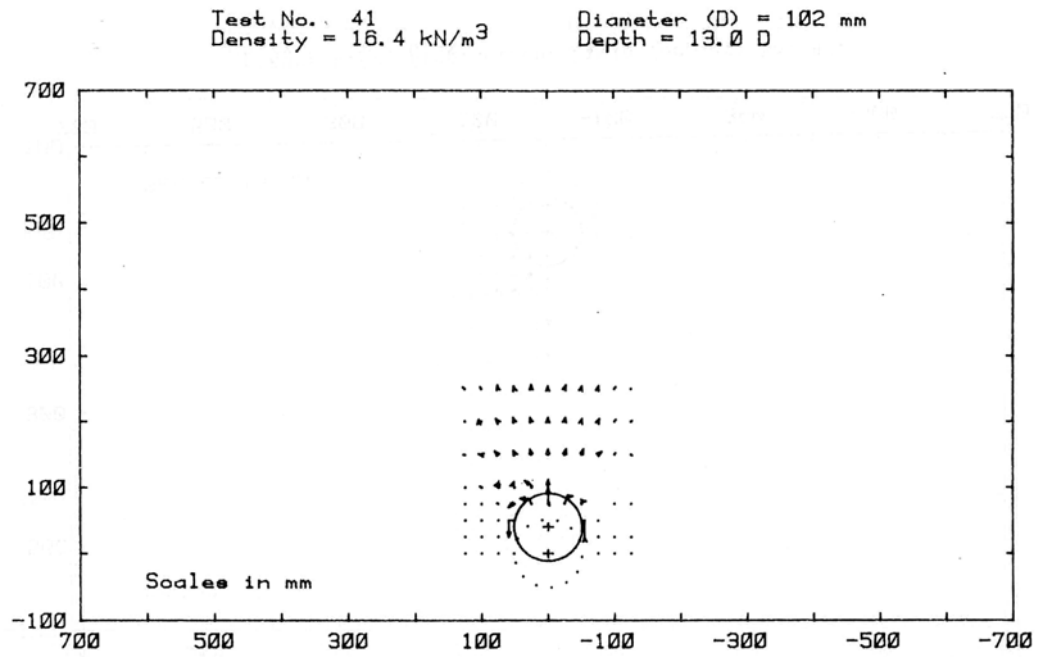
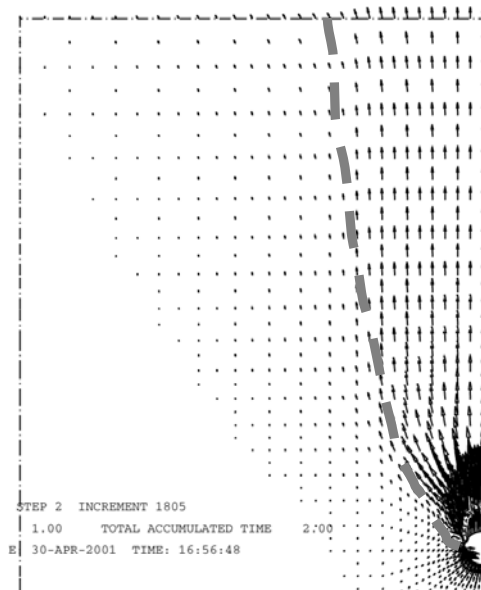


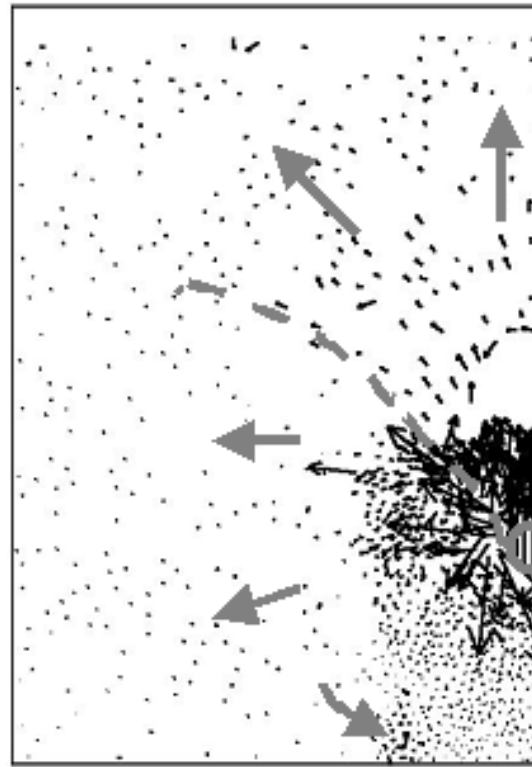
Fig. 7-13 shows that displacement pattern from the experimental tank test of medium sand at  $H_c/D = 13$ , which can be compared to those from FEM and DEM ( $\tan \phi_\mu = 3.0$ ) analyses shown in Fig. 7-14. Similarly, Fig. 7-15 shows that displacement pattern from the experimental tank test of dense sand at  $H_c/D = 13$ , which can be compared to those from FEM and DEM ( $\tan \phi_\mu = 3.0$ ) analyses shown in Fig. 7-16. It can be seen that the results from DEM better represent the displacement of sand around the pipe; however, the results from DEM involve larger soil mass compared with FEM, especially for dense sand. Fig. 7-17 shows the displacement pattern from DEM analysis at deep embedment depth. The results from both medium and dense sands show deep failure mechanism whereby the upward soil deformation does not extend to the ground surface. For medium sand case, this is consistent with the peak dimensionless force data in Fig. 7-12, which shows that a deep failure mechanism has been reached at  $H_c/D = 30$ . However, the dense sand case also shows a deep failure mechanism, although, at  $H_c/D = 30$ , it is still in the transition state. The extent of soil mass involved in the deformation pattern increases as the contact stiffness used increases (or the inter-particle friction angle used decreases). This makes the extent of soil deformation of dense sand at deep depth reaches the model boundary for the case of  $\tan \phi_\mu = 0.5$  (although the width of the testing compartment was already doubled to avoid or lessen the interference of boundary walls). This is consistent with the peak dimensionless force data in Fig. 7-12, which shows that the results for the case of  $\tan \phi_\mu = 0.5$  does not show deep failure mechanism due probably to this boundary effect. Fig. 7-18 presents the contact force chain pattern from DEM analysis. The results also show that the force chain involves large soil mass especially for dense sand.



**Figure 7-13** Displacement pattern of upward pipe loading from experimental tank test ( $H/D = 13$ , Medium sand) (Trautmann & O'Rourke, 1983)

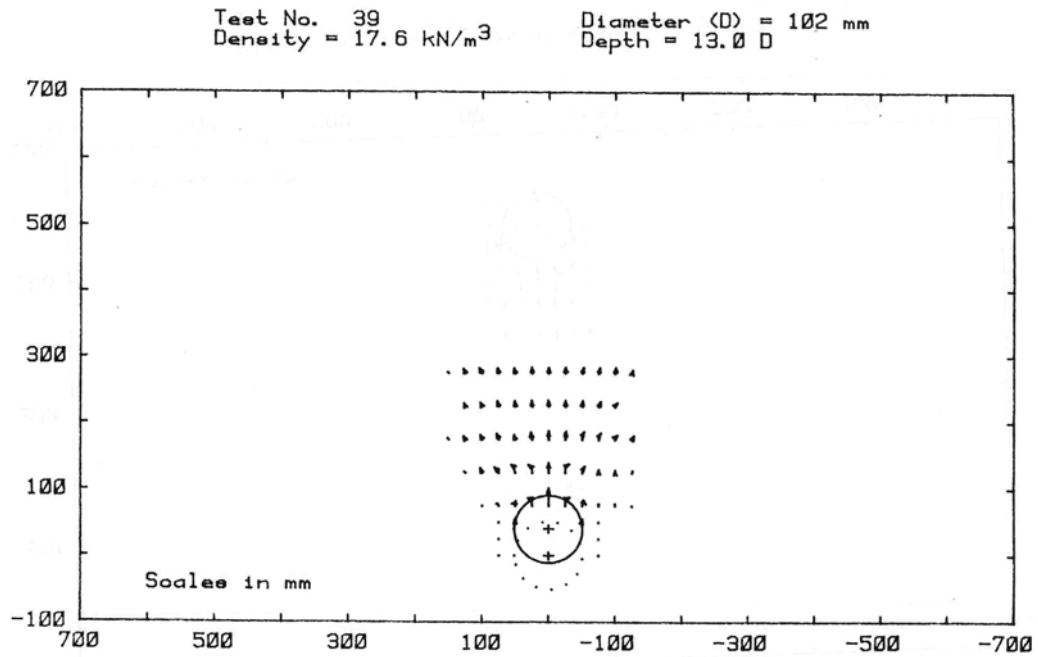


(a) FEM results

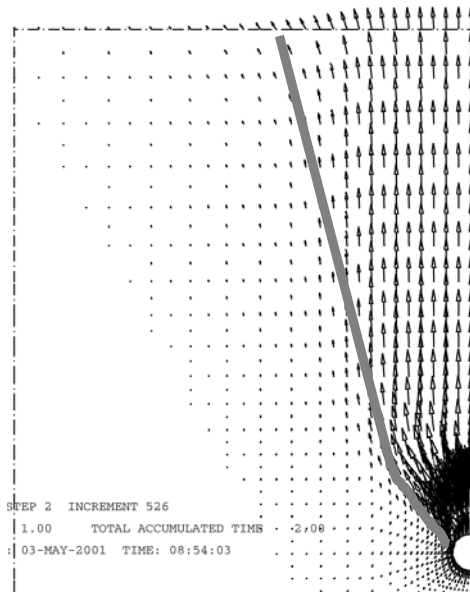


(b) DEM results ( $\tan \phi_\mu = 3.0$ )

**Figure 7-14** Comparison of displacement pattern of upward pipe loading from DEM and FEM ( $H/D = 13$ , Medium sand)



**Figure 7-15** Displacement pattern of upward pipe loading from experimental tank test ( $H/D = 13$ , Dense sand) (Trautmann & O'Rourke, 1983)

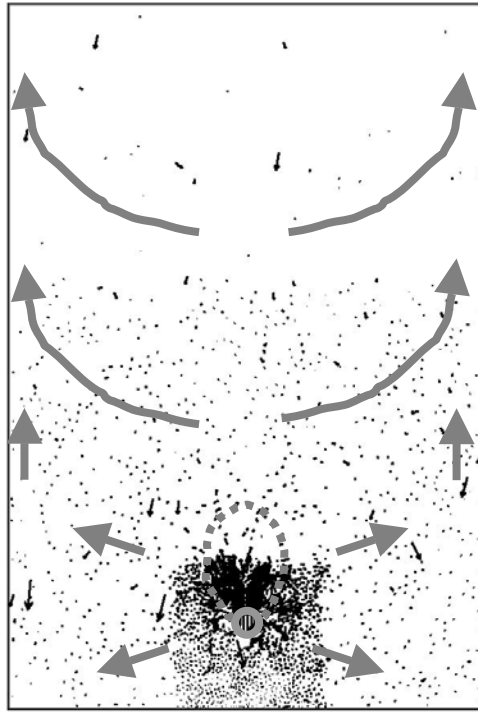


(a) FEM results

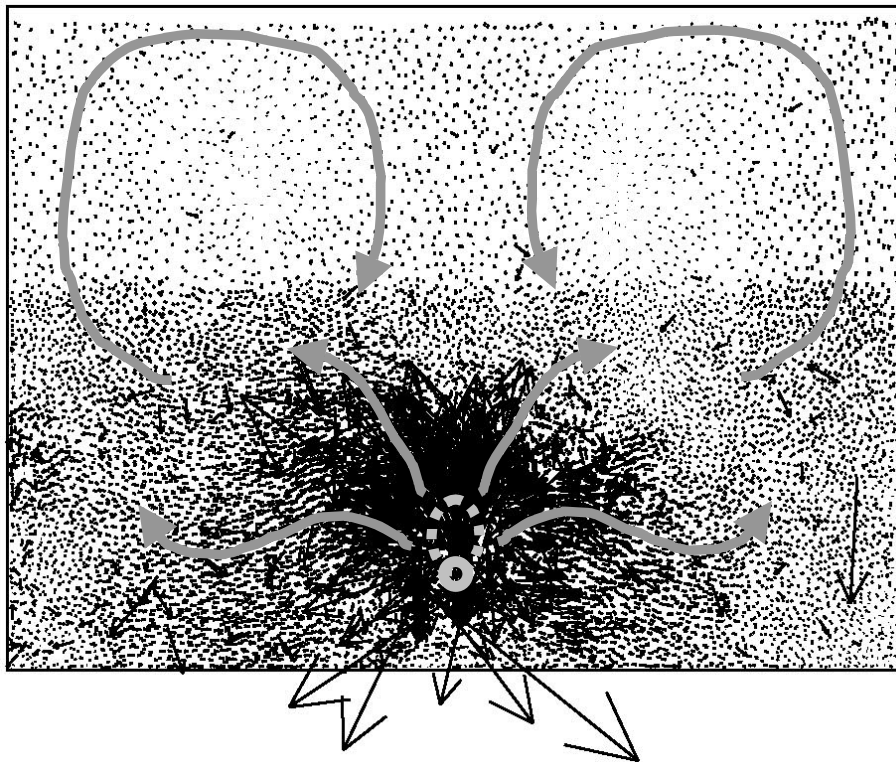


(b) DEM results ( $\tan \phi_{\mu} = 3.0$ )

**Figure 7-16** Comparison of displacement pattern of upward pipe loading from DEM and FEM ( $H/D = 13$ , Dense sand)

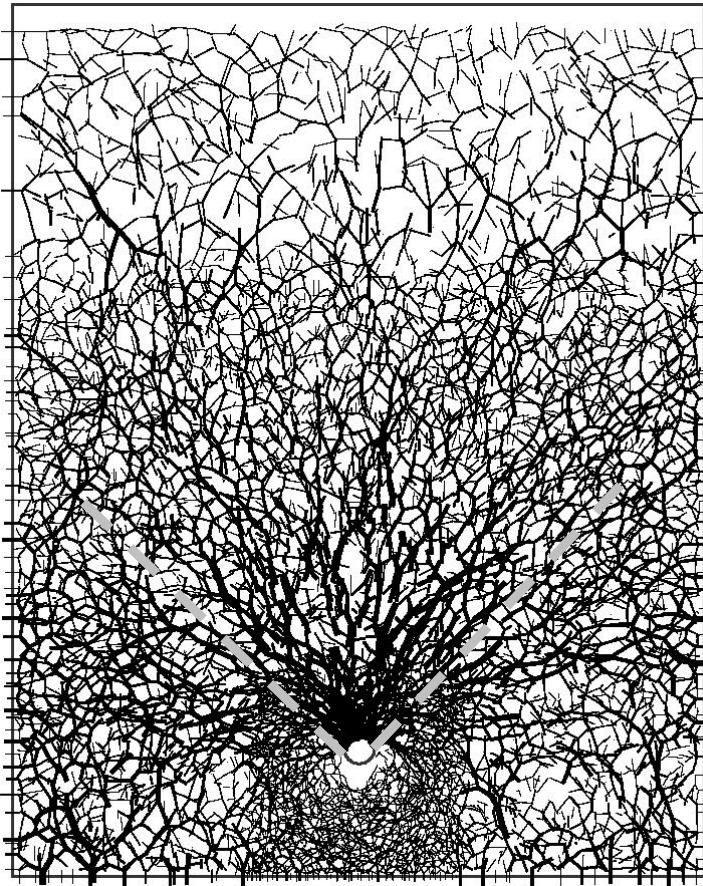


(a) Medium sand,  $\tan \phi_\mu = 3.0$

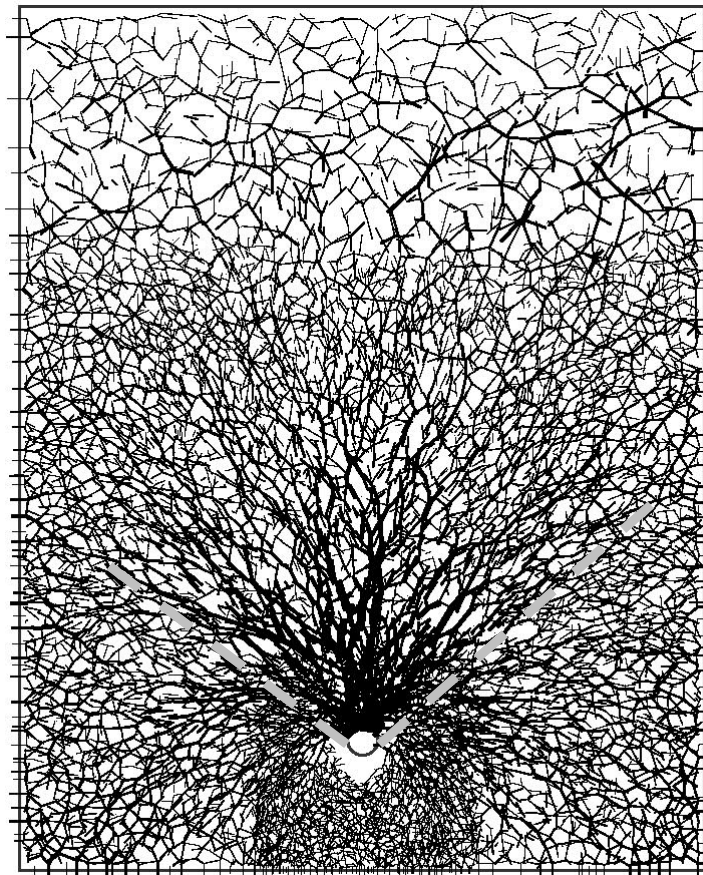


(b) Dense sand,  $\tan \phi_\mu = 3.0$

**Figure 7-17** Displacement pattern from DEM of upward pipe loading ( $H/D = 30$ )



(a) Medium sand,  $\tan \phi_\mu = 3.0$



(b) Dense sand,  $\tan \phi_\mu = 3.0$

**Figure 7-18** Contact force chain pattern from DEM of upward pipe loading ( $H_c/D = 25$ )

## 7.4 Conclusions

The soil-pipeline interactions under later and upward pipe movements in sand were investigated using DEM analysis. The simulations were performed for both medium and dense sand conditions at different embedment ratios of up to  $H/D = 60$  and  $H_c/D = 60$ . At shallow depth, the force-displacement relationships from the DEM analysis for medium sand match the experimental data well for all cases of  $\tan \phi_\mu$ , whereas the results for dense sand match the experimental data well only for the cases of  $\tan \phi_\mu = 0.5$  and  $1.0$  with too soft behavior for the case of  $\tan \phi_\mu = 3.0$ . At deep depth, the force-displacement relationships from medium sand still match the FE results well for all cases of  $\tan \phi_\mu$ ; however, the results for dense sand show that the case of  $\tan \phi_\mu = 3.0$  yield closest results with the FE analysis and a tendency of overestimation of the peak dimensionless force for the case of  $\tan \phi_\mu = 0.5$ .

