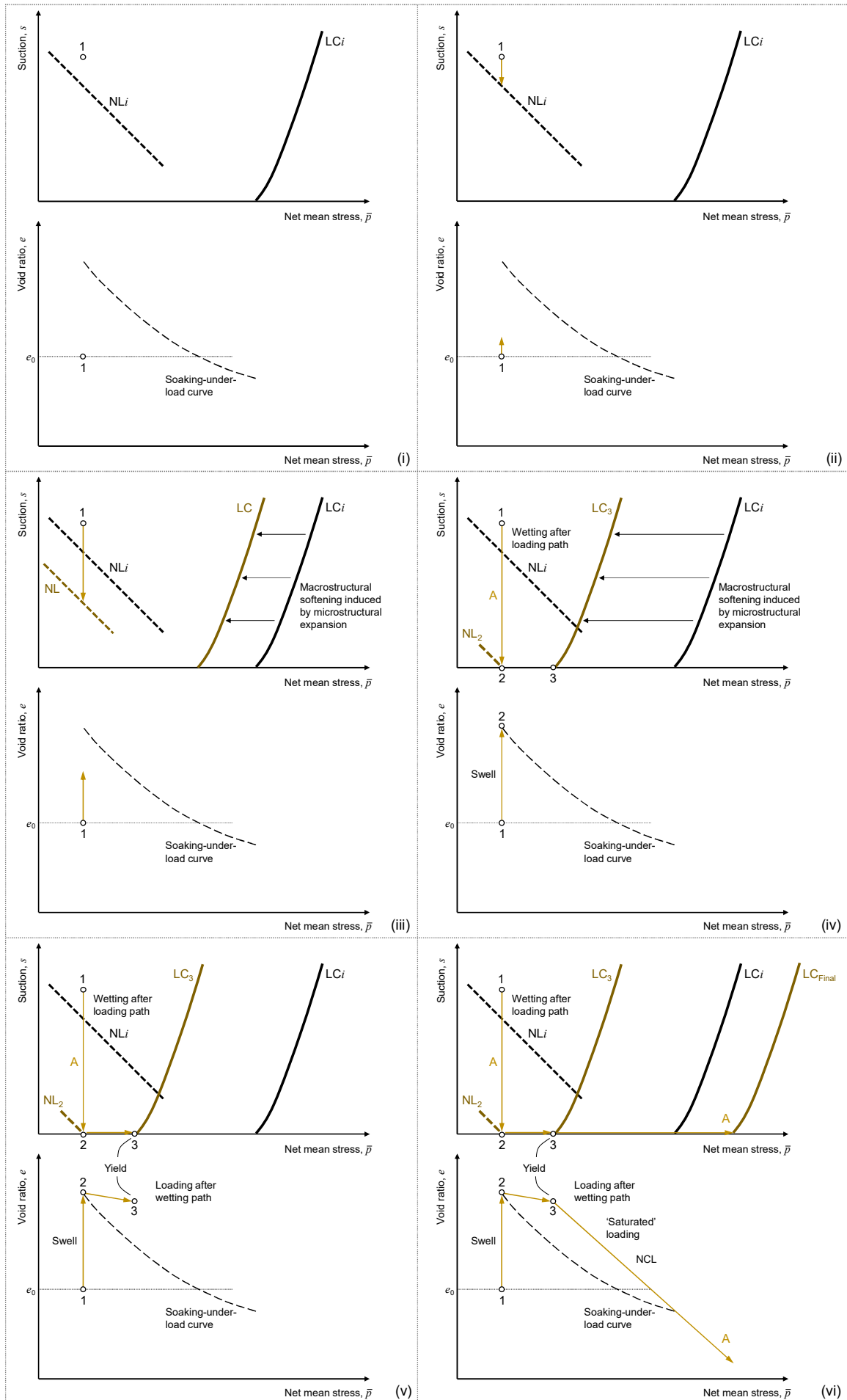
### Stress paths for different test methods according to the BExM

This supplementary document gives a detailed description of the generation of the stress paths depicted in Figure 5 of the main text, according to the Barcelona Extended Model for expansive clays (BExM) (Gens and Alonso, 1992).

