Landmarks in Earth Reinforcement, Ochiai et al. (eds),
© 2001 Swets & Zeitlinger, ISBN 90 2651 863 3

Kinematics and failure of soil-nailed excavation models in dynamic centrifuge tests

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ABSTRACT: The influence of nail length variation with depth on the kinematics and stability of soil nailed excavations under dynamic loads is analyzed from the results of three dynamic centrifuge tests. The centrifuge models represented prototype excavations 7.6 meters deep with three rows of nails. Length of nails varied between the tests such that the total nails expenditure per test remained constant. In the first model all nails had the same length that can be characterized as medium. In the second model the nails in the top row were long, in the middle row medium and in the bottom row short. In the third model the nails in the top row were short, in the middle row medium, and in the bottom row long. The difference in nails arrangement resulted in somewhat different movements of facing and nailed soil mass and a very different resistance to dynamic load.

1 INTRODUCTION

Soil nailing is an in-situ method of soil reinforcement for stabilizing excavations and slopes by placing passive inclusions in the ground as the excavation proceeds (Gassler, 1998; Juran and Elias, 1991; Mitchell and Christopher, 1990). The use of soil nailing systems in earthquake regions requires understanding of their behavior under seismic loads. Some of the first experiences with seismic stability of soil-nailed excavations were gained during the 1989 Loma Prieta Earthquake in San Francisco Bay area (Vucetic et al., 1998) and from two dynamic centrifuge tests studies. In the first centrifuge tests study (Vucetic et al., 1993) varying nail lengths and nail rigidities were investigated on 4 models, while in the second study (Vucetic et al., 1996) various parameters influencing seismic stability and kinematics of failure were investigated on a total of 14 models. In this paper the results of tests on three models from the second centrifuge study are analyzed in certain detail to examine the influence of nail length variation with depth on the kinematics of failure and overall seismic stability.

2 DESCRIPTION OF MODELS, TESTING PROCEDURE AND TESTING PROGRAM

Dynamic centrifuge tests were conducted according to the procedure described in Vucetic et al. (1993) and its modifications described in Vucetic et al. (1996). Only the information needed to understand the test results presented below are summarized here. The other details can be found in the above referenced publications.

The longitudinal cross section of one of the models displaying the size of the model box, arrangement of nails and facing, distribution of accelerometers and locations of LVDTs for recording of displacements is presented in Figure 1. The width of the model box was 203 mm. The centrifuge testing scaling factor was 50, meaning that the dynamic tests were performed in-flight at 50g and that the prototype excavation height was 7.6m. To obtain prototype accelerations, the recorded accelerations must be divided by 50. To obtain prototype displacements, the recorded displacements must be multiplied by 50.

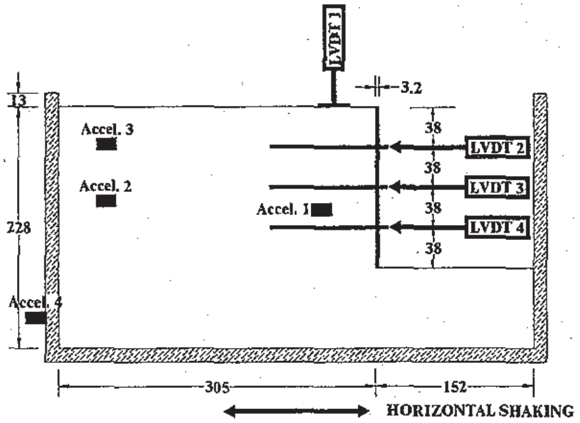
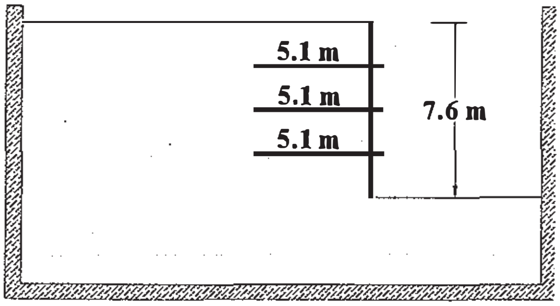
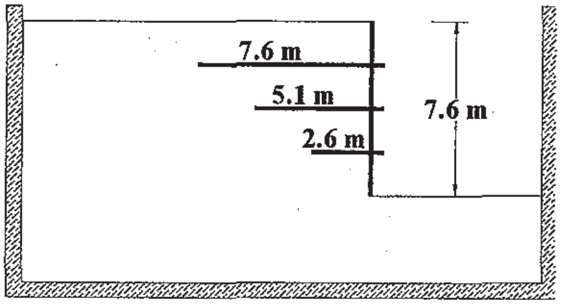


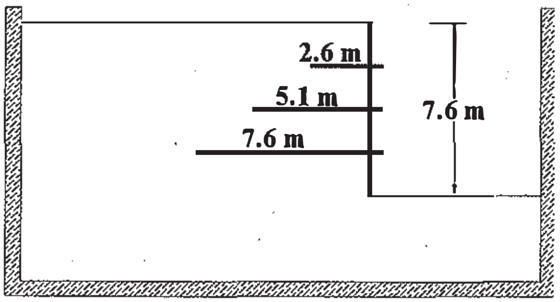
Figure 1. Longitudinal cross-section of the model with instrumentation configuration (dimensions are in millimeters).



a) TEST A (BENCHMARK)



b) TEST B (TOP NAILS - LONG)



c) TEST C (TOP NAILS - SHORT)

Figure 2. Investigated soil-nailing system configurations with varying prototype nail lengths.