The comparison of peak dimensionless forces from the DEM and FEM analysis shows that, for medium sand, the DEM results show deep failure mechanism and the results match the FE results well for all cases of  $\tan \phi_\mu$ . For dense sand, the DEM results from the cases of  $\tan \phi_\mu = 1.0, 3.0$  yield closest results with the FE analysis with gradual transition from shallow to deep failure mechanism and a tendency of overestimation of the peak dimensionless at very deep depth. However, the DEM results for the case of  $\tan \phi_\mu = 0.5$  show considerably overestimation and do not show any transition from shallow to deep failure mechanism which is due probably to model boundary interference.

The investigation on the displacement patterns shows that the results from DEM analysis, especially for dense sand, involve larger soil mass compared with FEM results.

The results from this DEM analysis together with earlier FEM analysis will serve as a Class-A prediction of the future full-scale tank test of this problem.



## **Appendix A**

### **Force-Displacement Curves of Pipe under Lateral Loading**

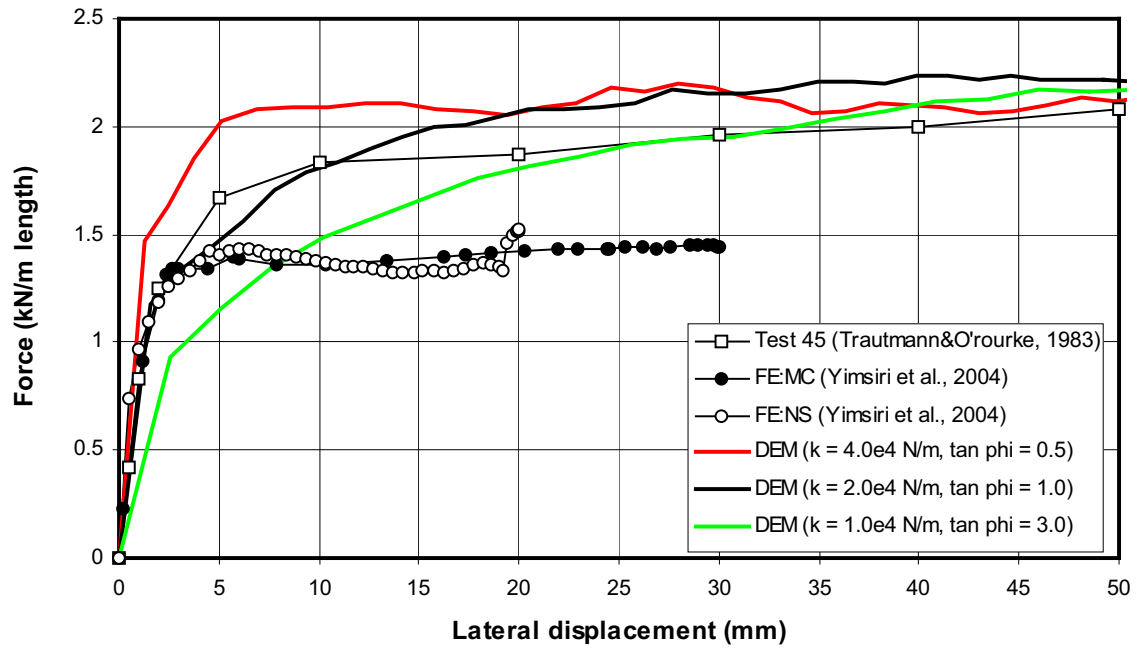


Figure A-1  $H/D = 2$ : Medium sand

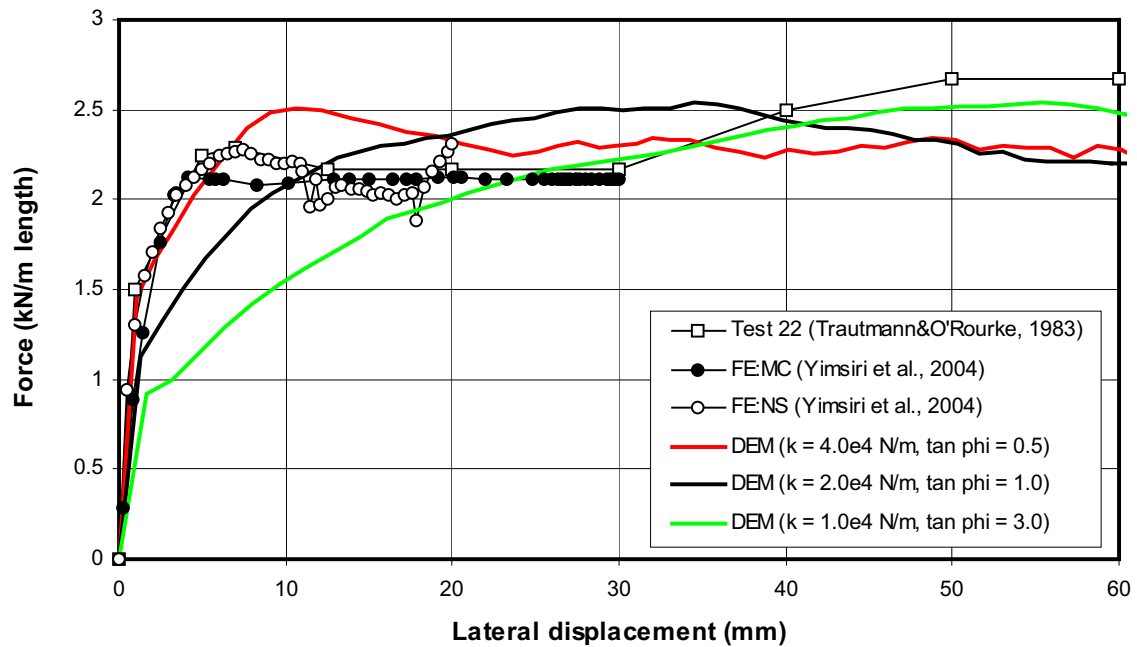


Figure A-2  $H/D = 2$ : Dense sand

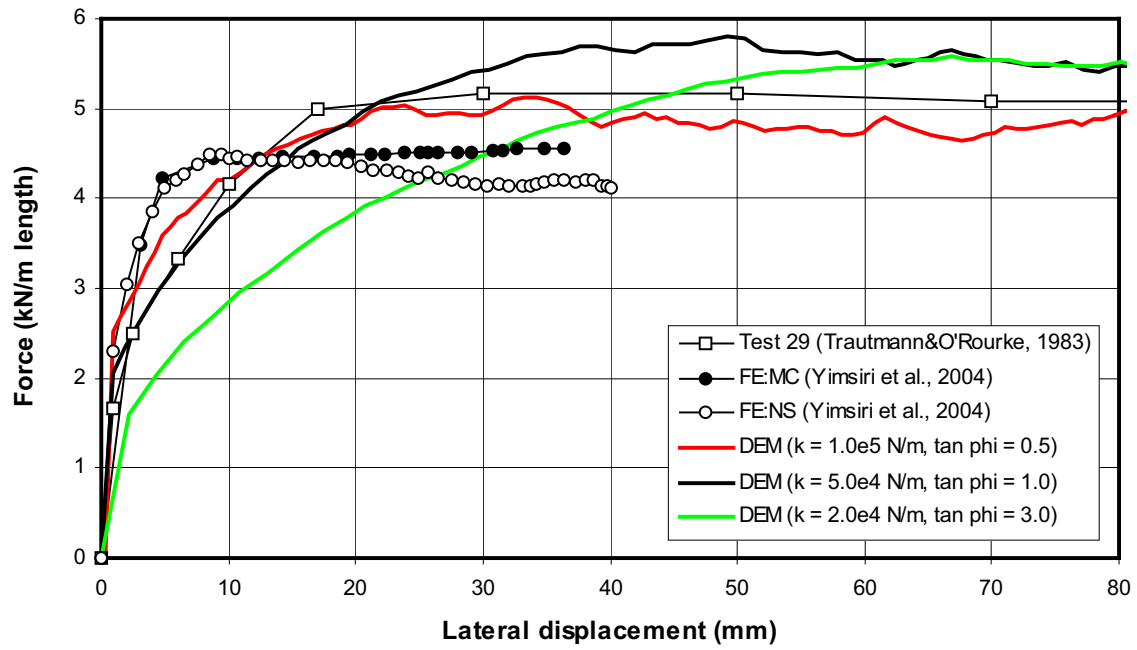


Figure A-3  $H/D = 4$ : Medium sand

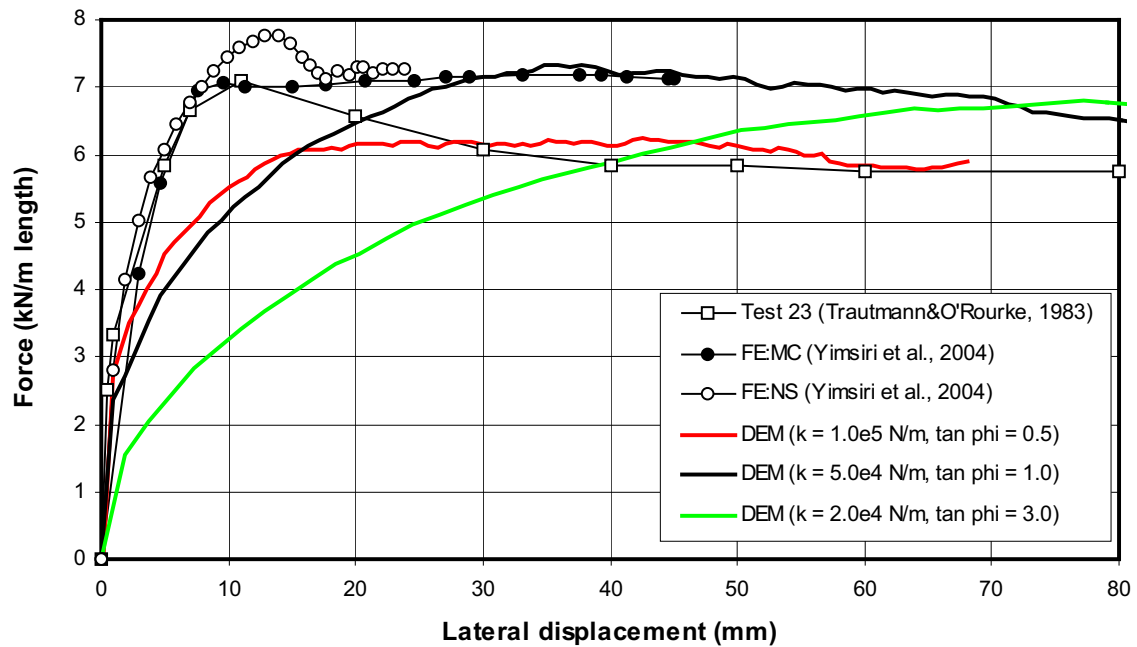


Figure A-4  $H/D = 4$ : Dense sand

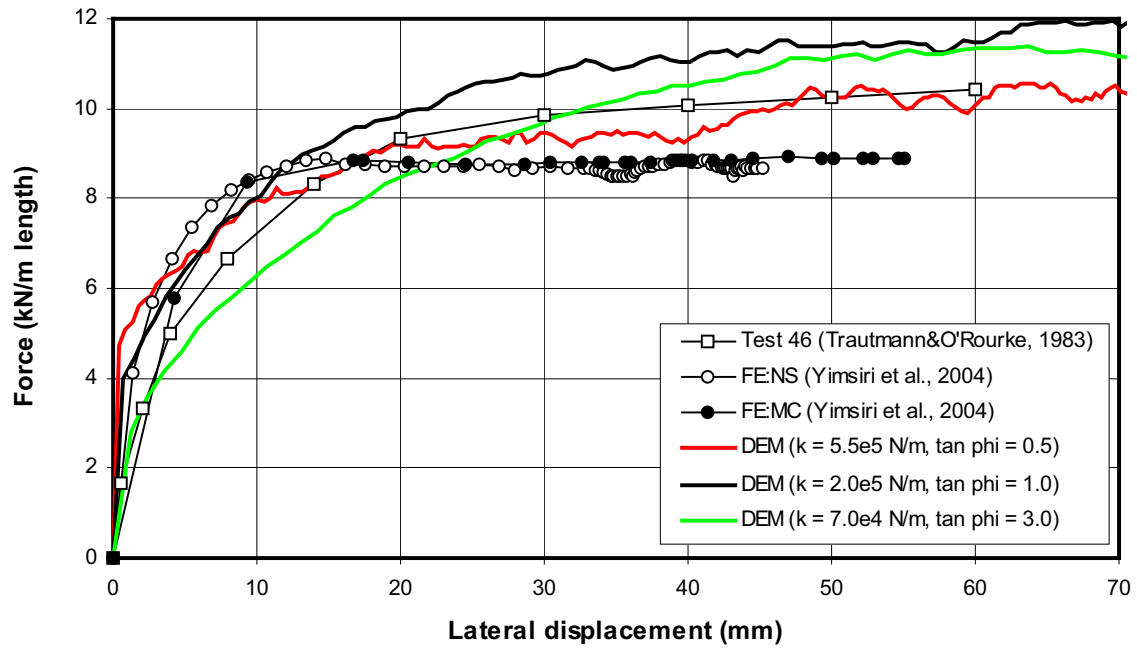


Figure A-5  $H/D = 6$ : Medium sand

