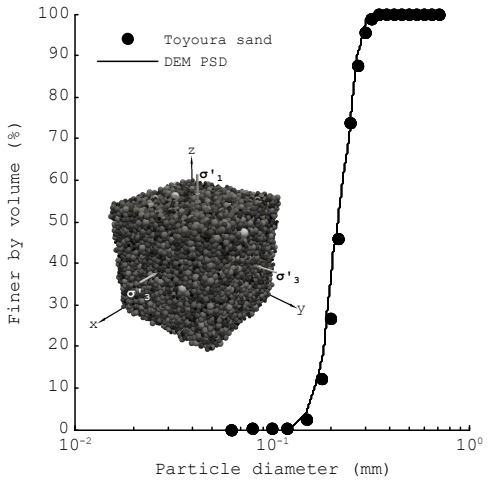


Figure 1. Particle size distribution of numerical samples compared with laboratory data for Toyoura sand. The inset figure shows a representative sample for simulations following isotropic compression.

Figure 2. Stress paths adopted: (a) drained shearing followed by CSD simulation; (b) drained shearing followed by CV simulation.

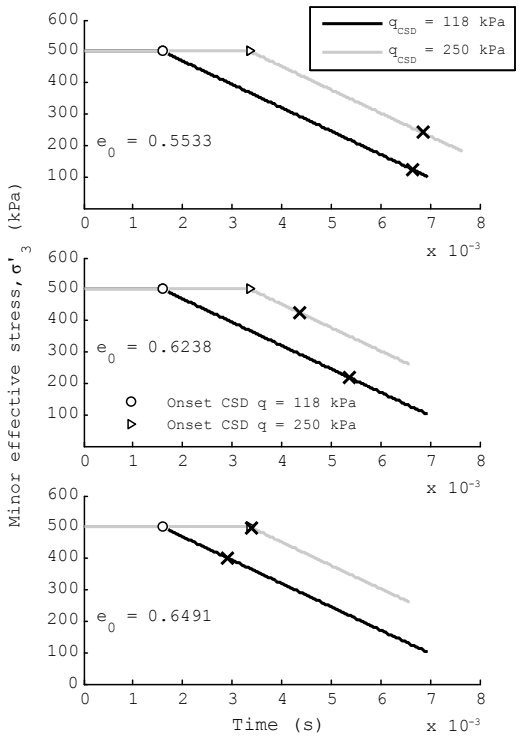


Figure 3. Minor principal effective stress σ'_3 against time. Cross markers indicate the onset of instability for CSD tests. The open circle indicates the onset of CSD conditions for $q_{\mathrm{CSD}} = 118$ kPa, while the open triangle indicates the onset of CSD conditions for $q_{\mathrm{CSD}} = 250$ kPa.

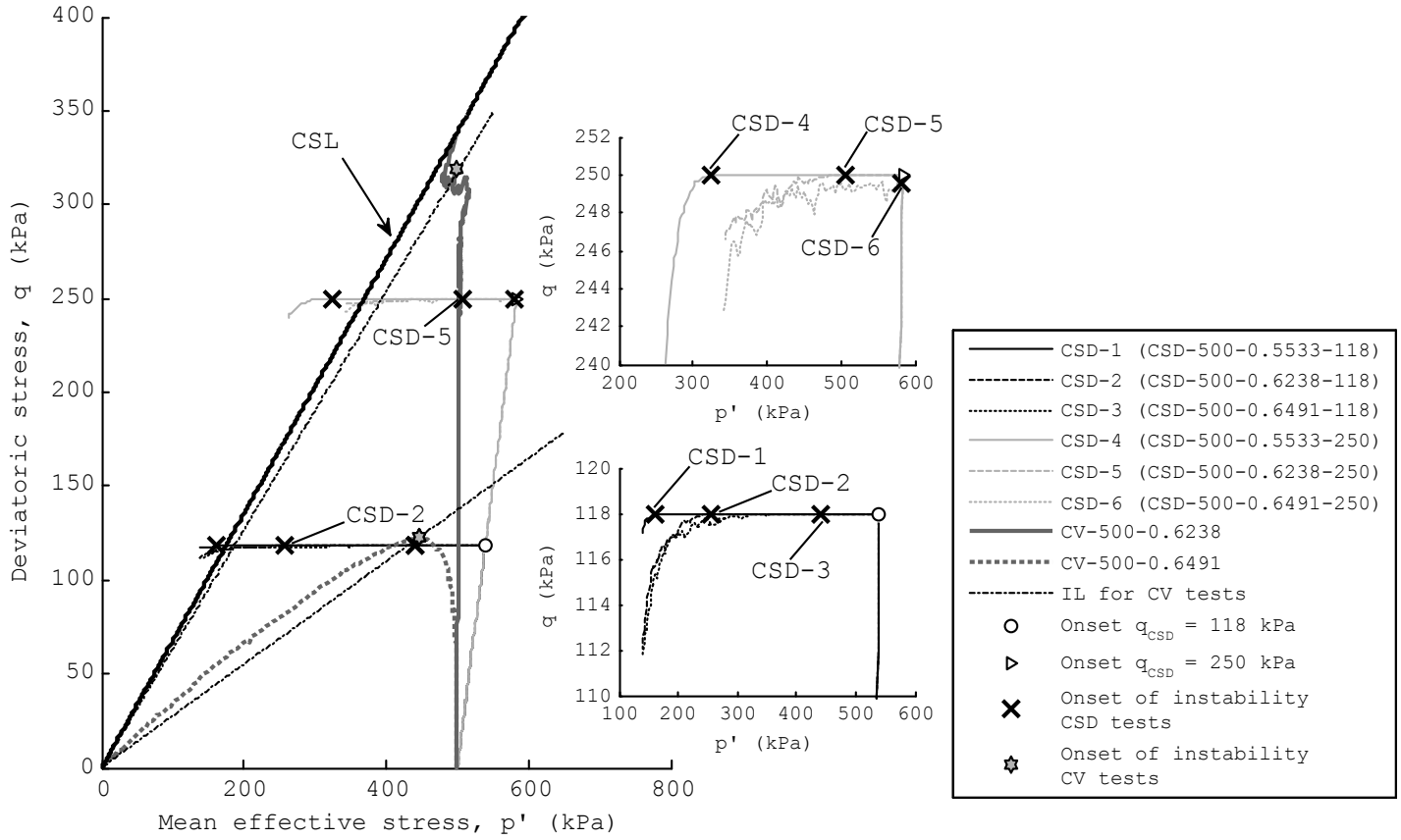
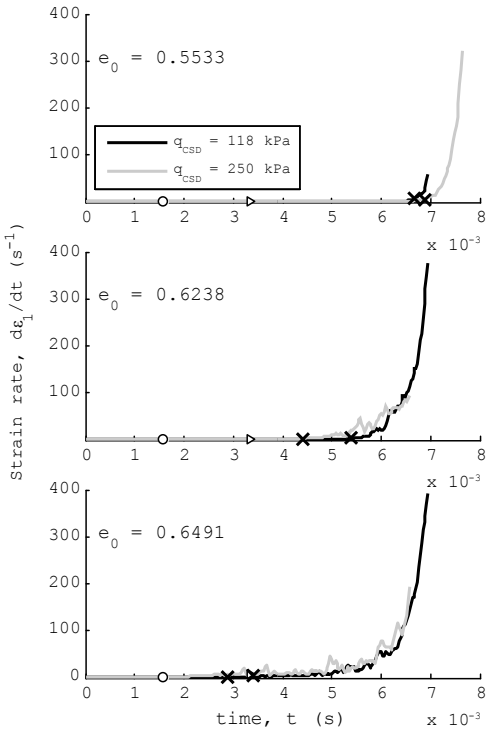
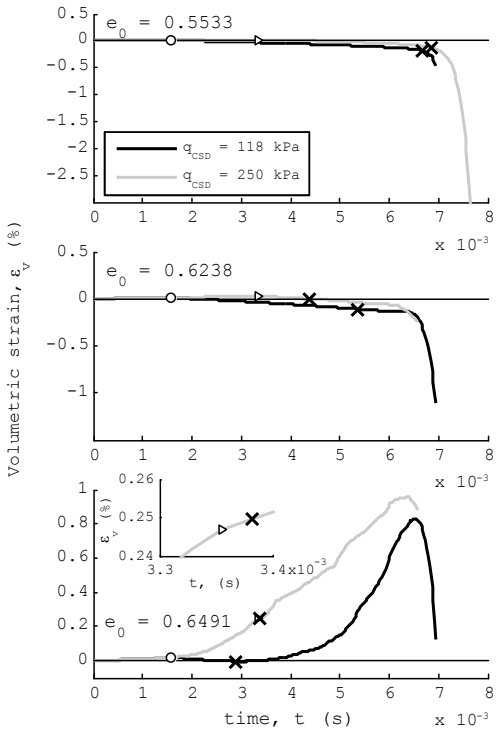