Consider a soil element existing at an initial state given by void ratio  $e_0$ , suction  $s_0$ , and a nominal net mean stress  $\bar{p}_0$ . This initial state has been termed Point 1 in Figures A1 through A3. For this initial state, the initial macrostructural load–collapse yield curve for the sample lies at a position  $LC_i$ . Gens and Alonso (1992) defined the neutral loading line (NL) as a relationship of net stress and suction combinations resulting in no volume change on a microstructural level. If the microstructure is always assumed to be fully saturated, this relationship can be described by a line inclined at  $45^\circ$  (i.e.  $\bar{p} + s = \text{constant}$ ). In the original BExM formulation it is assumed that an NL line corresponding with the lowest  $(\bar{p} + s)$  combination in the element’s history “plays a role similar to that of a yield locus” (Gens and Alonso, 1992) – i.e. plastic macrostructural swelling due to microstructural expansion, as well as swell-induced softening of the LC yield curve, only occur after this NL line has been crossed. For the state at Point 1, this initial microstructural neutral loading line is given by  $NL_i$ .

Three different hypothetical tests have been carried out from Point 1, as described by Gens and Alonso (1992). It is recognised that isotropic stress conditions and suction control apply to these hypothetical tests, rather than the oedometric conditions to which the samples tested in the current study were subjected.

Consider first a loading after wetting test conducted at a soaking stress equal to the initial stress (Figure A1). The sample is inundated with water under constant confining stress. Elastic swelling begins to commence as the suction is decreased, until the initial microstructural yield locus  $NL_i$  is engaged by the stress path (Frame ii). Hereafter, plastic macrostructural swelling strains begin to accumulate along with the elastic strains. During this process, the position of the new neutral loading line is moved downwards along with the stress path, and swell-induced softening due the microstructural expansion is marked by movement of the LC yield curve to the left (Frame iii). The migration of the NL and LC loci continues until the sample reaches equilibrium at zero suction. At this stage, the state path has met the soaking-under-load curve at Point 2 (Frame iv). After soaking, the sample is loaded at a constant suction of zero. Compressive strains are elastic and the loading path of the overconsolidated sample is inclined at a slope of  $\kappa(0)$  in  $e$ - $\ln \bar{p}$  space until yielding occurs upon engagement of the LC yield curve at Point 3 (Frame v). After yielding, elastic and plastic compressive strains are accumulated as the state path of the sample traverses along the ‘saturated’ normal consolidation line (NCL) in Frame vi, and the loading path in  $e$ - $\ln \bar{p}$  space is thus inclined at  $\lambda(0)$ . The LC yield curve is shifted to the right along with the stress path due to strain-induced hardening. The complete state path followed in this test has been termed Path A in Figure 5 of the main text. Path A represents a case similar to the *loading after wetting* tests where samples were soaked under 1.1 kPa.