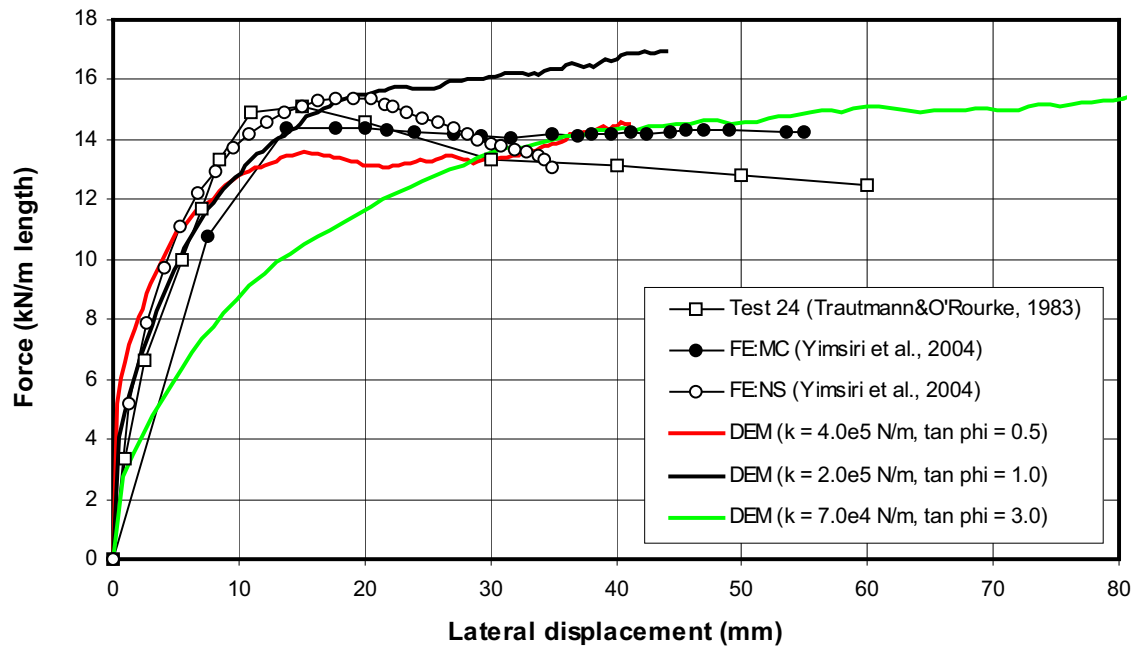


Figure A-6  $H/D = 6$ : Dense sand

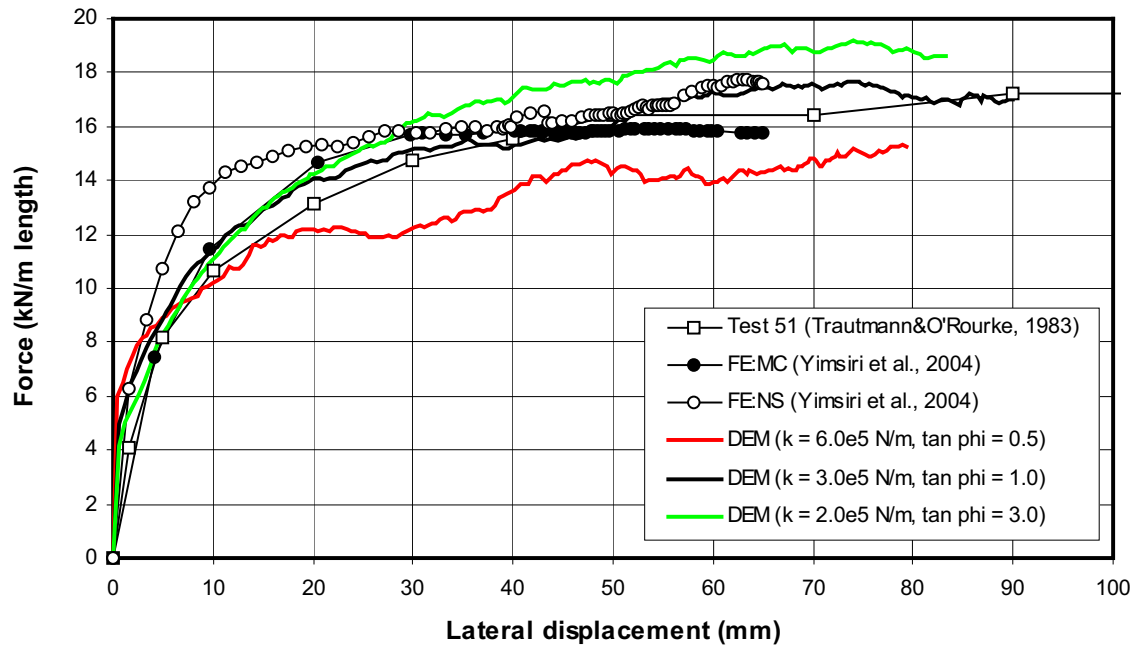


Figure A-7  $H/D = 8.5$ : Medium sand

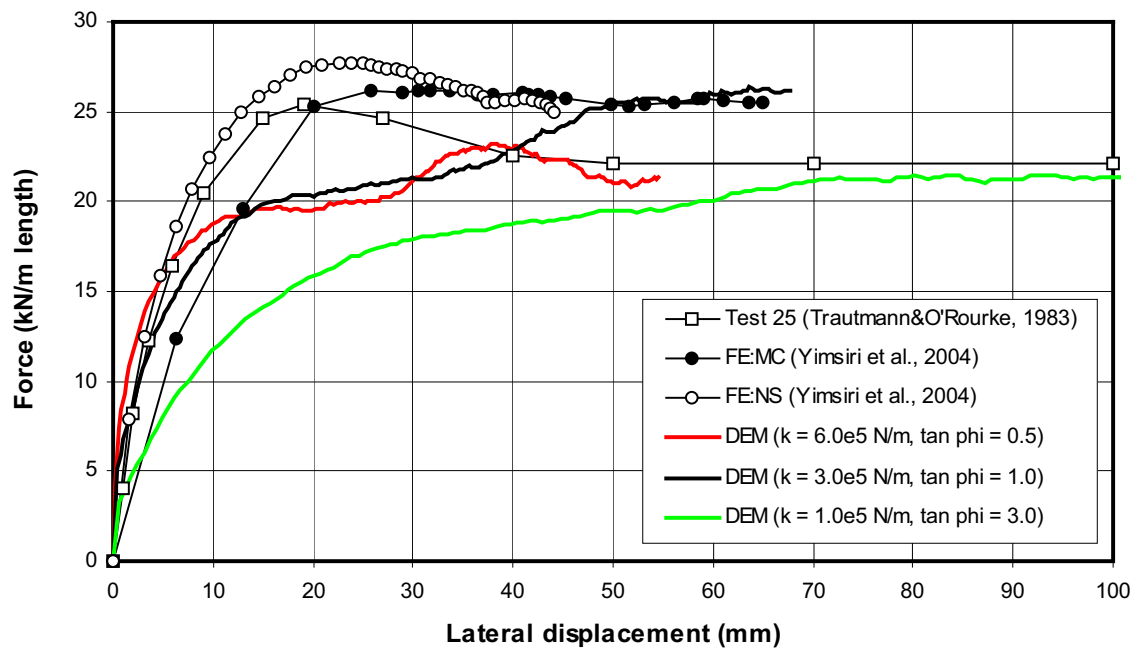


Figure A-8  $H/D = 8.5$ : Dense sand

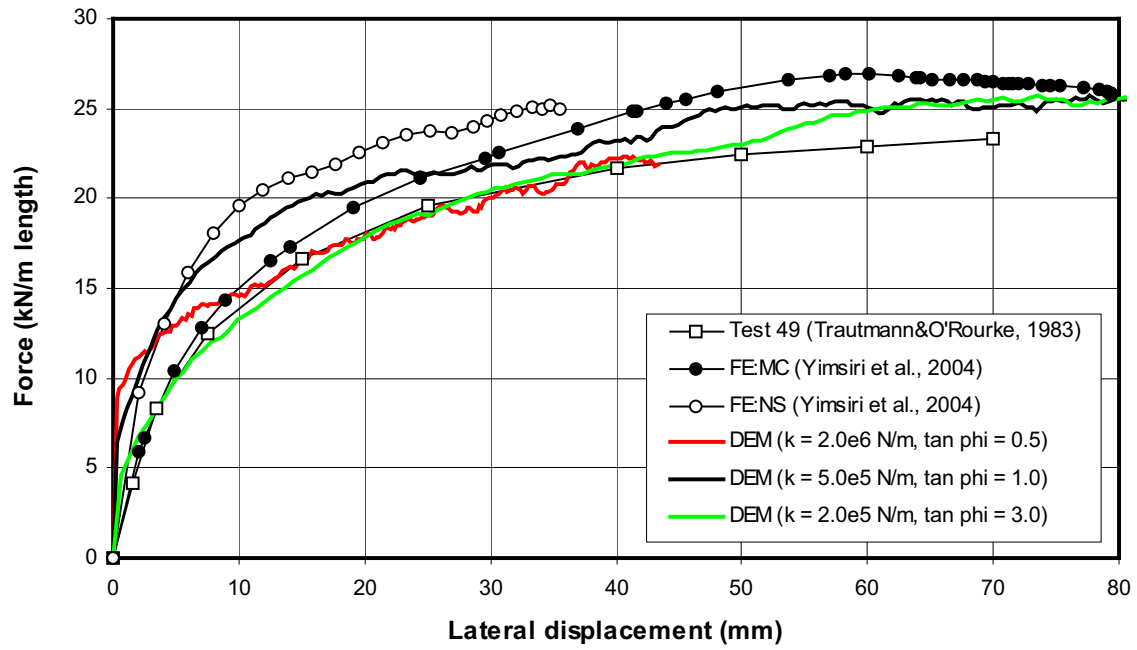


Figure A-9  $H/D = 11.5$ : Medium sand

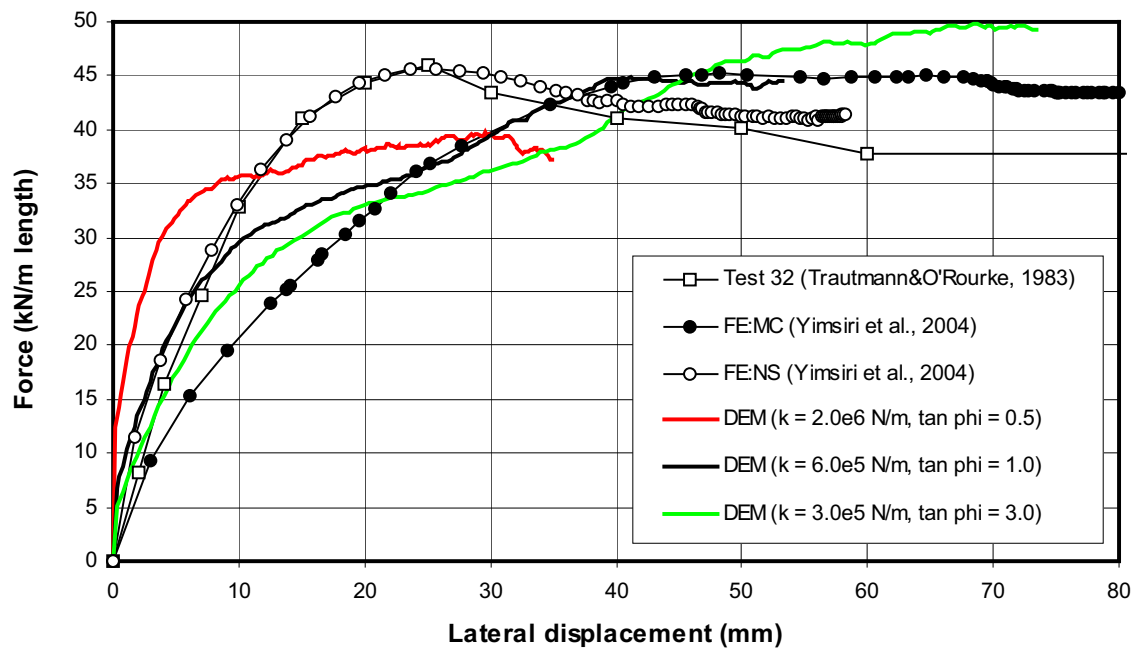


Figure A-10  $H/D = 11.5$ : Dense sand

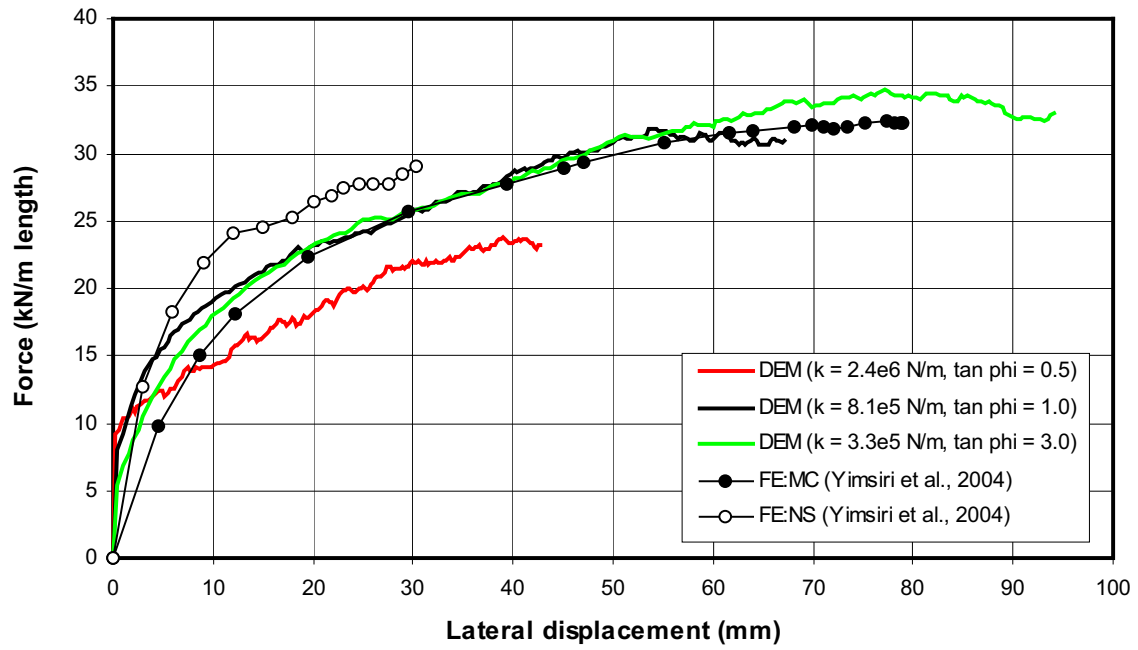


Figure A-19  $H/D = 14.5$ , Medium sand

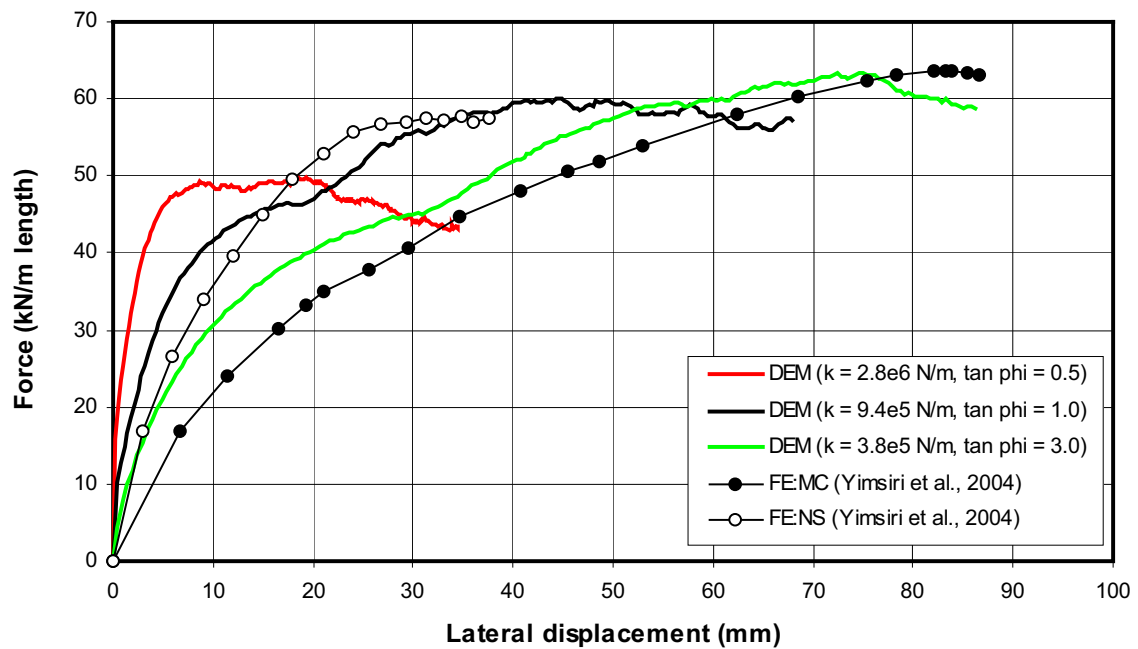


Figure A-20  $H/D = 14.5$ , Dense sand

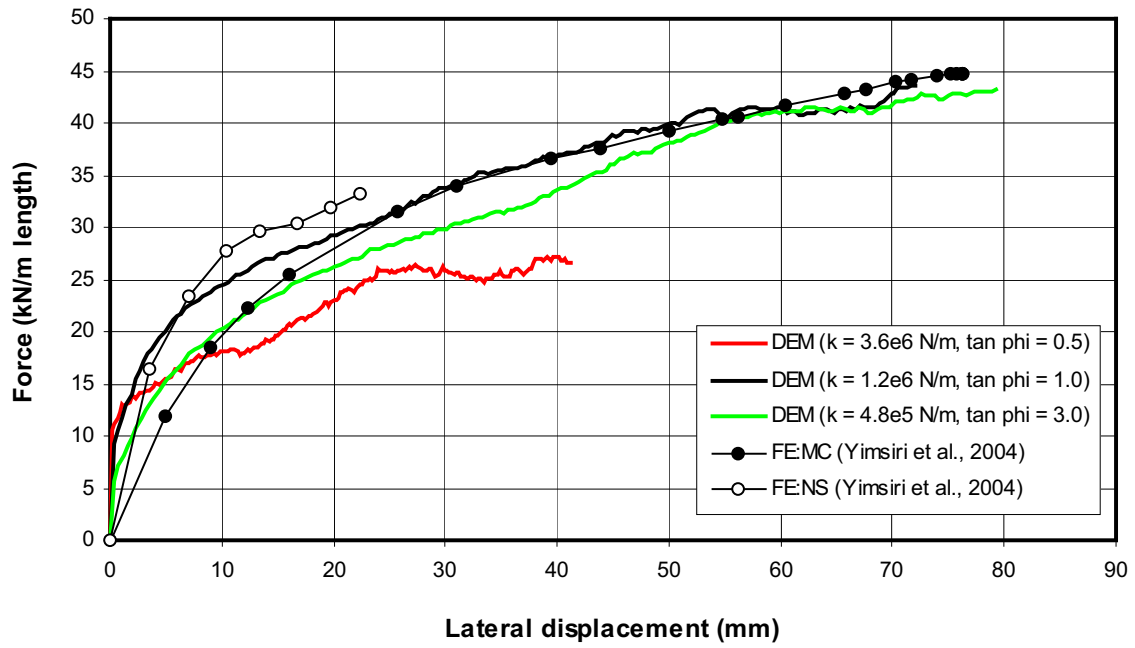


Figure A-21  $H/D = 17.5$ , Medium sand

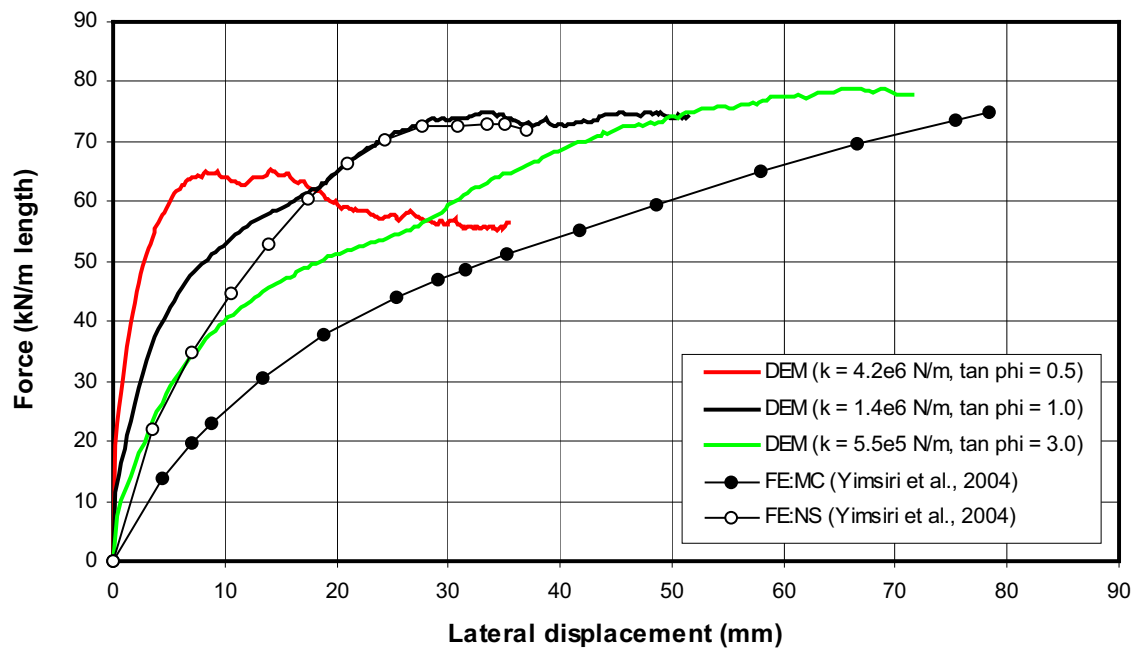


Figure A-22  $H/D = 17.5$ , Dense sand