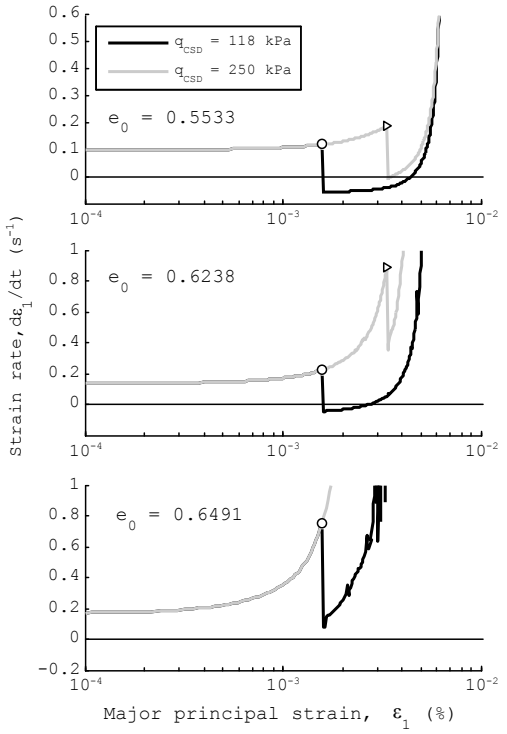
Figure 4. Deviatoric stress q against mean effective stress p' for CSD and CV simulations. Inset figures zoom in to the onset of instability of the CSD tests.



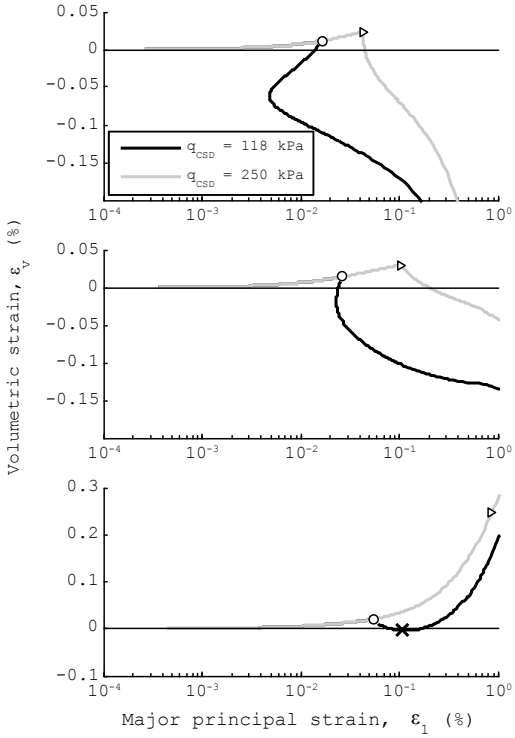
(a)



(b)