**Figure A1: Stress Path A – loading after wetting test soaked at a nominal seating stress**

Next, consider Path B in Figure A2, which represents a test where a sample is loaded at constant suction (1-6), *wetting after loading* is conducted at a higher soaking stress (6-7), after which the sample is consolidated along a *loading after wetting* path (7-4-5). The initial state once again starts at Point 1, with the same positions  $LC_i$  and  $NL_i$  for the yield loci on macrostructural and microstructural levels respectively (Frame i). The loading path at constant suction  $s_0$  from Point 1 to 6 will be inclined at a slope of  $\kappa(s_0)$  in  $e-\ln \bar{p}$  space, as elastic compressive strains are generated (Frame ii). As suction is reduced, the initial NL line is engaged in Frame iii, after which permanent swelling strains are generated and swell-induced softening shifts the LC yield curve to the left until its final position at  $LC_4$  (Frame iv). Note that a lesser degree of swell-induced softening has occurred in this case, when compared to that of Path A. Equilibrium is achieved at Point 7 on the soaking-under-load curve. Loading after wetting commences at constant zero suction and the overconsolidated sample follows a loading path inclined at  $\kappa(0)$  until yielding upon  $LC_4$  (Frame vi). Note that since the NCL is assumed to be unique, Point 4 lies upon the NCL followed by loading Path A. After yielding, the state path follows along the NCL, and strain-induced hardening shifts the LC yield curve to the right (Frame vi). The final position of the load-collapse yield curve ( $LC_{Final}$ ) coincides with that of Path A. The stress path followed in this test (Path B) represents a case similar to *wetting after loading* to 100 kPa, for example, followed by consolidation. A series of such tests is used to construct the soaking-under-load curve, which is assumed to be a unique relationship given the initial conditions in this analysis.

Finally, consider Path C (Figure A3), which represents a test where loading is carried out at constant suction to a high net mean stress (i.e. greater than the initial yield stress at zero suction – e.g. along 1-6-8), followed by wetting after loading (8-5). Once more, the sample starts at Point 1 with initial yield loci  $LC_i$  and  $NL_i$  (Frame i). The sample is loaded at a constant suction and elastic compression occurs at a slope of  $\kappa(s_0)$  in  $e-\ln \bar{p}$  space in Frame ii. The state of the unsaturated element at Point 8 is beyond the normal consolidation line, and thus the sample exists in a state that is only attainable due to the presence of suction. Hereafter, if the sample were to be wetted to zero suction, the LC yield curve would be engaged during wetting, inducing yielding followed by permanent strains during collapse of the sample (Frame iii). Strain-induced hardening shifts the LC yield curve to the right until it reaches position  $LC_5$  as the sample collapses onto the NCL. The sample is then loaded at zero suction and follows along the same NCL as that of Paths A and B (Frame iv). Prior to wetting (1-6-8), this test resembles something similar to the constant water content tests conducted on the two clays. A key difference is that suction control was not imposed on the oedometer sample, but the philosophy of maintaining the initial water content is to achieve a similar goal. Note that the unsaturated loading path (1-6-8) has been drawn parallel to the nonvirgin saturated loading paths (2-3 and 7-4) in these analyses, which implies the original Barcelona Basic Model assumption that  $\kappa$  is not dependent on suction (i.e.  $\kappa(s_0) = \kappa(0)$ ) (Alonso et al., 1990). This is an acknowledged limitation, and was found not to be true for the clays tested in the main text. However, this is purely a graphical assumption, and bears no influence on the analysis and consequences discussed in the main text. The wetting path (8-5) resembles a *wetting after loading* path which results in compression onto the soaking-under-load curve, such as the samples soaked under 1200 kPa for the Olive Clay and 800 kPa for the Black Clay in the main text.

Combining Paths A, B, and C, as well as the applicable neutral loading lines and load-collapse yield curves, gives the framework outlined in Figure 5 of the main text.