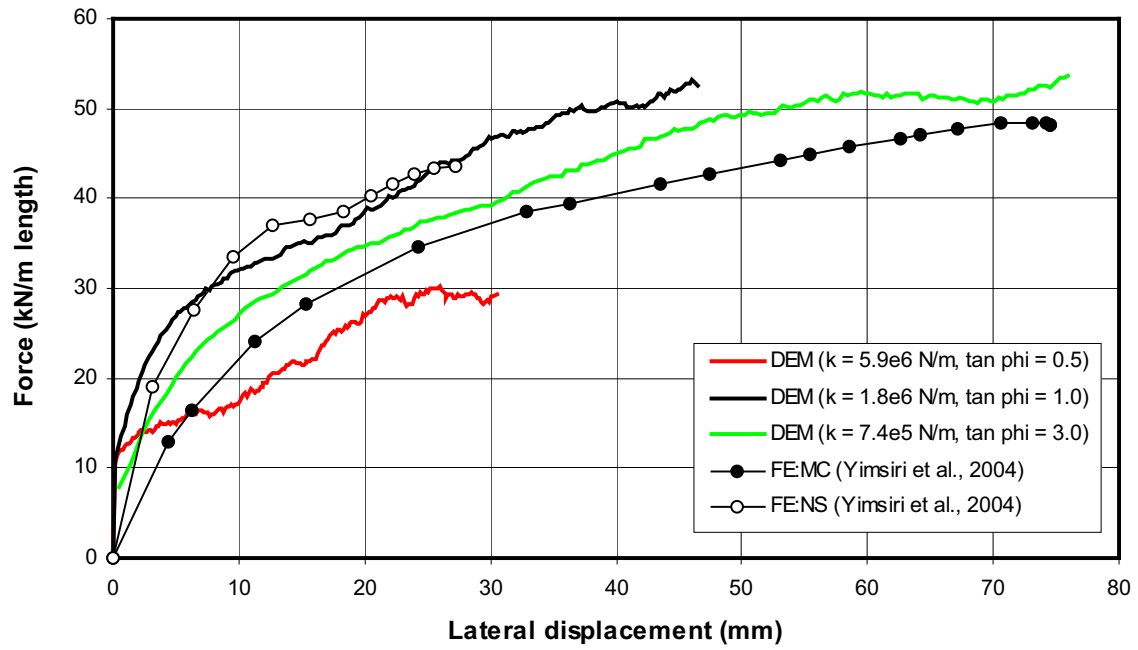


Figure A-23  $H/D = 22$ , Medium sand

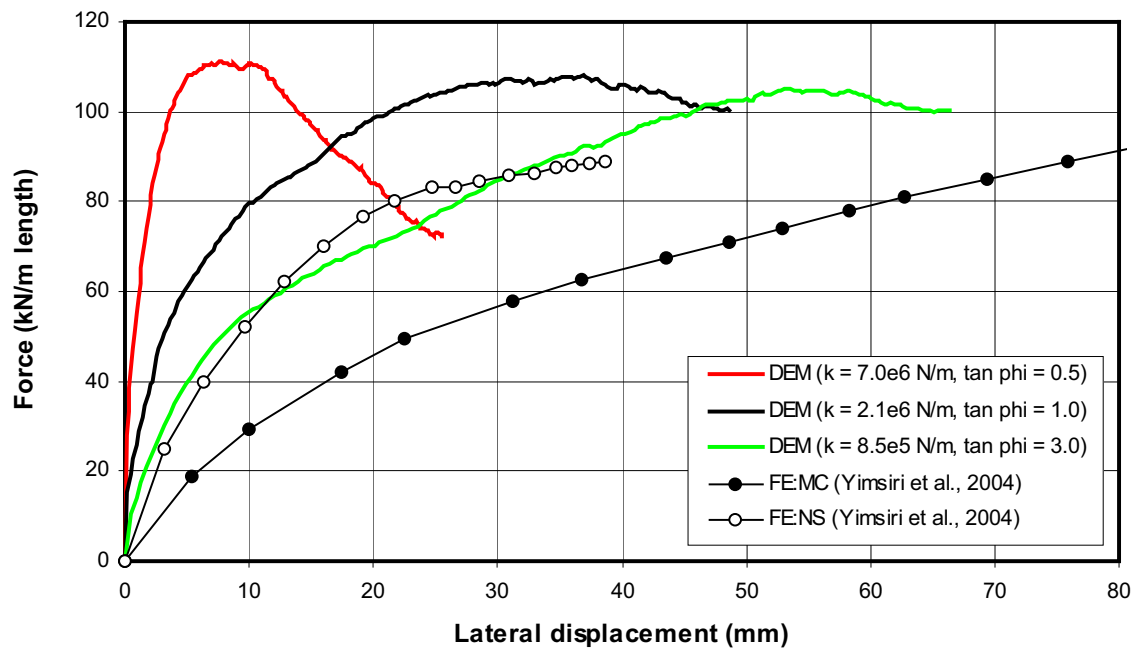


Figure A-24  $H/D = 22$ , Dense sand

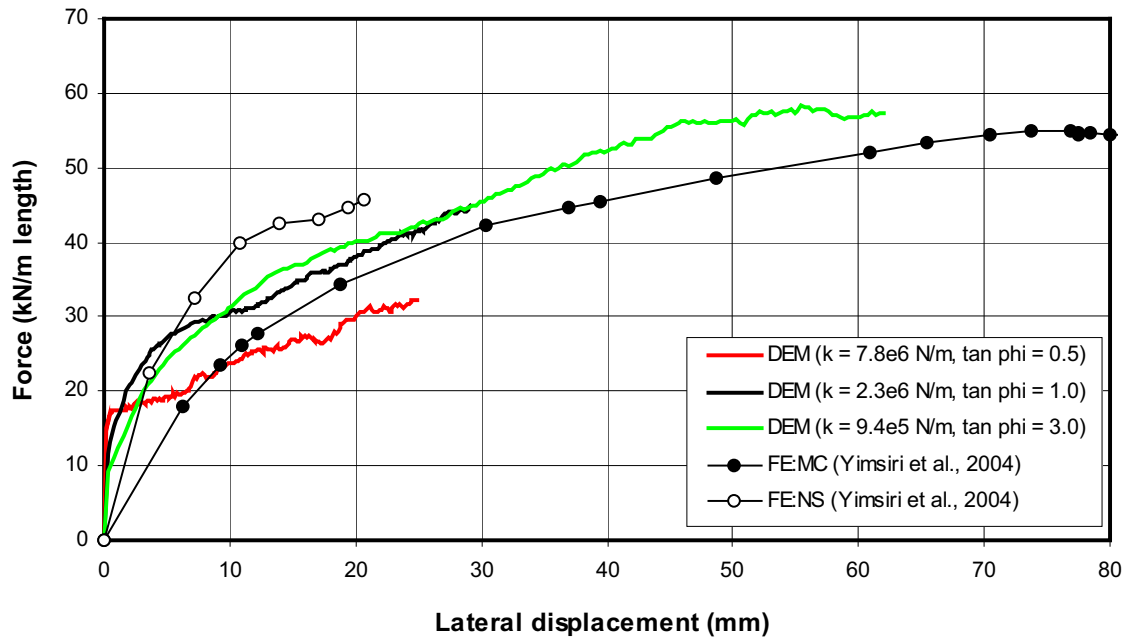


Figure A-25  $H/D = 25$ , Medium sand

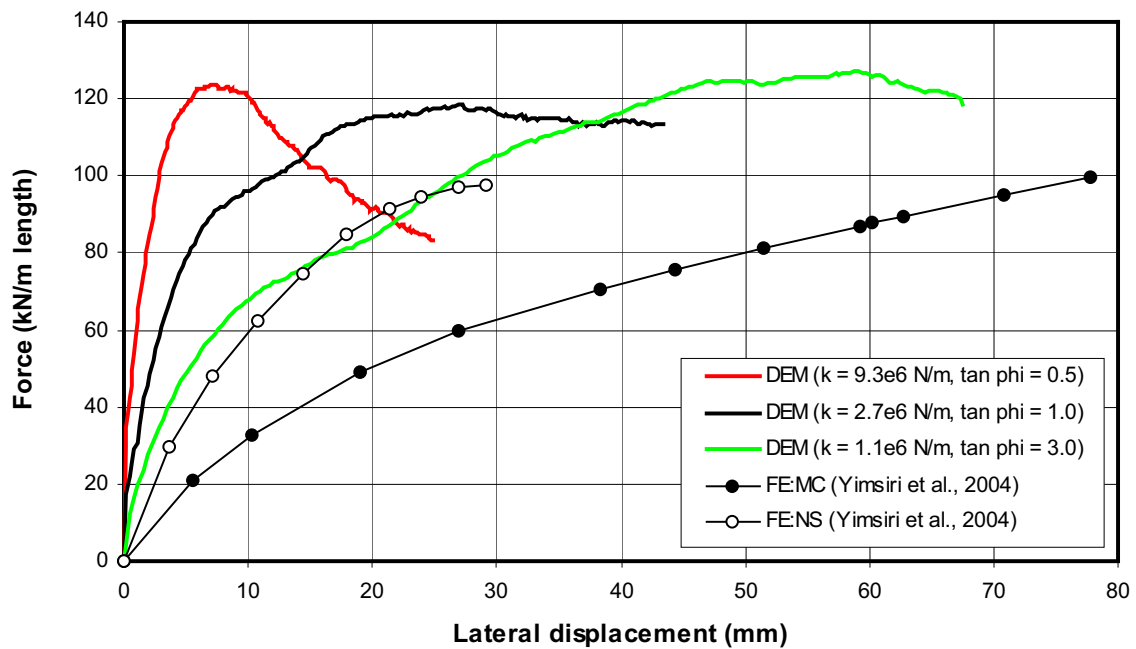


Figure A-26  $H/D = 25$ , Dense sand

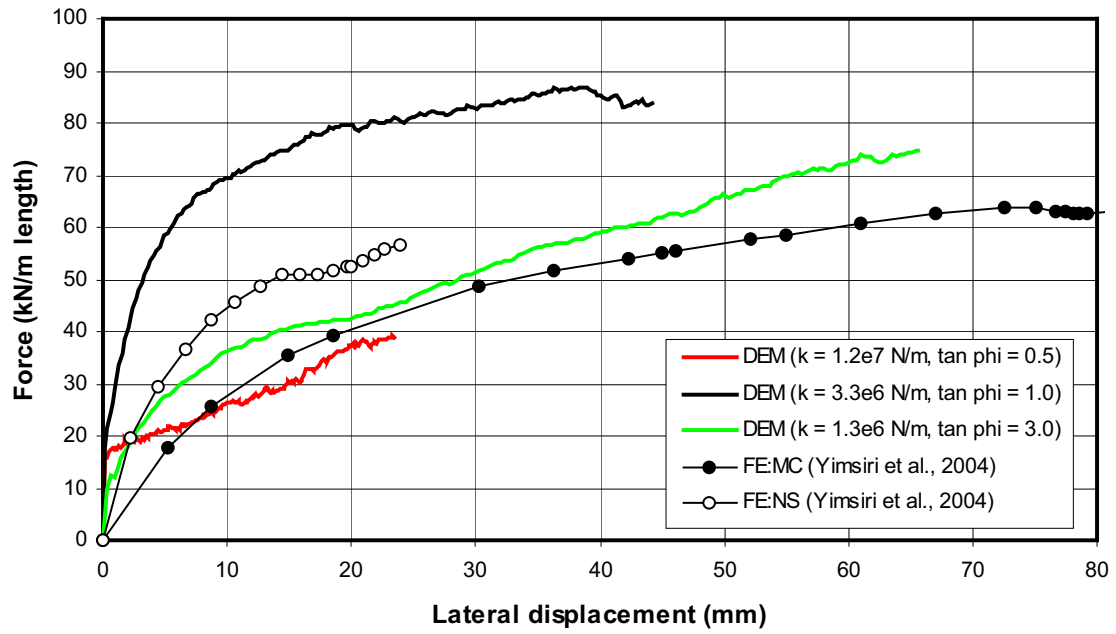


Figure A-27  $H/D = 30$ , Medium sand

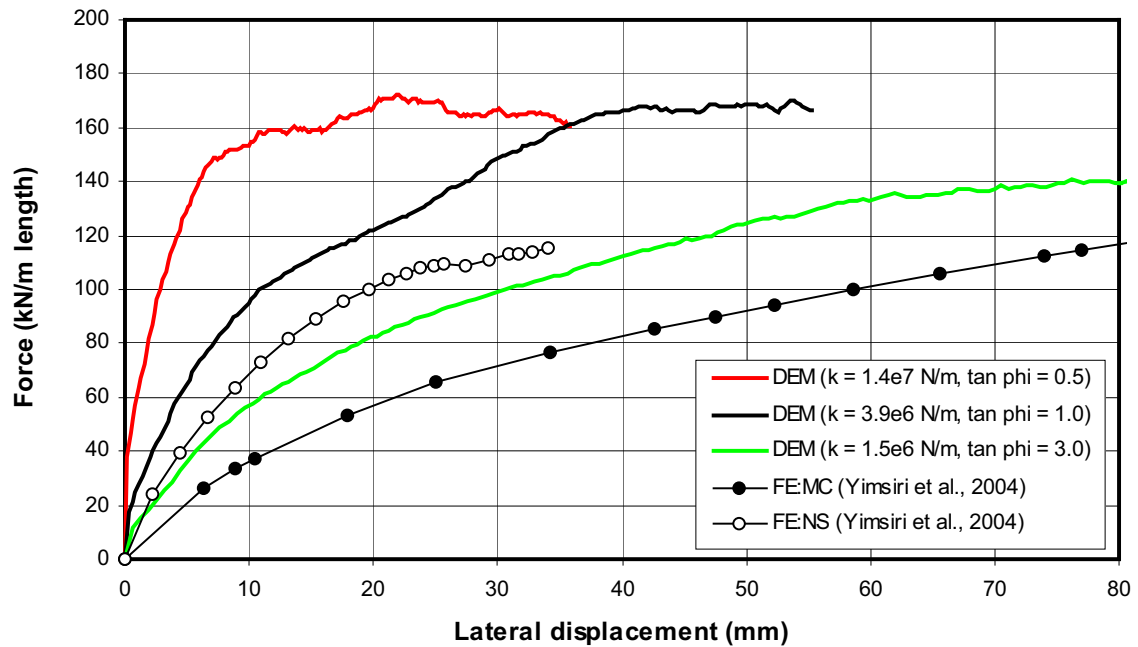


Figure A-28  $H/D = 30$ , Dense sand

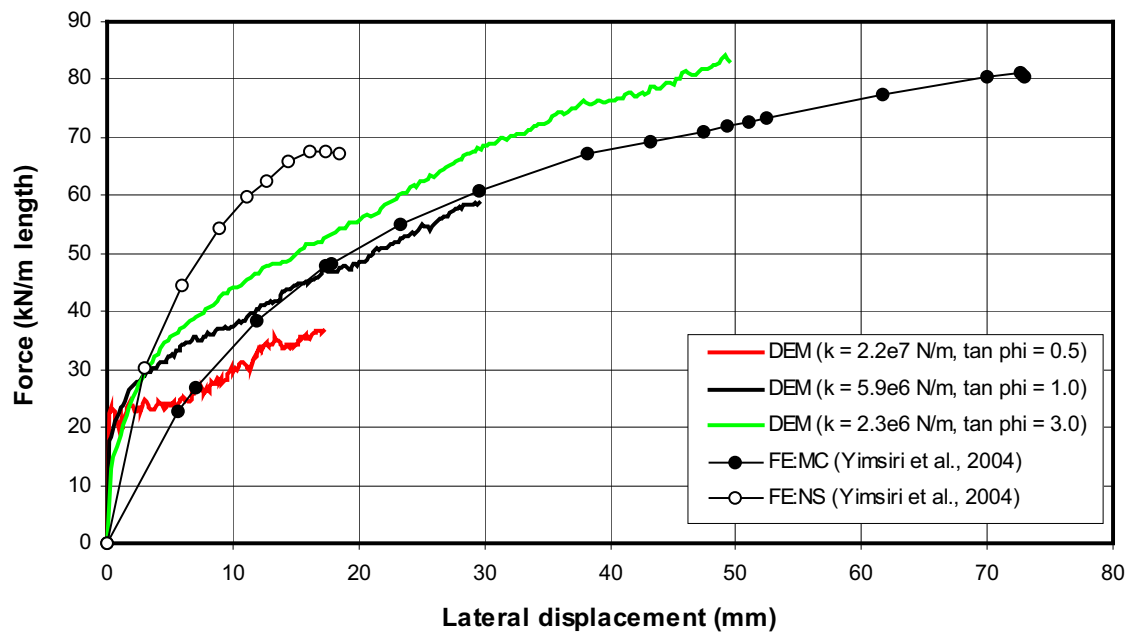


Figure A-29  $H/D = 40$ , Medium sand

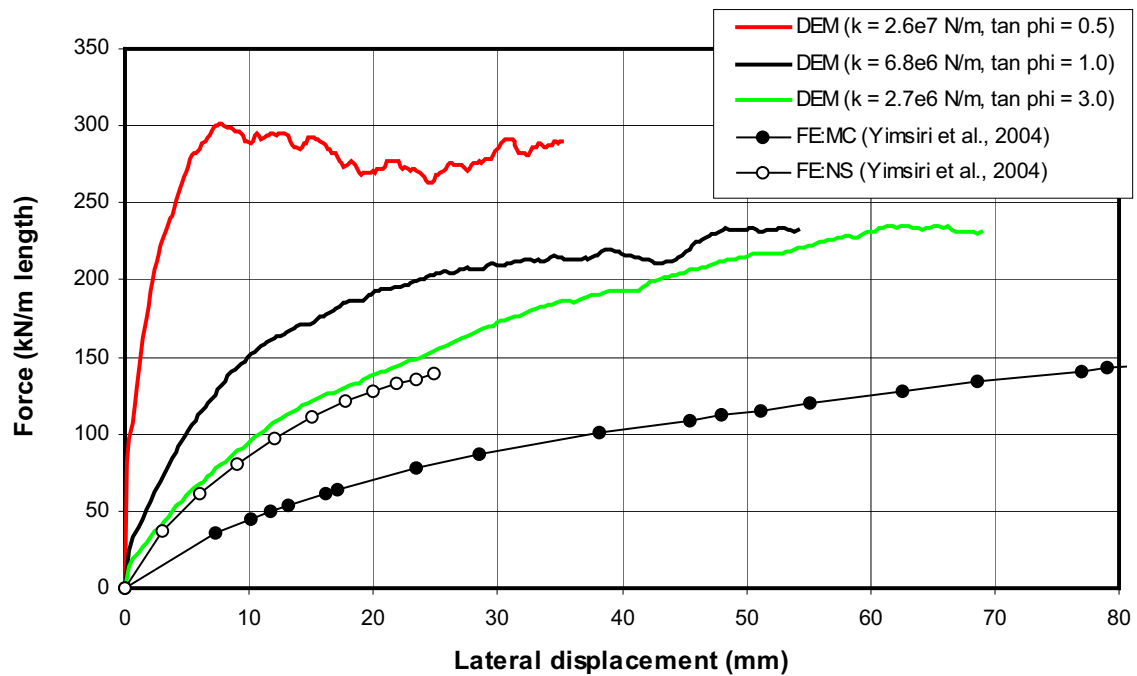


Figure A-30  $H/D = 40$ , Dense sand

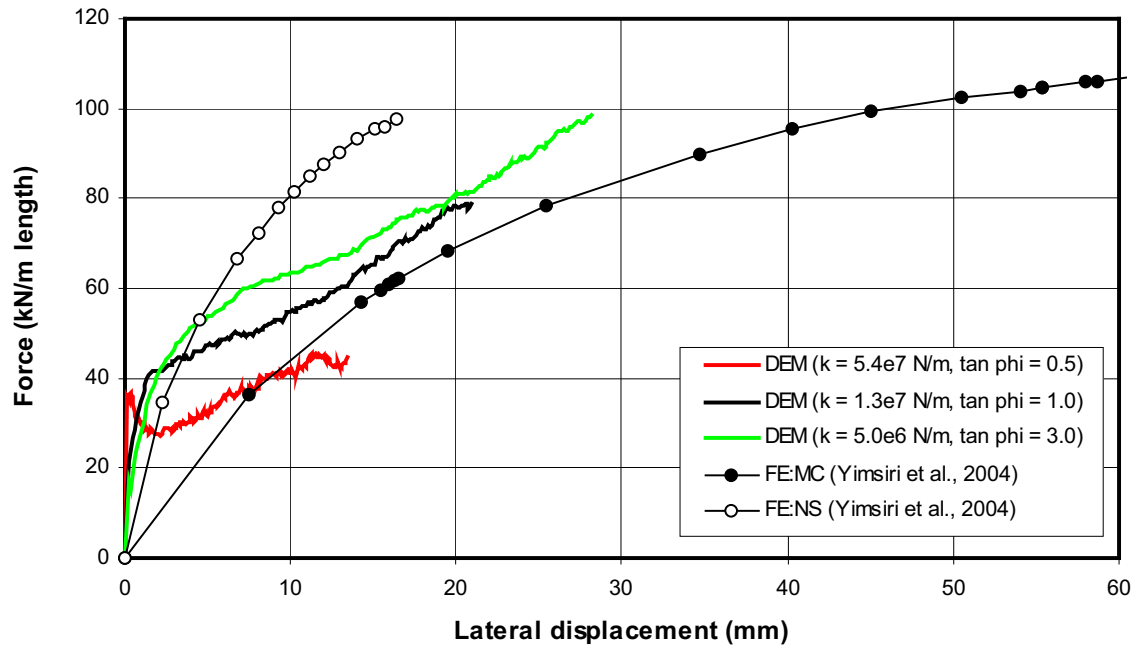


Figure A-31  $H/D = 60$ , Medium sand

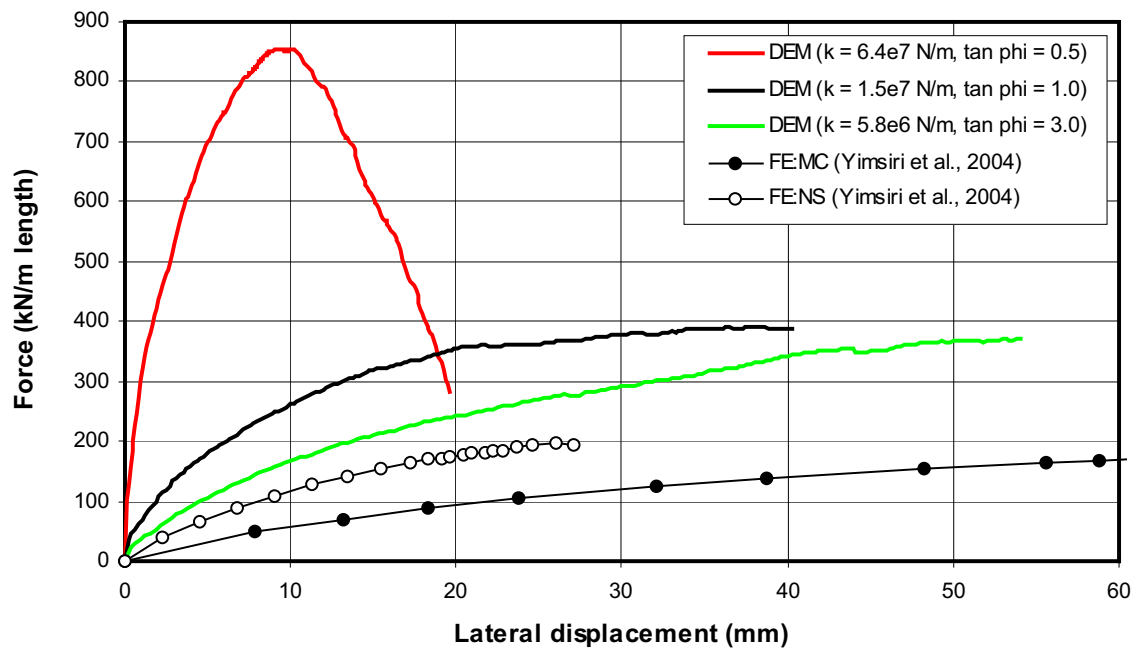