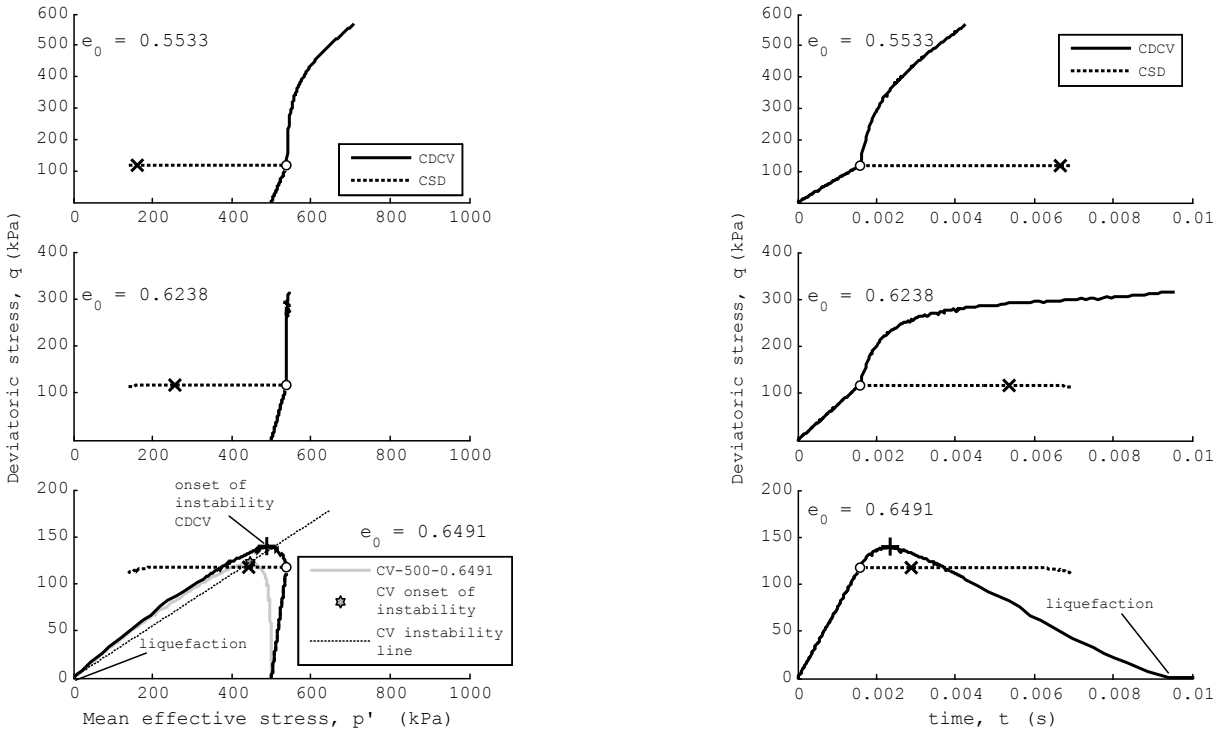


(c)



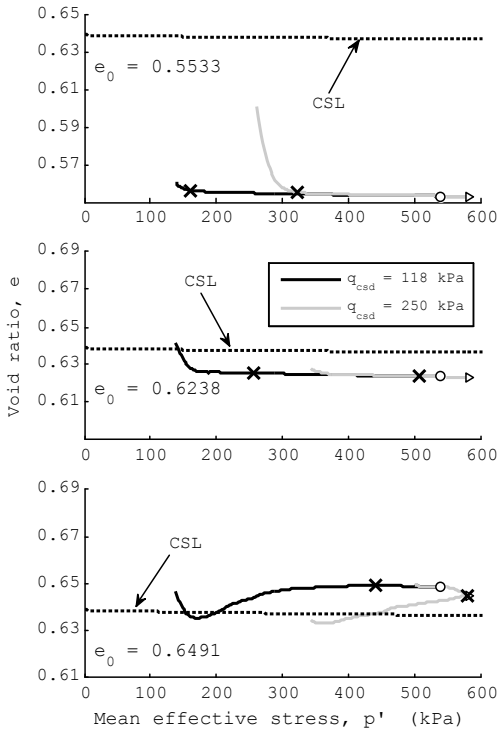
(d)

Figure 5. (a) Strain rate against time, (b) Volumetric strain against time and (c) Strain rate against axial strain for the CSD tests and (d) Volumetric strain against axial strain. Cross markers indicate the onset of instability.

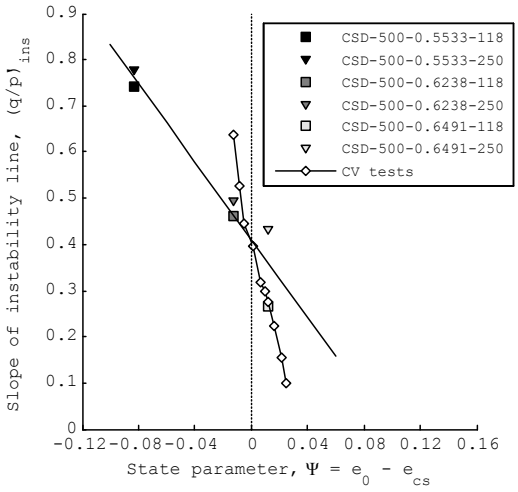


(a) (b)

Figure 6. Comparing the macro-scale responses between CSD test and CDCV tests. (a) q against p'; (b) q against time. Cross markers indicate the onset of instability for CSD tests while plus sign markers indicate the onset of instability for the CDCV test.