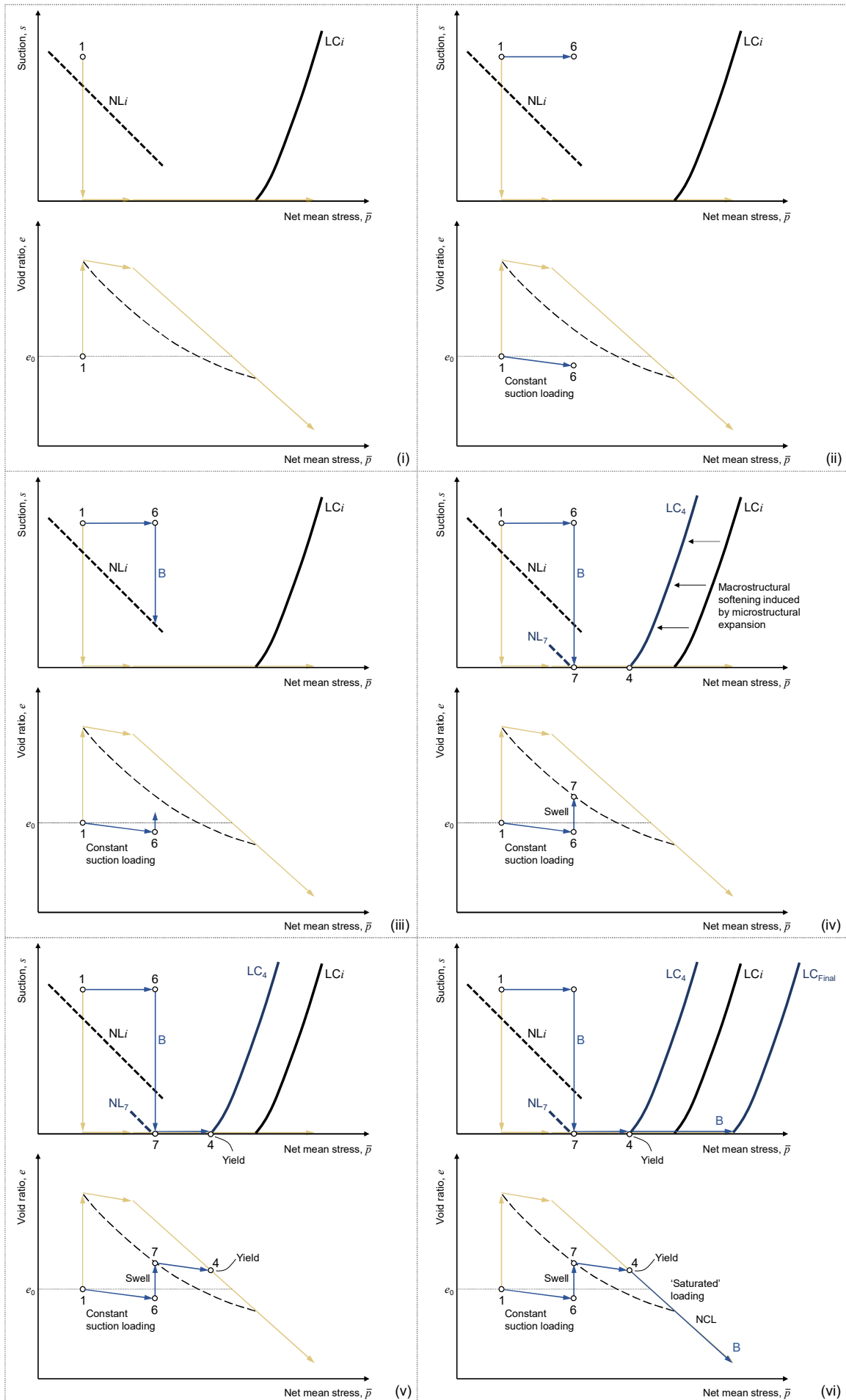
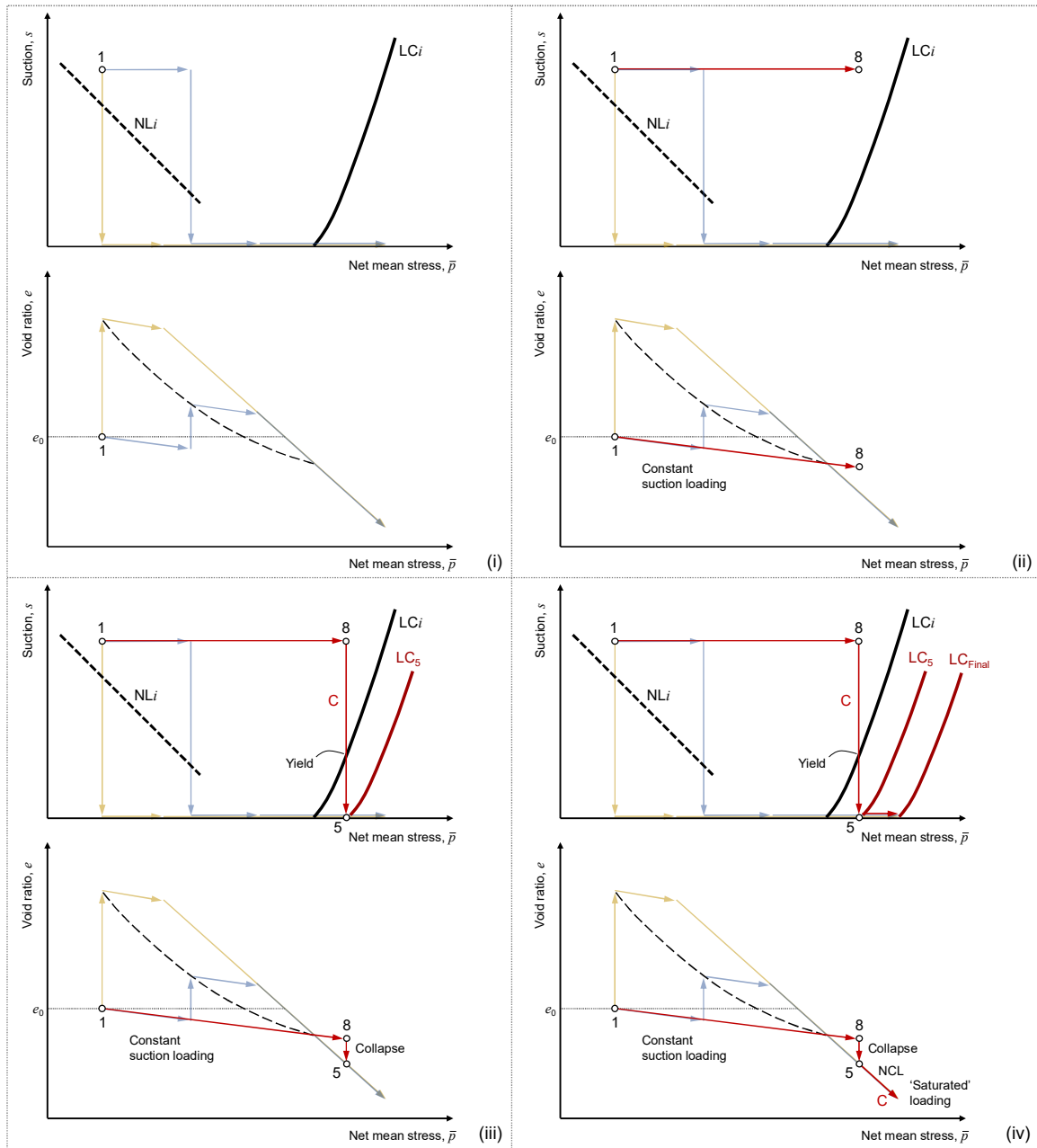


Figure A2: Stress Path B – wetting after loading test, followed by consolidation



**Figure A3:** Stress Path C – constant suction loading, followed by wetting after loading at a stress in the collapsing range, followed by consolidation

## References

- Alonso, E.E., Gens, A. and Josa, A. (1990). A constitutive model for partially saturated soils. *Géotechnique* **40**(3): 405-430. <https://doi.org/10.1680/geot.1990.40.3.405>
- Gens, A. and Alonso, E.E. (1992). A framework for the behaviour of unsaturated expansive clays. *Canadian Geotechnical Journal* **29**(6): 1013-1032. <https://doi.org/10.1139/t92-120>