Figure A-32  $H/D = 60$ , Dense sand

## **Appendix B**

### **Force-Displacement Curves of Pipe under Upward Loading**

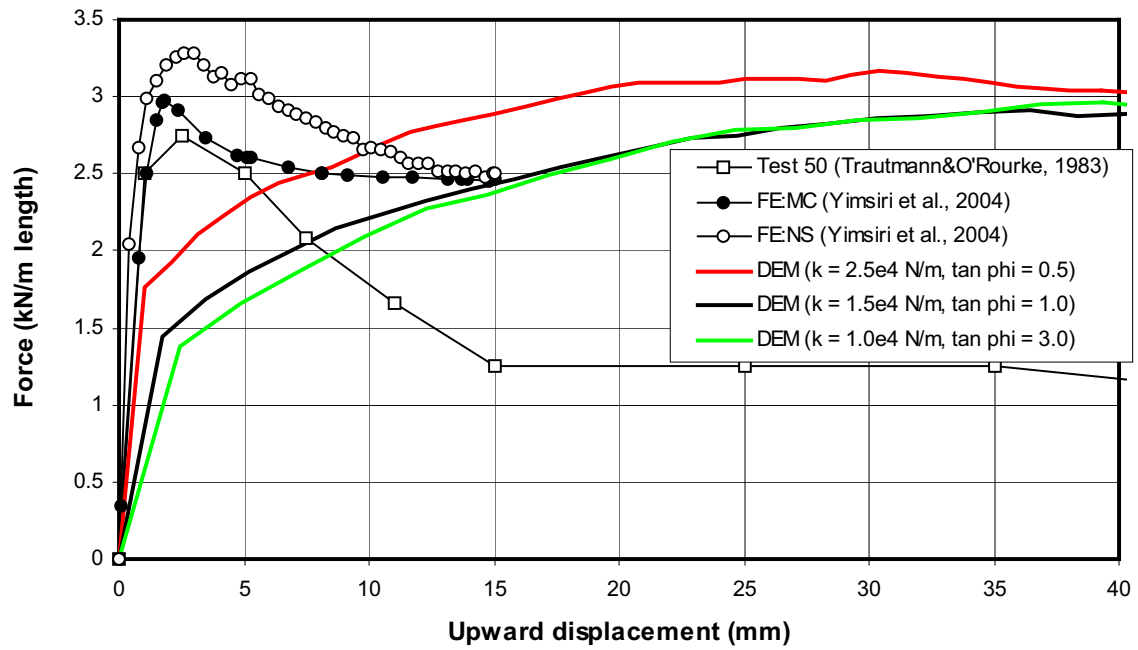


Figure B-1  $H/D = 4$ : Dense sand

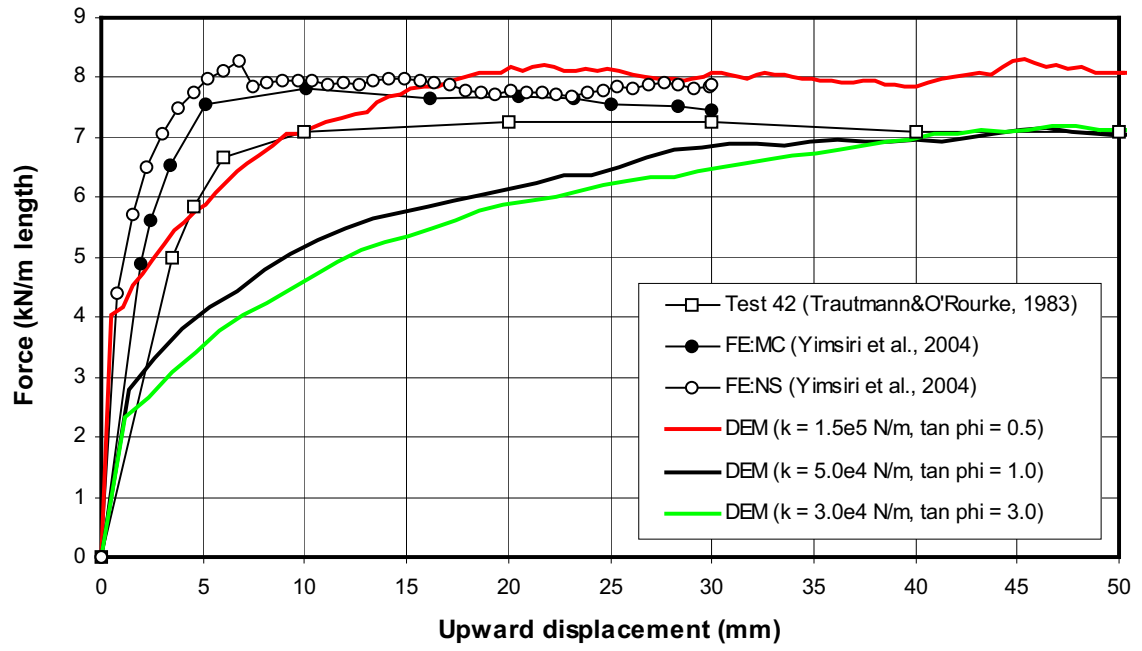


Figure B-2  $H_c/D = 8$ : Medium sand

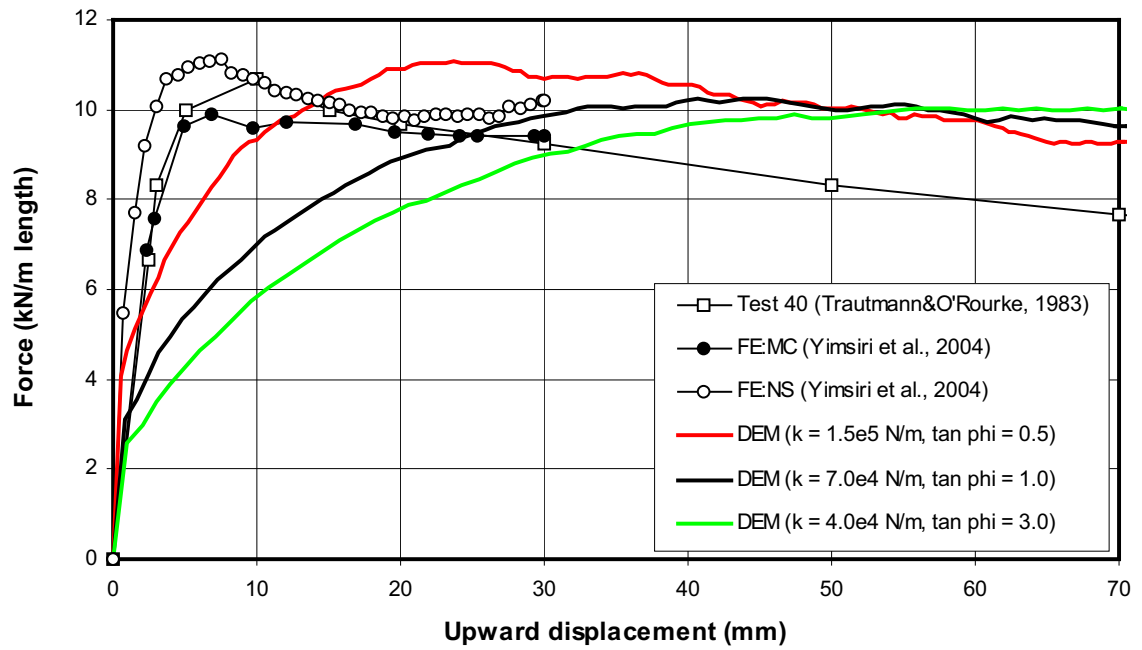


Figure B-3  $H_c/D = 8$ : Dense sand



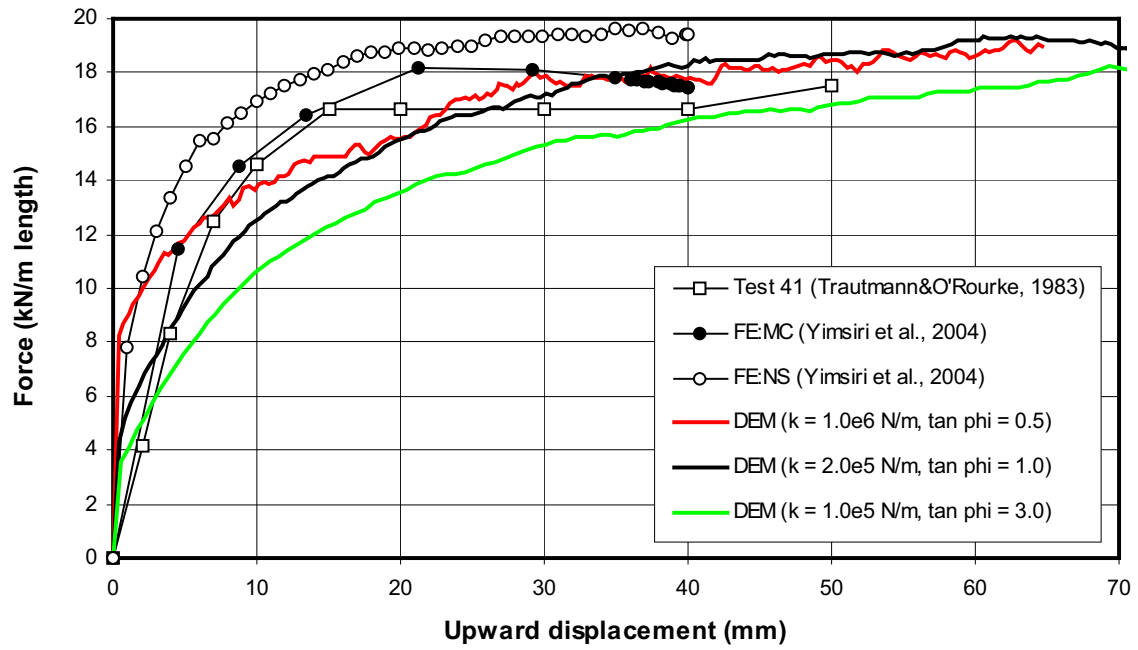


Figure B-4  $H_c/D = 13$ : Medium sand

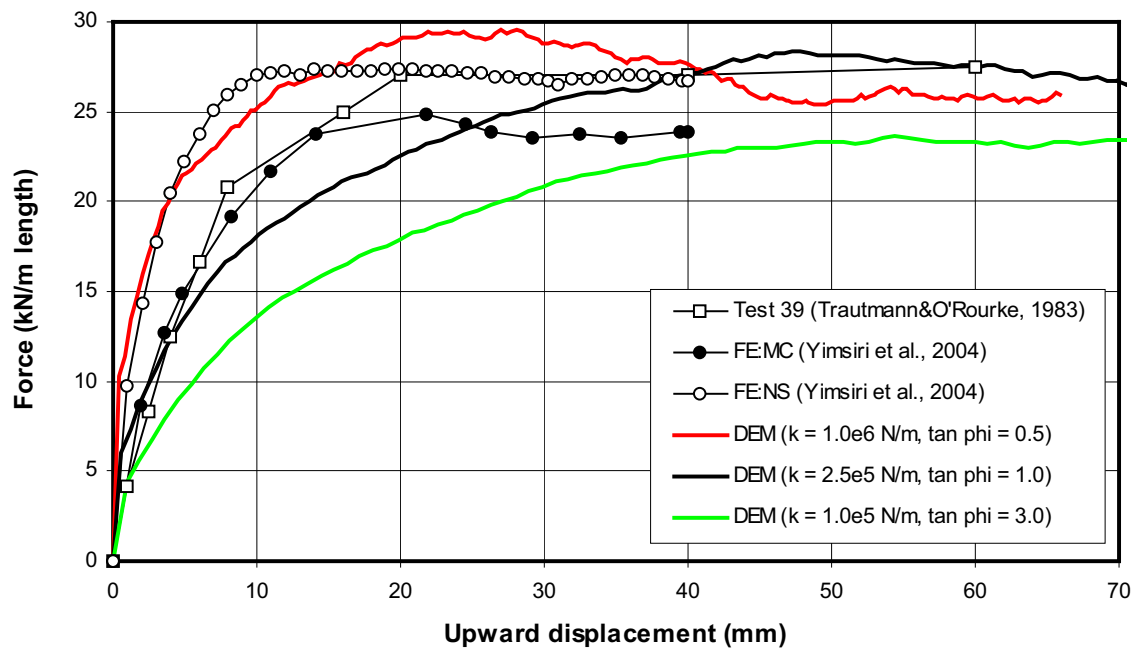


Figure B-5  $H_c/D = 13$ : Dense sand

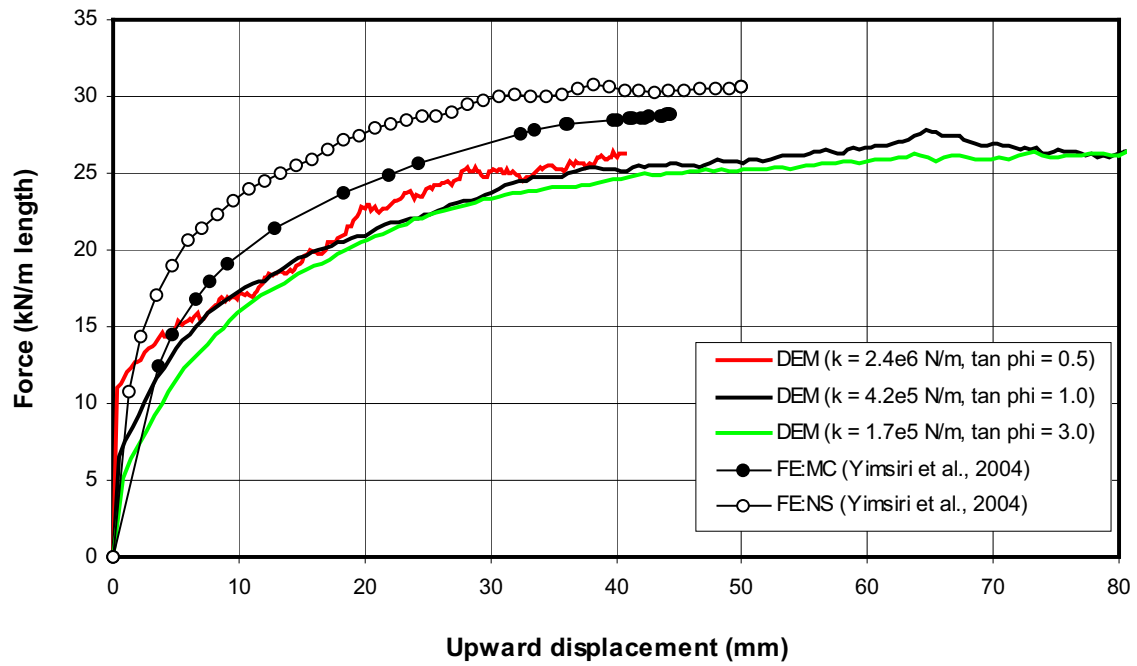


Figure B-6  $H_c/D = 17$ , Medium sand

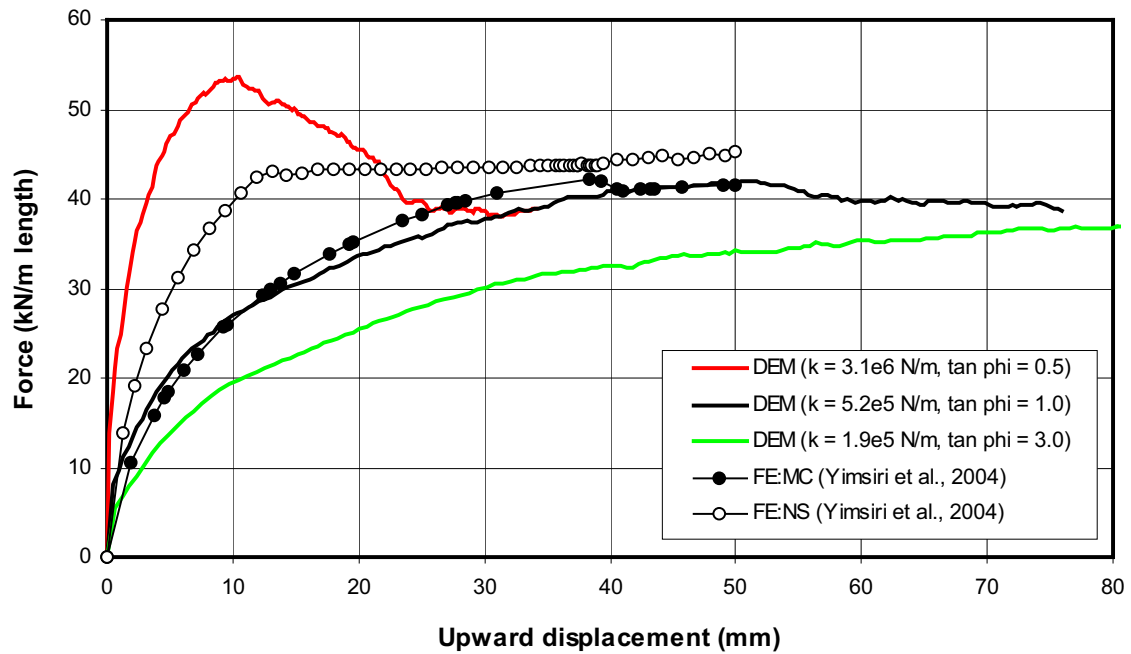


Figure B-7  $H_c/D = 17$ , Dense sand

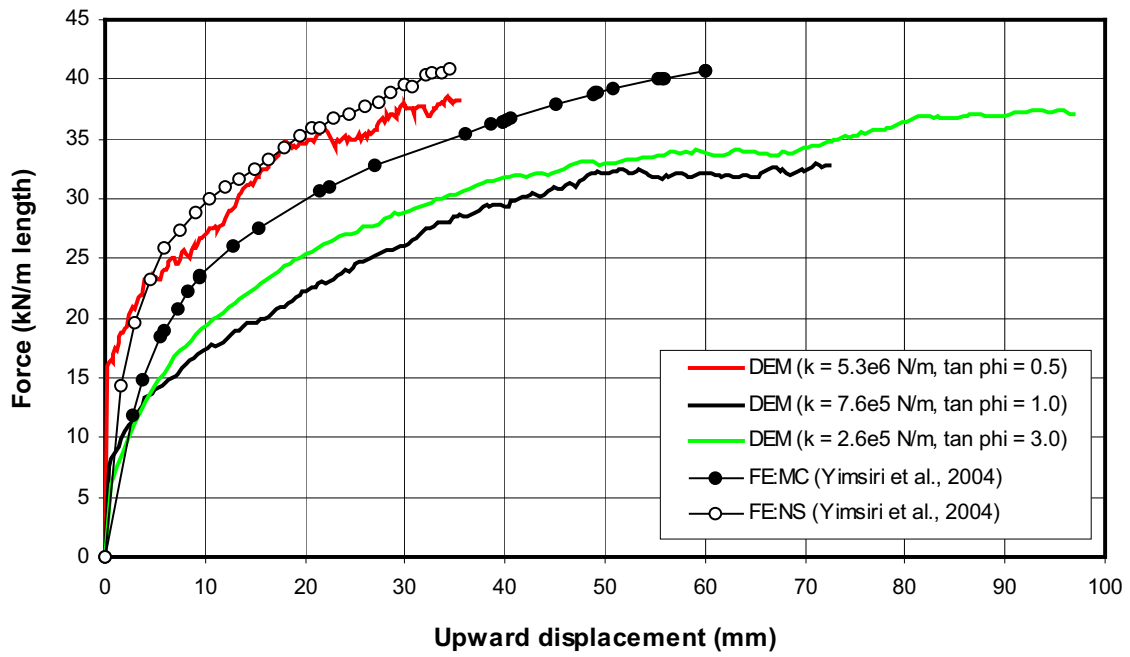


Figure B-8  $H_c/D = 21$ , Medium sand