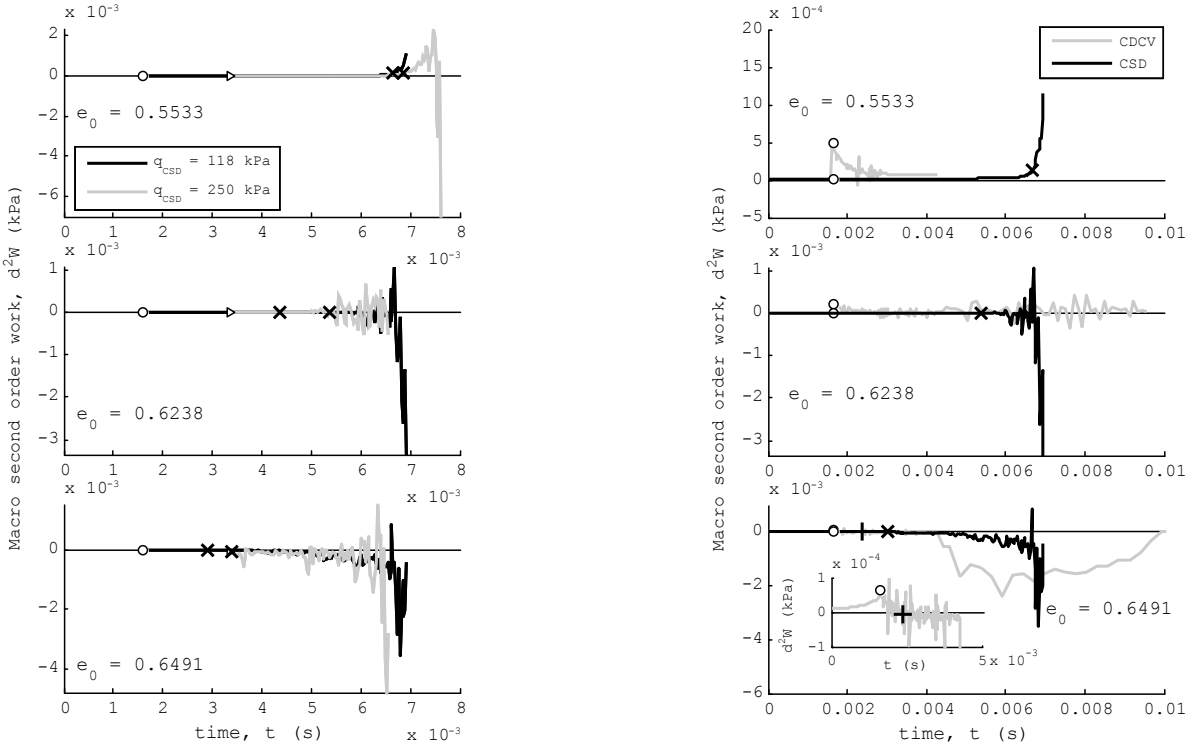


(a)



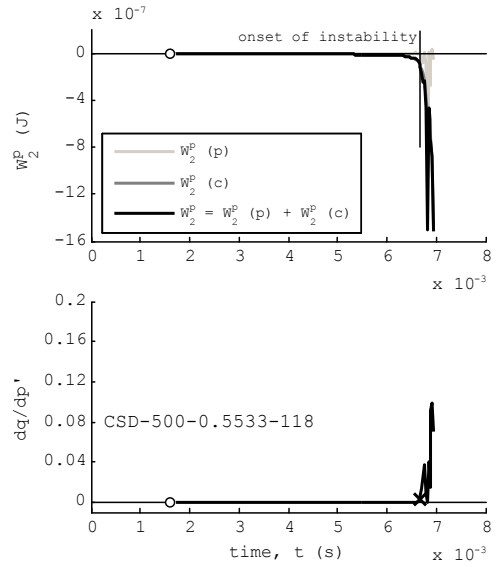
(b)

Figure 7. (a) Void ratio e against mean effective stress p' during CSD shearing; (b) Stress ratio at the onset of instability against state parameter, showing CSD tests and CV tests. Cross markers in Figure 7(a) indicate the onset of instability.

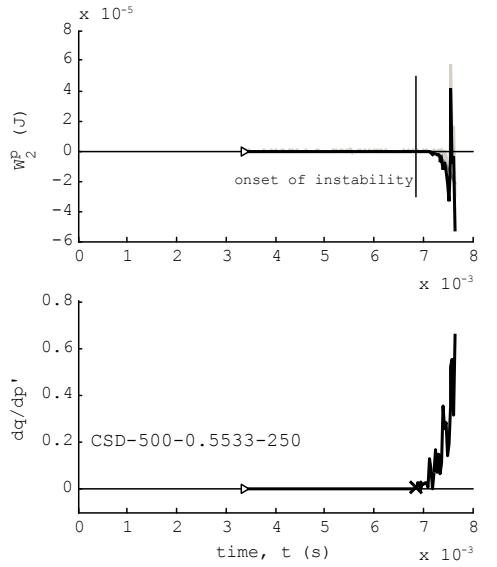


(a) (b)

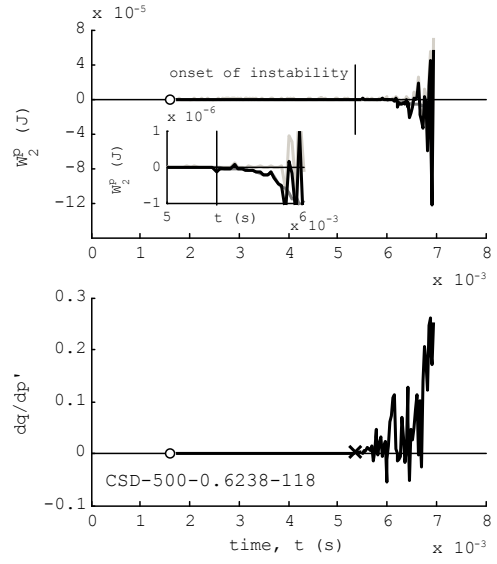
Figure 8. Macro-scale second-order work against time for (a) all CSD tests and (b) CSD tests with $q_{\mathrm{CSD}} = 118$ kPa and CDCV tests. Cross markers indicate the onset of instability for CSD tests while plus sign markers indicate the onset of instability for the CDCV test



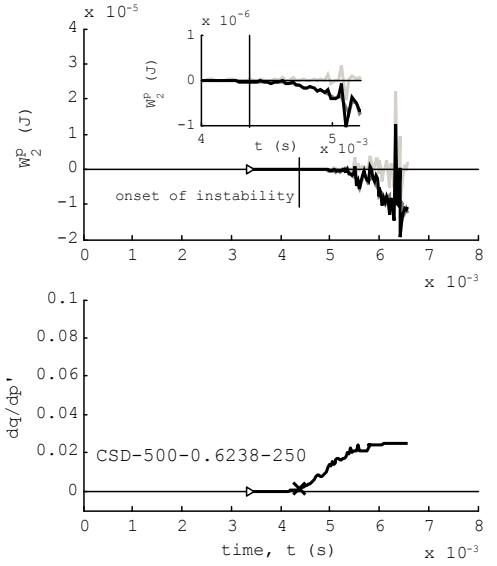
(a)



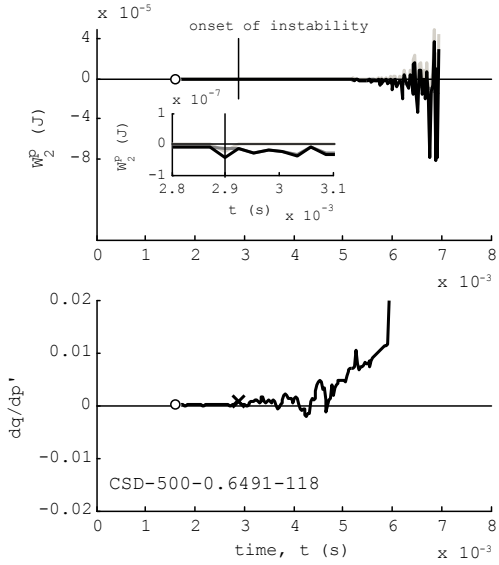
(b)



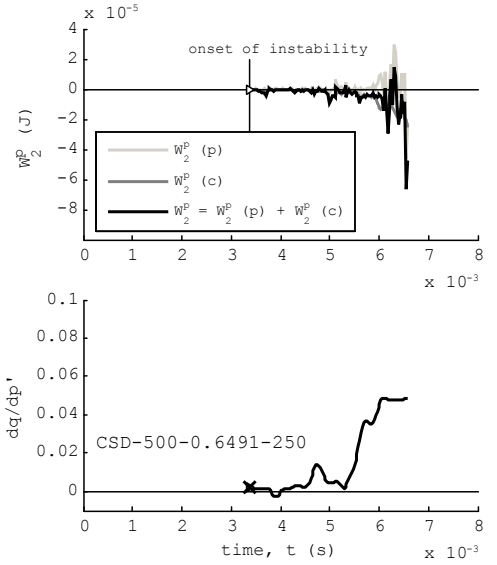
(c)



(d)



(e)



(f)

Figure 9. Micro-scale second-order work and gradient dq/dp' against time for the CSD tests. Cross markers and vertical lines indicate the onset of instability.

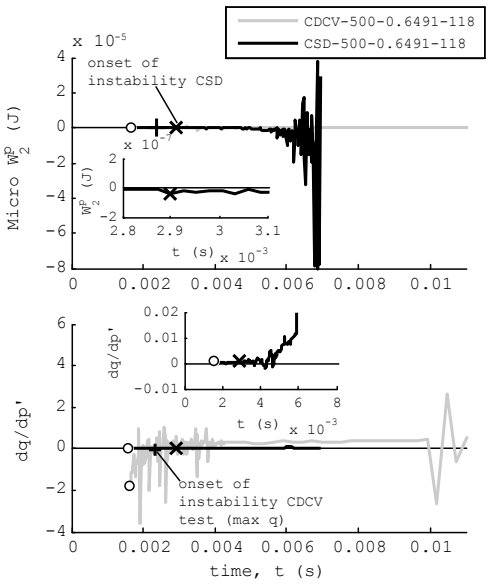
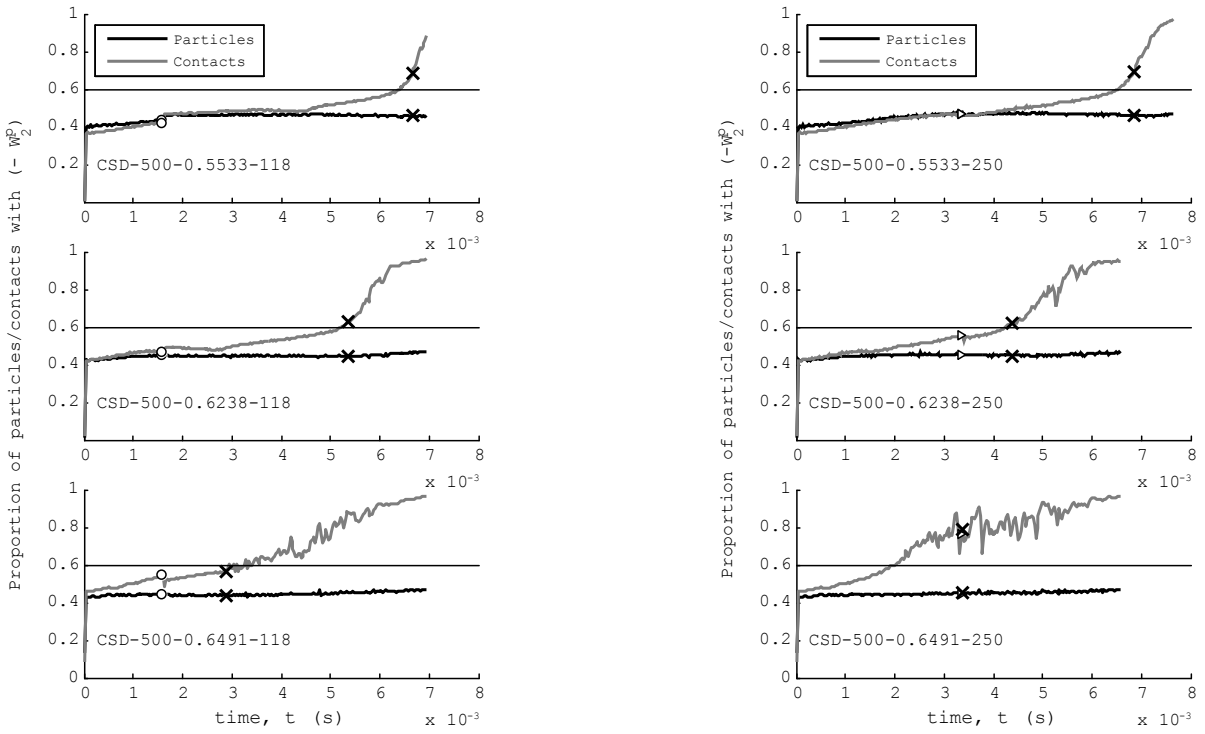


Figure 10. Comparison of micro-scale second-order work and gradient dq/dp' against time between CDCV and CSD tests. Cross markers indicate the onset of instability for CSD tests while plus sign markers indicate the onset of instability for the CDCV test.