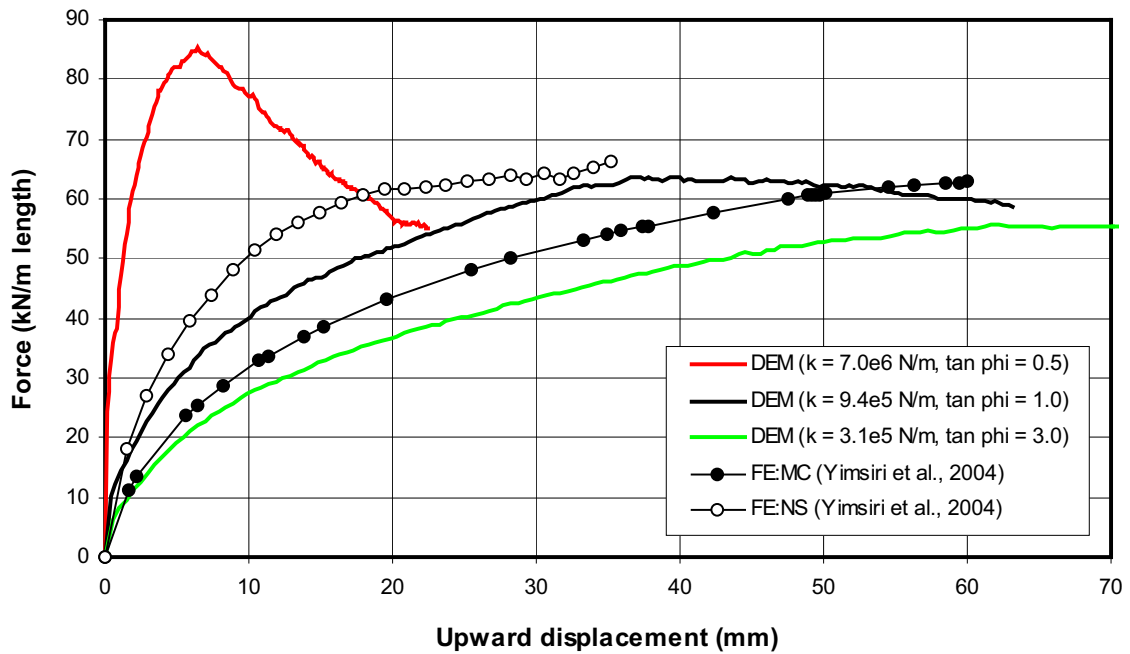


Figure B-9  $H_c/D = 21$ , Dense sand

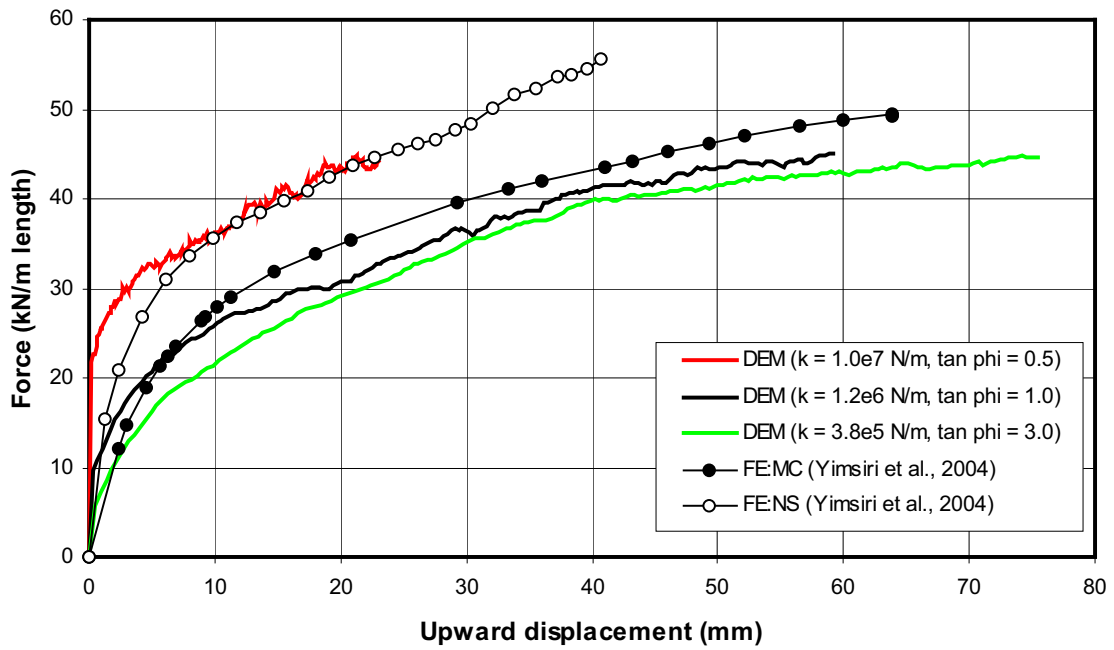


Figure B-10  $H_c/D = 25$ , Medium sand

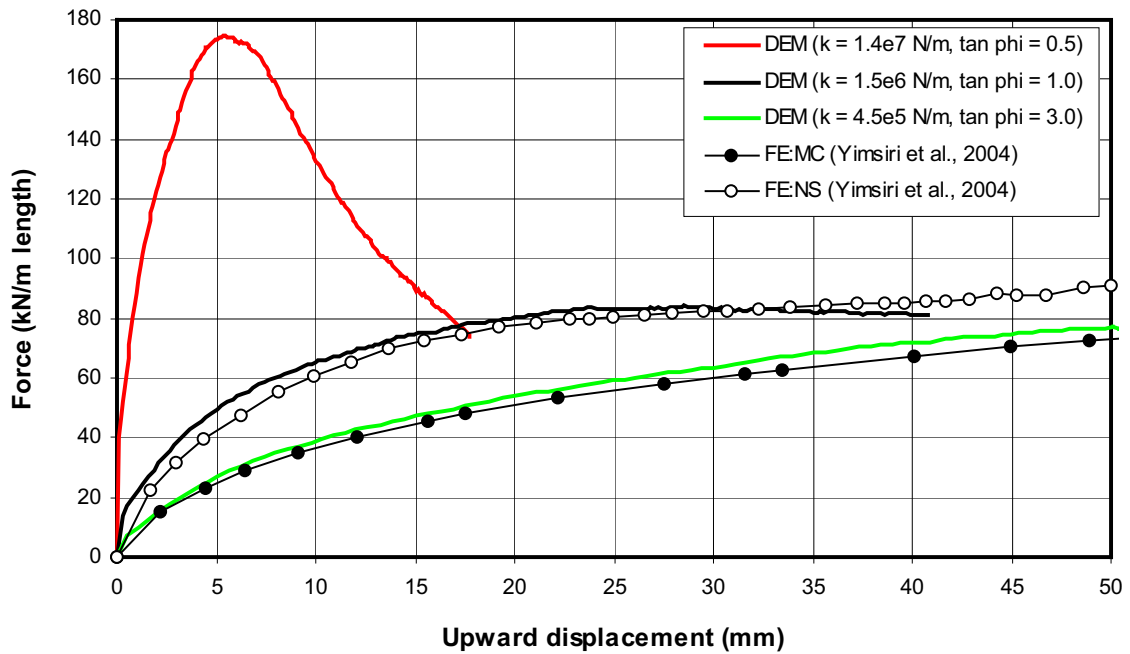


Figure B-11  $H_c/D = 25$ , Dense sand

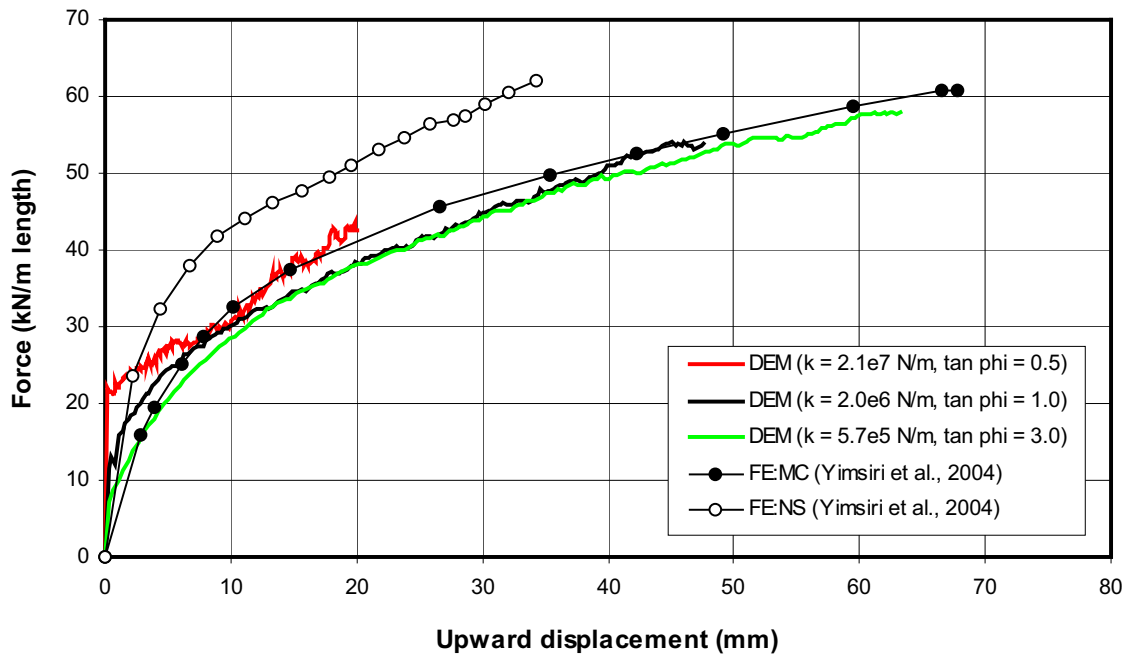


Figure B-12  $H_c/D = 30$ , Medium sand

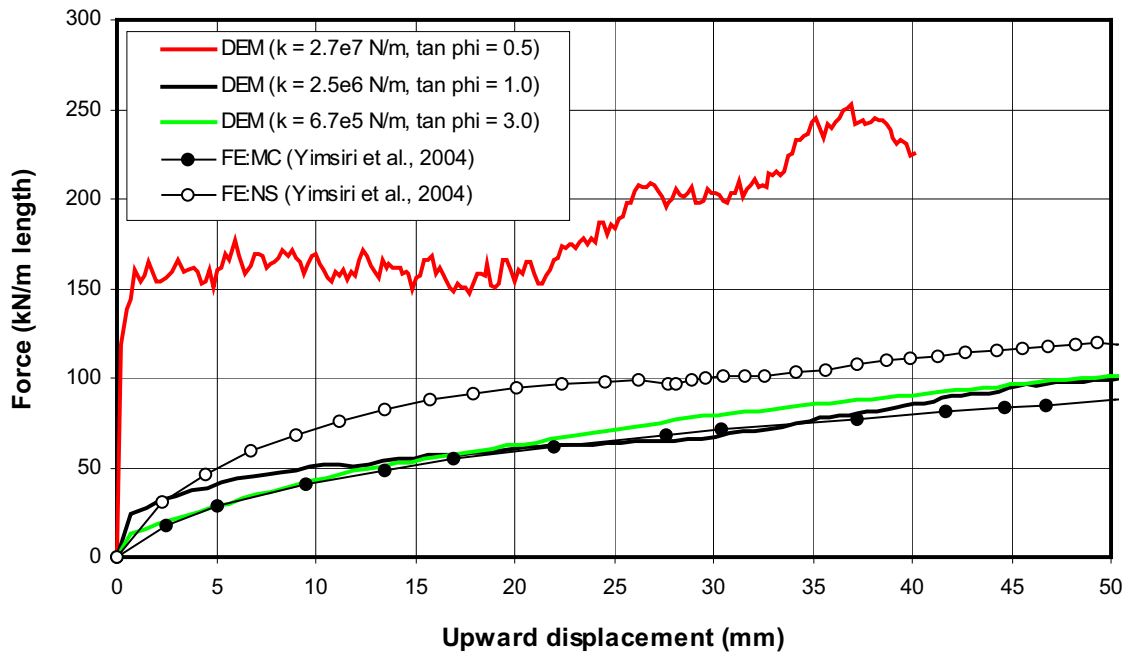


Figure B-13  $H_c/D = 30$ , Dense sand

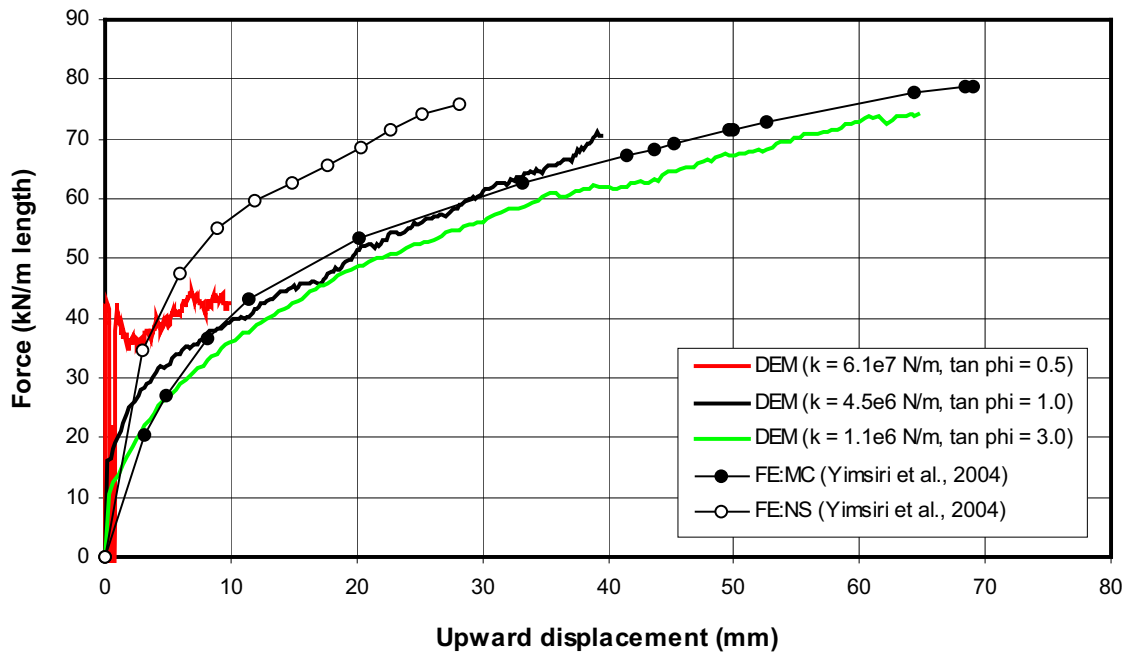


Figure B-14  $H_c/D = 40$ , Medium sand

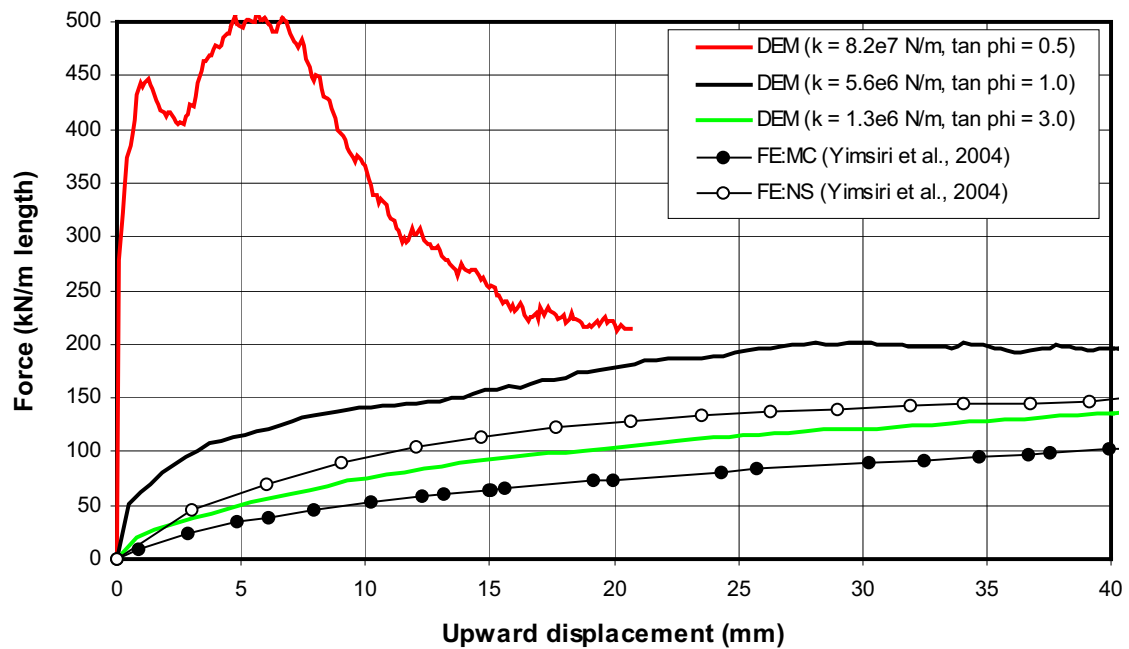


Figure B-15  $H_c/D = 40$ , Dense sand

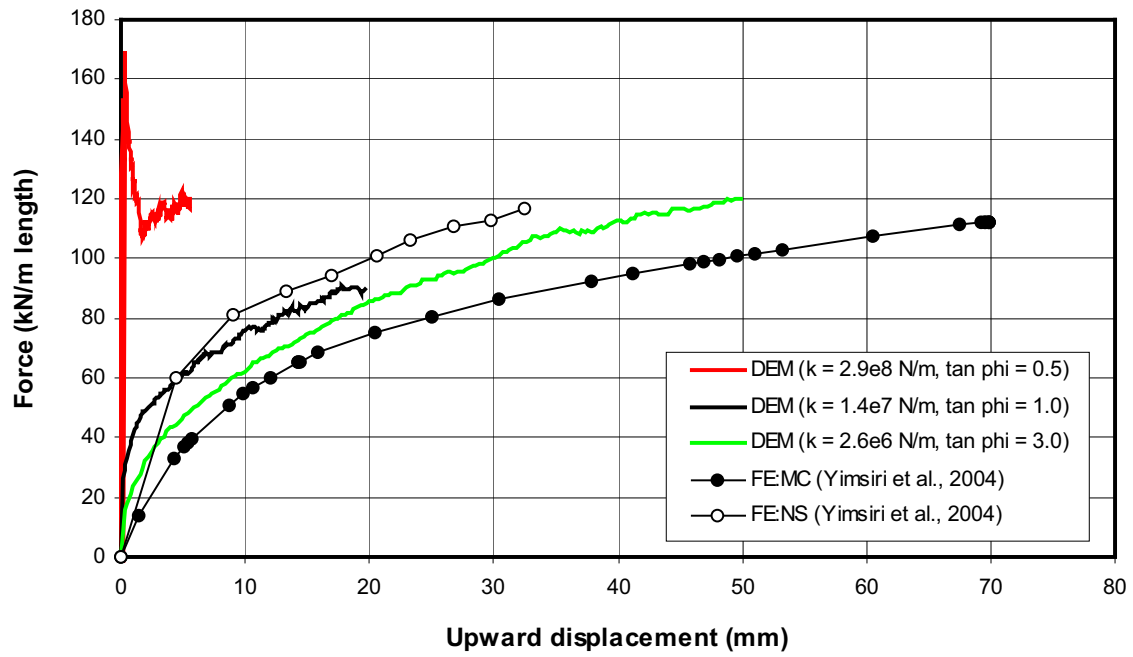


Figure B-16  $H_c/D = 60$ , Medium sand

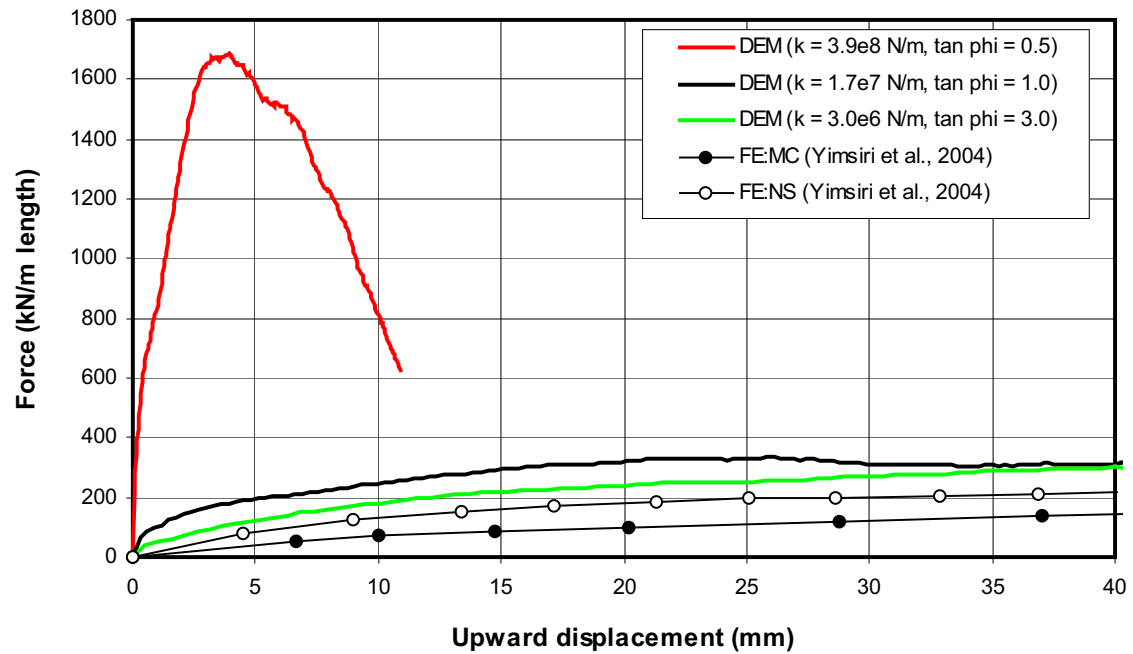
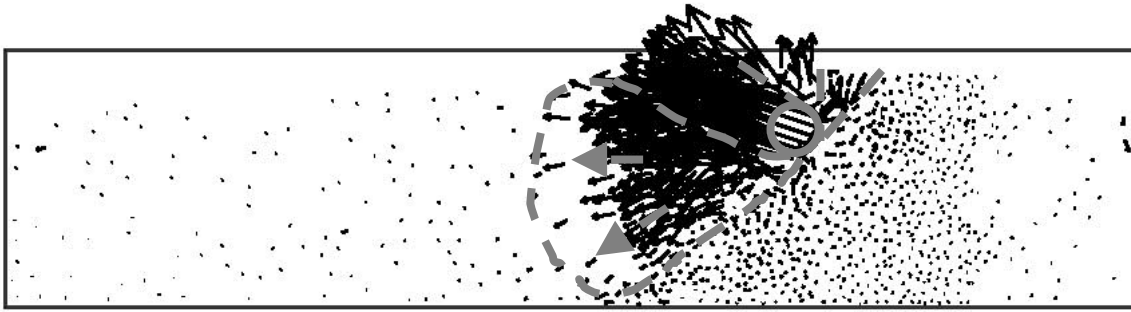