(a) (b)

Figure 11. Proportion of particles and contacts carrying negative micro second order work. (a) $q_{\mathrm{CSD}} = 118$ kPa and (b) $q_{\mathrm{CSD}} = 250$ kPa. Circle and triangle markers indicate the onset of CSD conditions for $q_{\mathrm{CSD}} = 118$ kPa and $q_{\mathrm{CSD}} = 250$ kPa respectively. Cross markers indicate the onset of instability.

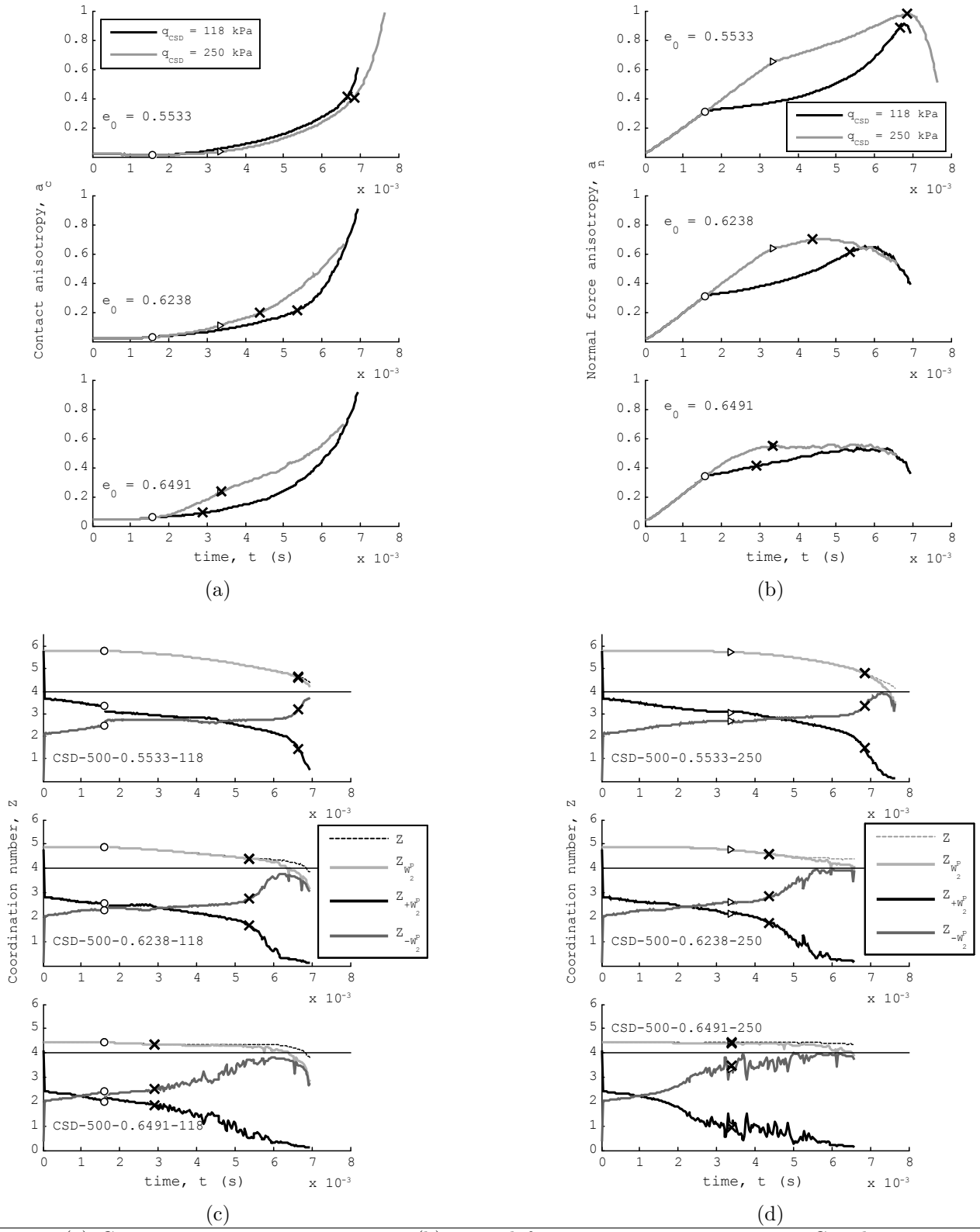
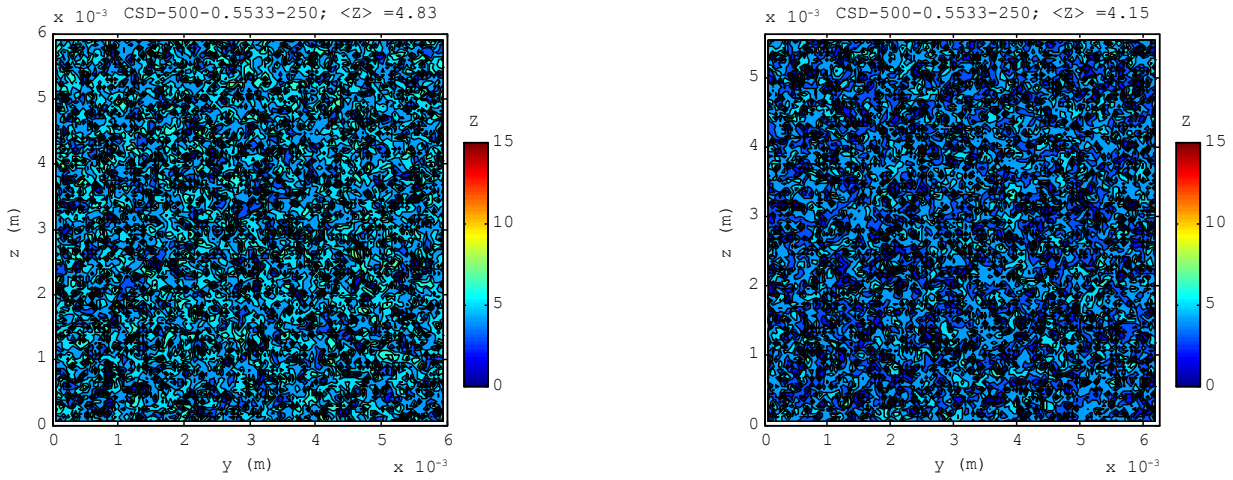


Figure 12. (a) Contact anisotropy against time; (b) normal force anisotropy against time, Coordination number against time for (c) qcsd = 118 kPa and (d) qcsd = 250 kPa. Circle and triangle markers indicate the onset of CSD conditions for $q_{\mathrm{CSD}} = 118$ kPa and $q_{\mathrm{CSD}} = 250$ kPa respectively. Cross markers indicate the onset of instability.



(a) (b)

Figure 13. Contour plots of coordination number across the plane Y-Z for the dense sample CSD-500-0.5533-250. (a) At onset of instability with a mean coordination number ($<Z>$) of 4.83 and (b) at end of test with $<Z> =$ 4.15.

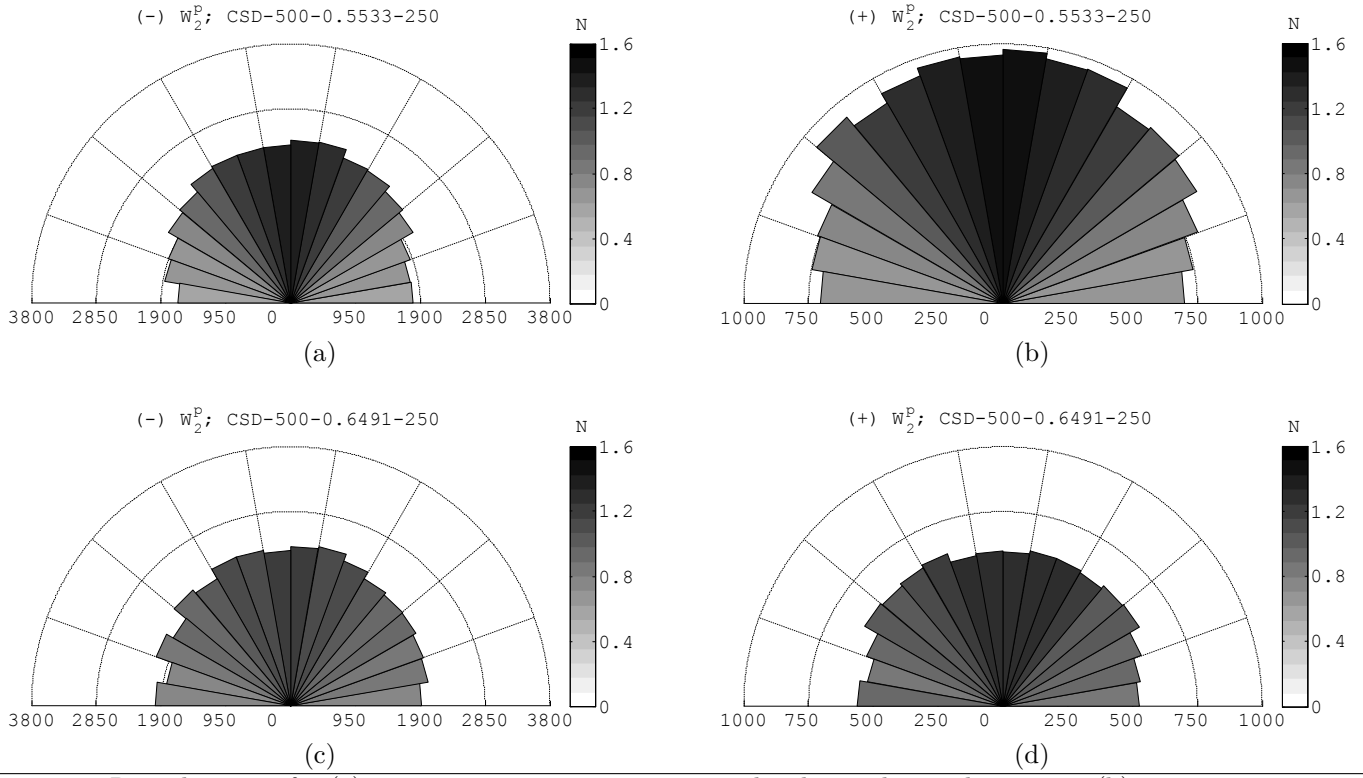


Figure 14. Rose diagrams for (a) contacts carrying negative second order work in a dense state (b) contacts carrying positive second order work in a dense state (c) contacts carrying negative second order work in a loose state and (d) contacts carrying positive second order work in a loose state