Figure B-17  $H_c/D = 60$ , Dense sand

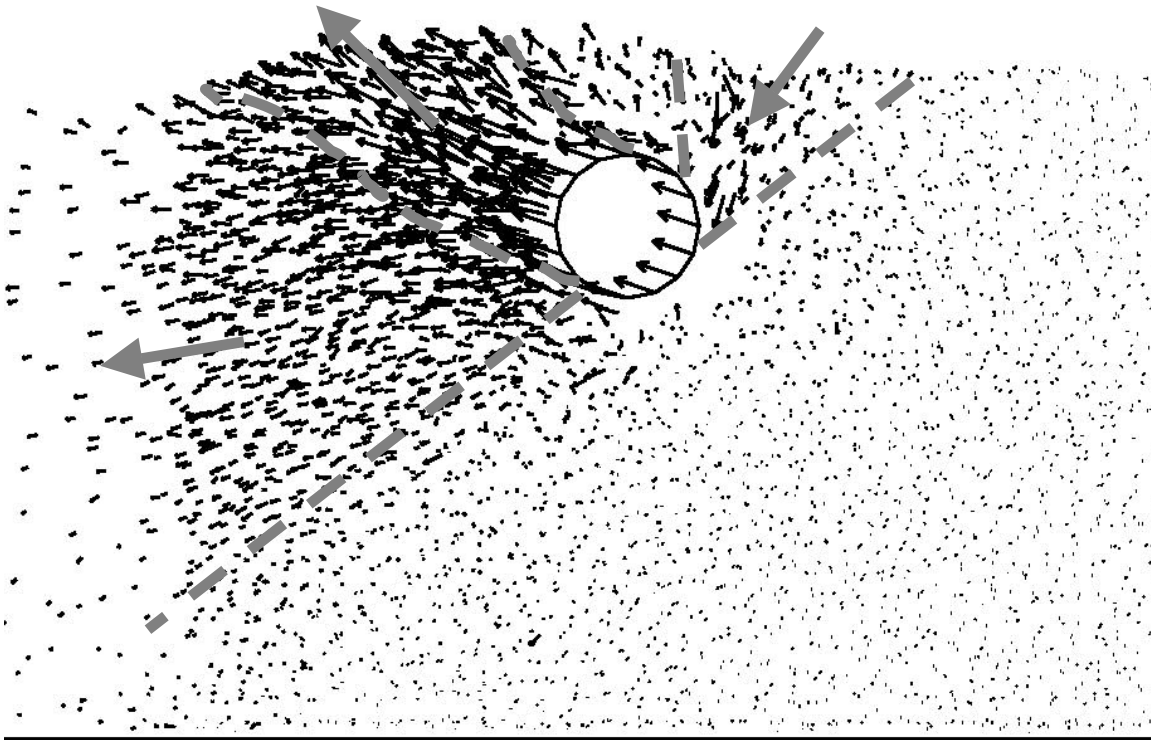
## **Appendix C**

### **Displacement Pattern under Lateral Loading (Velocity Vector)**



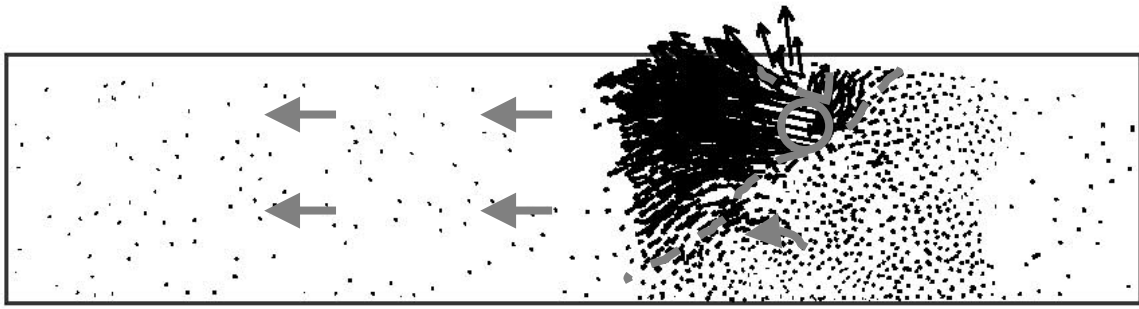


(a) Full-sized scale

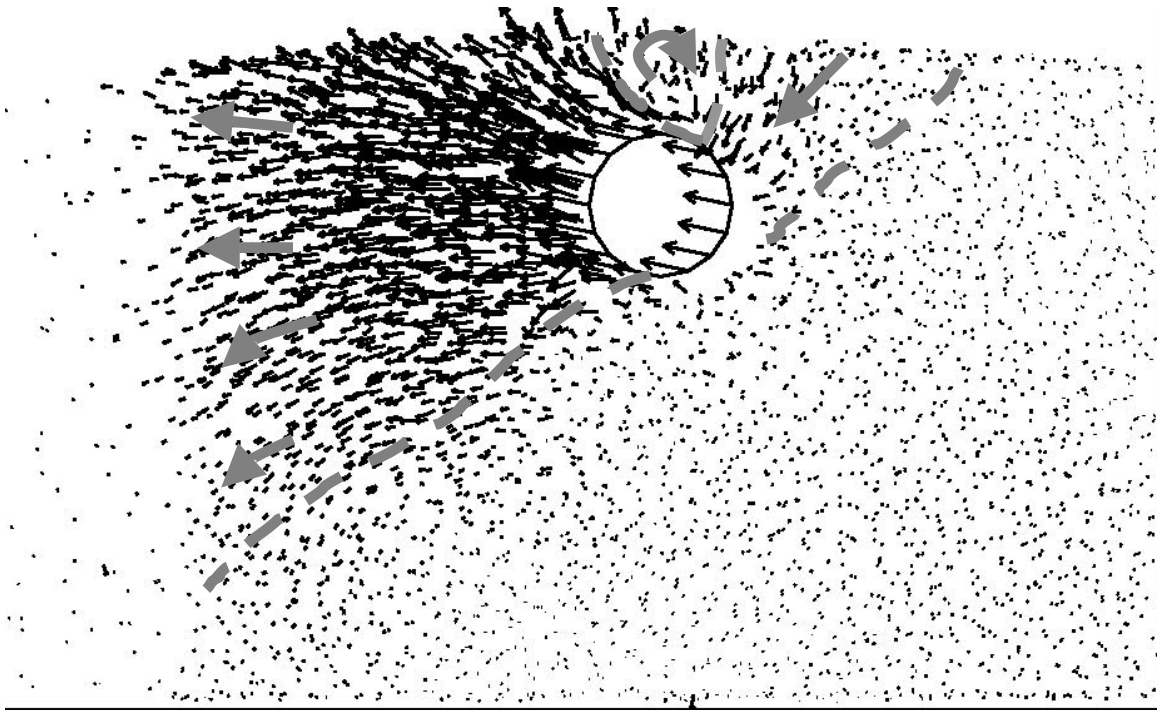


(b) Enlarged scale

Figure C-1  $H/D = 2$ , Medium sand,  $\tan \phi_\mu = 3.0$

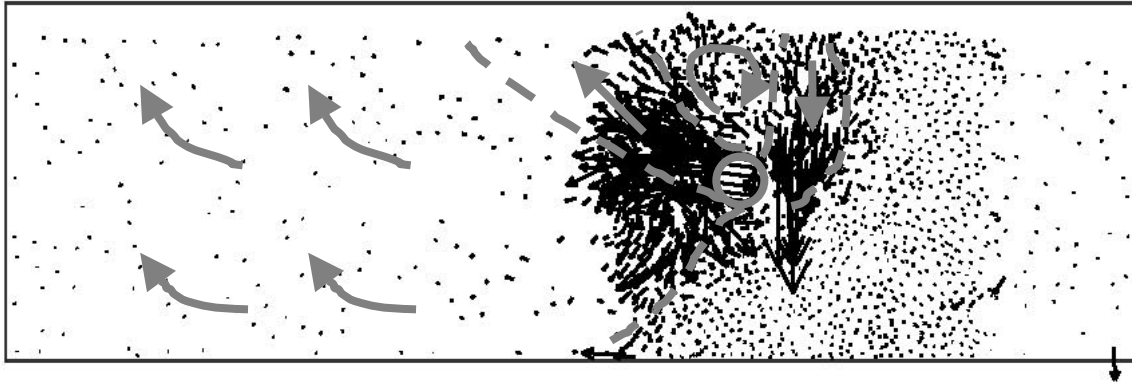


(a) Full-sized scale

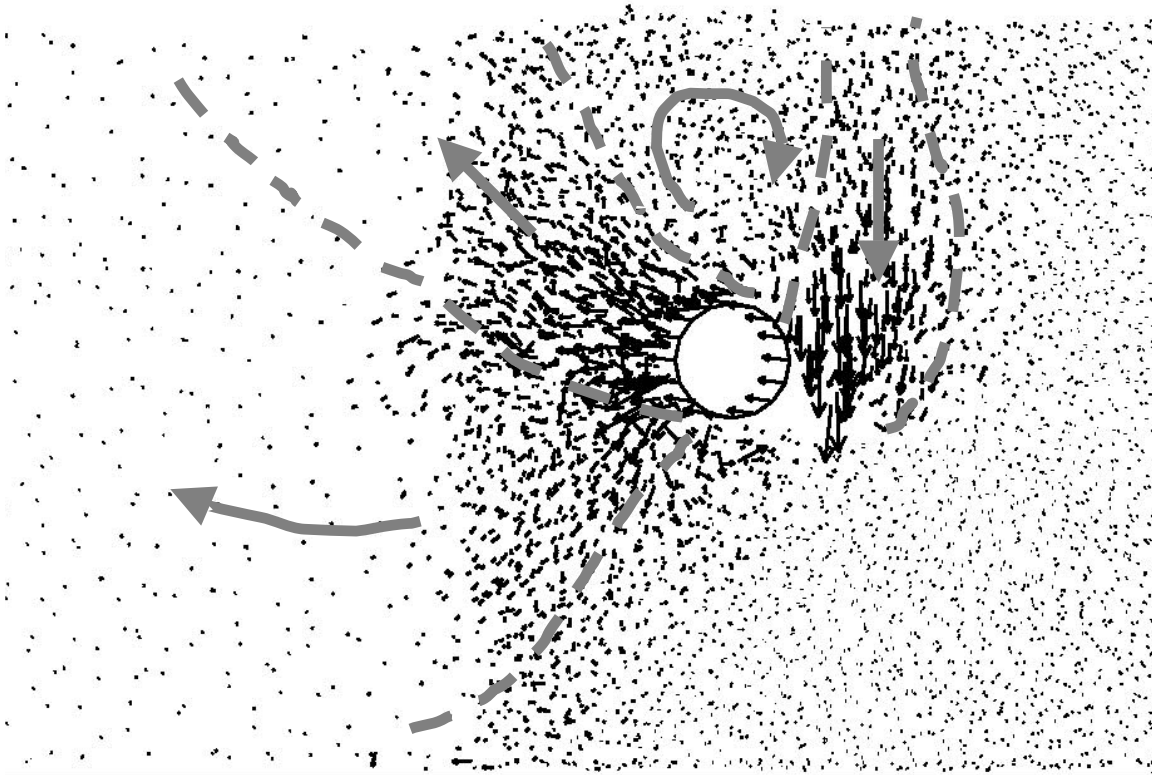


(b) Enlarged scale

Figure C-2  $H/D = 2$ , Dense sand,  $\tan \phi_\mu = 3.0$

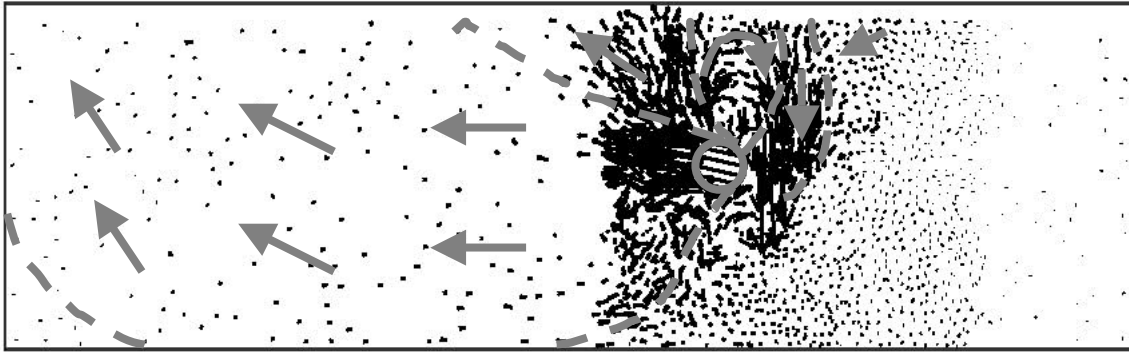


(a) Full-sized scale

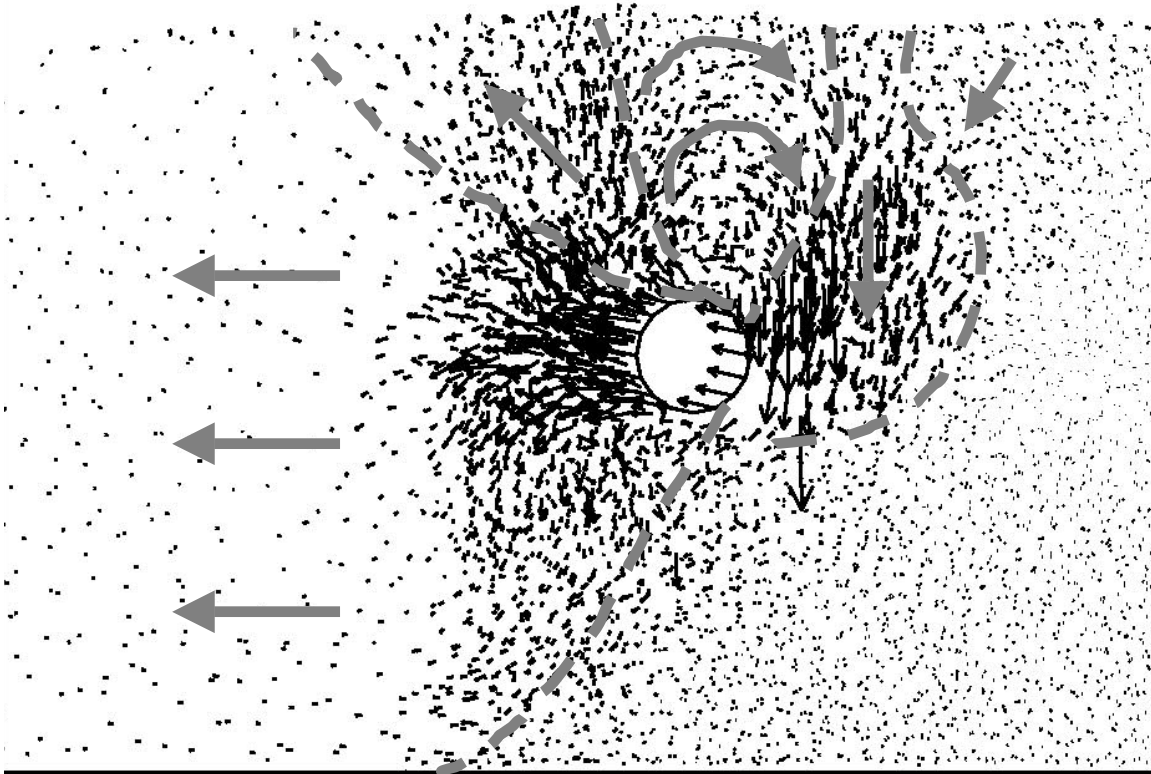


(b) Enlarged scale

**Figure C-3**  $H/D = 4$ , Medium sand,  $\tan \phi_\mu = 3.0$

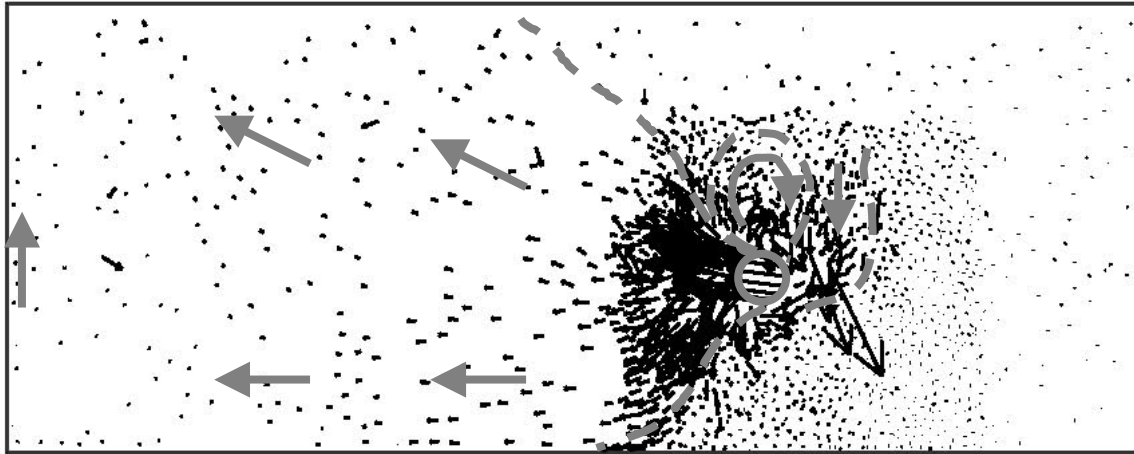


(a) Full-sized scale

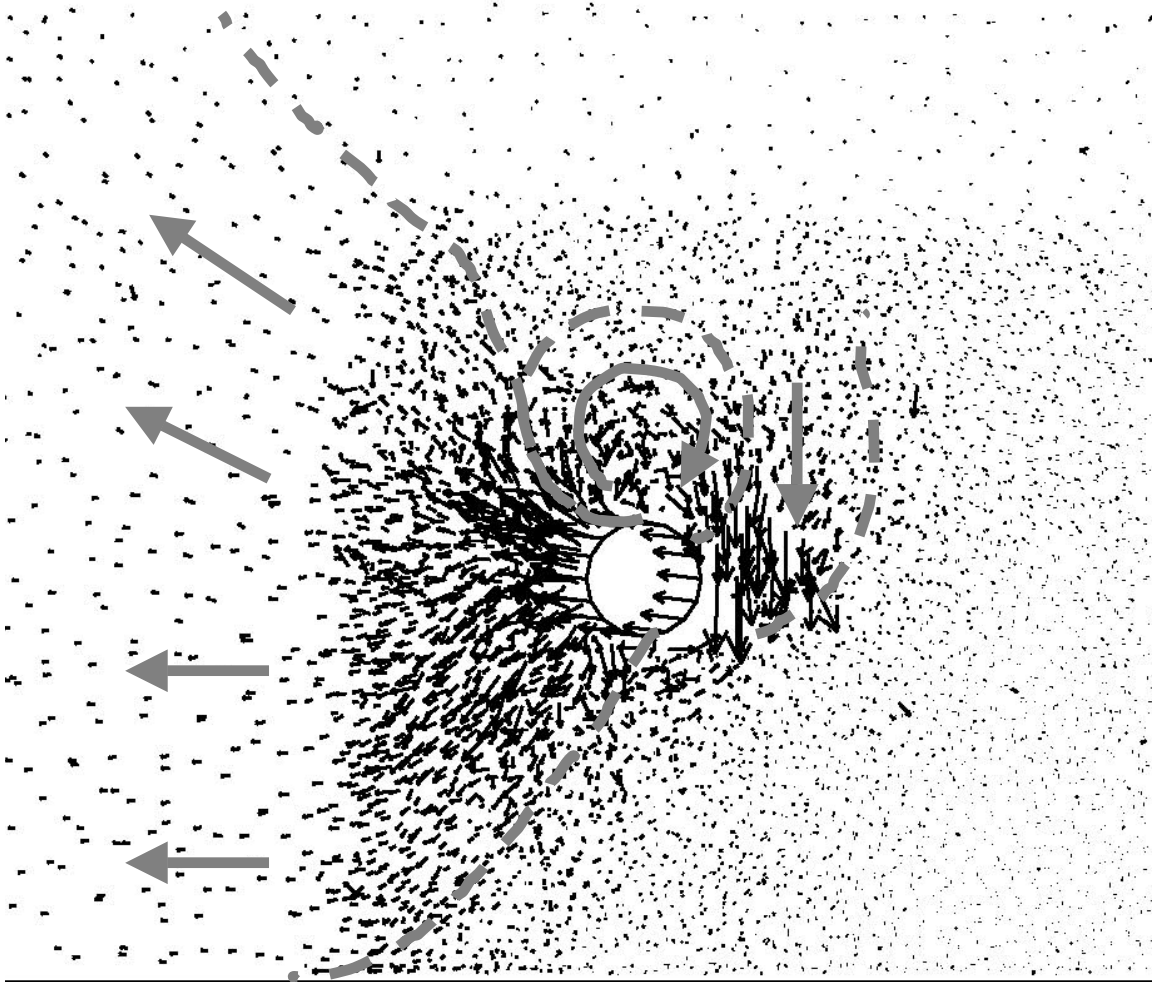


(b) Enlarged scale

**Figure C-4**  $H/D = 4$ , Dense sand,  $\tan \phi_\mu = 3.0$



(a) Full-sized scale



(b) Enlarged scale

Figure C-5  $H/D = 6$ , Medium sand,  $\tan \phi_\mu = 3.0$