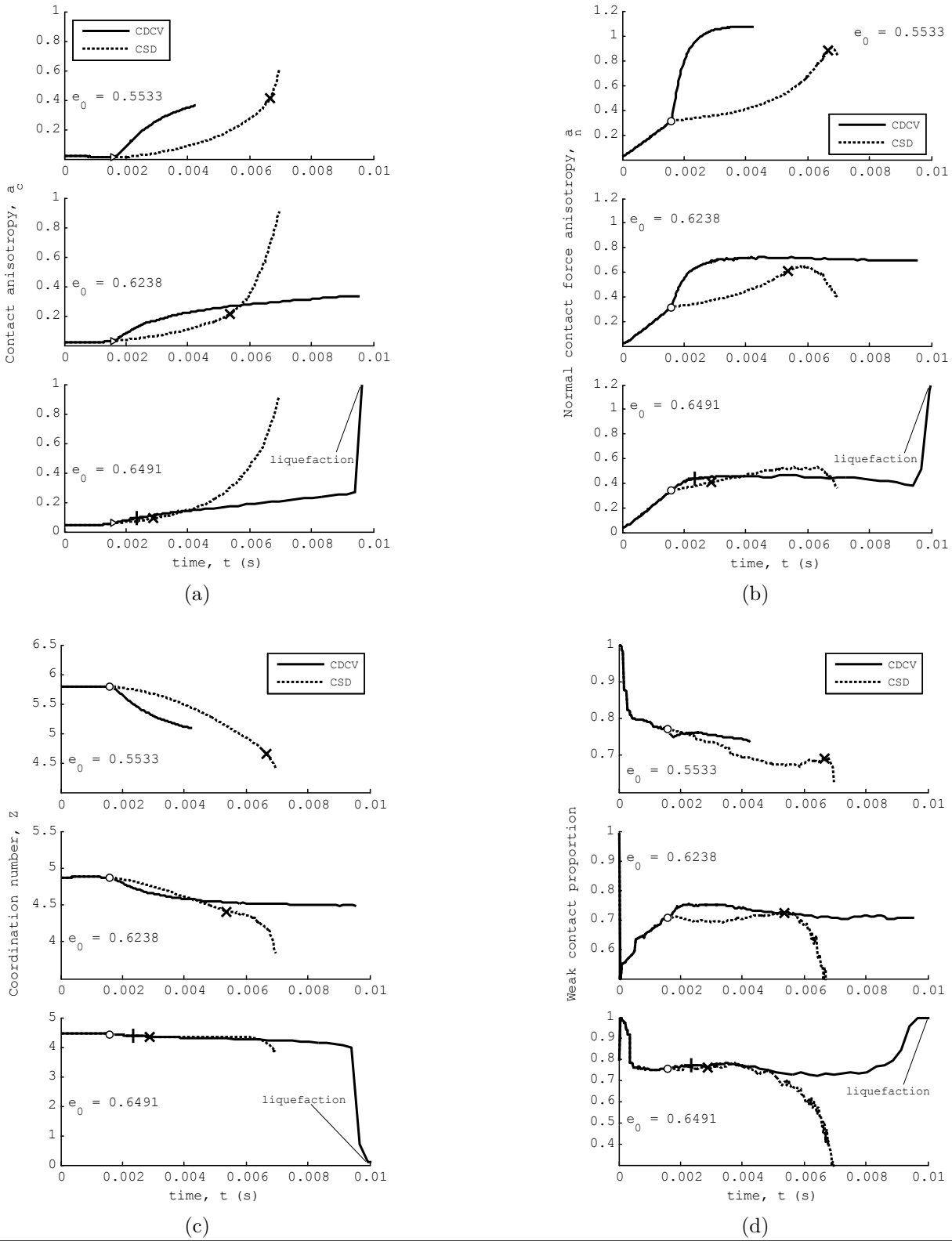


Figure 15. Comparison of the micro response against time for CSD and CDCV tests: (a) Contact anisotropy a_c (b) Normal contact force anisotropy a_n (c) Coordination number (d) Weak contact proportion. Cross markers indicate the onset of instability for CSD tests while plus sign markers indicate the onset of instability for the CDCV test.

Table 1. List of tests conducted

Test ID	e_0	e_{CSD}	p'_0 (kPa)	q_{csd} (kPa)	q_{cv} (kPa)	e_{cs}	p'_{cs} (kPa)	q_{cs} (kPa)
CSD-500-0.5533-118	0.5533	0.5532	500	118	-	-	-	-
CSD-500-0.6238-118	0.6238	0.6236	500	118	-	-	-	-
CSD-500-0.6491-118	0.6491	0.6488	500	118	-	-	-	-
CSD-500-0.5533-250	0.5533	0.5530	500	250	-	-	-	-
CSD-500-0.6238-250	0.6238	0.6234	500	250	-	-	-	-
CSD-500-0.6491-250	0.6491	0.6450	500	250	-	-	-	-
CDCV-500-0.5533-118	0.5533	0.5532	500	-	118	-	-	-
CDCV-500-0.6238-118	0.6238	0.6236	500	-	118	-	-	-
CDCV-500-0.6491-118	0.6491	0.6488	500	-	118	-	-	-
CV-500-0.6238	0.6238	-	500	-	-	0.6238	5176.8	3586.6
CV-500-0.6280	0.6280	-	500	-	-	0.6280	4064.0	2795.6
CV-500-0.6312	0.6312	-	500	-	-	0.6312	2775.7	1893.2
CV-500-0.6381	0.6381	-	500	-	-	0.6381	32.11	22.10
CV-500-0.6438	0.6438	-	500	-	-	-	-	-
CV-500-0.6469	0.6469	-	500	-	-	-	-	-
CV-500-0.6491	0.6491	-	500	-	-	-	-	-
CV-500-0.6533	0.6533	-	500	-	-	-	-	-
CV-500-0.6585	0.6585	-	500	-	-	-	-	-
CV-500-0.6614	0.6614	-	500	-	-	-	-	-
CD-100-0.5928	0.5928	-	100	-	-	0.6369	128.7	86.77
CD-500-0.5533	0.5533	-	500	-	-	0.6304	659.1	477.3
CD-500-0.6059	0.6059	-	500	-	-	0.6325	656.03	468.06
CD-500-0.6142	0.6142	-	500	-	-	0.6341	1309.7	928.9
CD-2500-0.5781	0.5781	-	2500	-	-	0.6303	3232.7	2197.6
CD-5000-0.6482	0.6482	-	5000	-	-	0.6238	6477.7	4432.3