In each model there were three rows of model nails made of glass-filled polycarbonate plastic having axial and flexural rigidities that roughly represent prototype grouted nails often used in practice (Bruce and Jewel, 1986; 1987). Horizontal distance between the model nails was 50mm. The model facing in all models was made of thin plexiglass sheet representing relatively strong and rigid prototype facing. The connection between the nails and facing was strong enough to hold throughout the testing.

Soil used was uniform moist silica sand. The sand was build into the model box in alternating layers. Every other layer was black-dyed to facilitate the recognition of failure patterns and failure surfaces during the test and after the removal of the models from the centrifuge platform.

As shown in Figure 1, every model was instrumented with four accelerometers and four LVDTs. Accelerometer No. 4 was used to control the applied acceleration of the model box. Accelerometer No. 1 was installed in the nailed soil mass to record accelerations of the soil nailed block, while accelerometers No.2 and 3 were installed in the soil behind the potential failure surfaces. LVDT 1 recorded settlement of the nailed soil mass behind the facing, while LVDTs 2, 3 and 4 recorded horizontal movement and deformation of the facing.

Three different models analyzed in this paper are presented in prototype dimensions in Figure 2. In Model A all of the nails had the same length. In Model B the nails in the top row were long and in the bottom row short. In the third Model C the nails in the top row were short and in the bottom row long. The corresponding length ratios (nail length divided by excavation height) are given in Table 1. Standard length ratio recommended in practice is between 0,5 and 0.8, which is labeled here as "medium". It must be noted that the total nail expenditure per model was the same, i.e., cumulative length of nails in every model was constant. In this context, the test data presented below suggest which configuration of soil nails is more economical.

Table 1. Nail length ratio distribution

Test	Nail	Length Ratio
TEST A (Benchmark)	top	0.67 - medium
	middle	
	bottom	
TESTB (Top nails-long)	top	1.00 - long
	middle	0.67 - medium
	bottom	0.33 - short
TEST C (Top nails-short)	top	0.33 - short
	middle	0.67 - medium
	bottom	1.00 - long

Table 2. Cyclic loading program

Test	Cyclic Loading Series Number	Prototype Horizontal Shaking Acceleration Amplitude Accelerometer No. 4 (g)	Prototype Cumulative Settlement Behind Facing - LVDT1 (mm)	Prototype Cumulative Horizontal Displacement of Top Nails - LVDT 2 (mm)
TEST A	1	0.18	50	50
	2	0.31	150	225
	3	0.40	650	700
TEST B	1	0.17	50	75
	2	0.35	575	725
TEST C	1	0.18	75	50
	2	0.30	150	150
	3	0.35	250	250
	4	0.34	300	300
	5	0.42	385	375
	6	0.44	550	550

Each model was subjected in-flight at 50g to several consecutive series of 10 cycles of approximately uniform acceleration amplitude, a_{cy}. The magnitude of average a_{cy} applied (via accelerometer No. 4) varied from series to series as listed in Table 2. The table also includes cumulative settlements behind the facing (LVDT 1) and horizontal displacements of top nails (LVDT 2) at the end of each cyclic series. In the first cyclic series a_{cy} was around 0.18 (g/50). In the subsequent cyclic series a_{cy} was larger, from 0.30 to 0.35 (g/50), and afterwards it was even larger from 0.40 to 0.44 (g/50).

3 KINEMATICS OF FACING AND FAILURE PATTERNS

Horizontal movement of facing was recorded during tests with three LVDTs placed as shown in Figure 1. Recorded data are presented in Figures 3 to 6. Figures include input accelerations (box accelerometer No. 4), settlement behind the facing (vertical LVDT 1) and horizontal displacements of the facing (top, middle and bottom horizontal LVDTs 2,3 and 4).

Data from test on Model A are presented on Figure 3, showing that three cyclic series with a_{cy}= 0.18, 0.31 and 0.40 g/50 were applied before a catastrophic failure took place. In every series the facing experienced oscillatory motions with the residual displacements towards the excavation and downwards. Records of the vertical LVDT 1 indicate that the soil nailed mass behind the upper part of the facing oscillated accordingly. Cyclic Series 1 with a_{cy}=0.18 g/50 has not produced significant displacements towards the excavation. Series 2 with a_{cy}=0.31 g/50 produced relatively large displacements, while Series 3 with a_{cy}=0.40 g/50 brought the system to complete failure. Such movement of facing and soil mass behind it is graphically portrayed on Figure 7a. The displacements recorded by LVDTs 2, 3 and 4 are connected with straight lines which in a simple manner describe the outward movements of the facing. Beginning and the end of each cyclic series are represented by solid lines, while the facing positions after cycles 3 and 6 within each series are represented by dashed lines. Facing was deformed according to the forces and moments applied to it, so in reality, of course, it was not shaped as a broken line but a continuous curve.

To gain better insight into the kinematics of the nailed soil mass and the mechanism of ultimate catastrophic failure, after each test the centrifuge models were dissected and thoroughly analyzed. The resulting failure patterns are presented on Figure 8.

The following observations can be made about the behavior of Model A from Figures 3, 7a and 8a. During cyclic shaking facing rotated around its toe due to the anchoring effect of the bottom row of nails and passive resistance of the soil in front of the

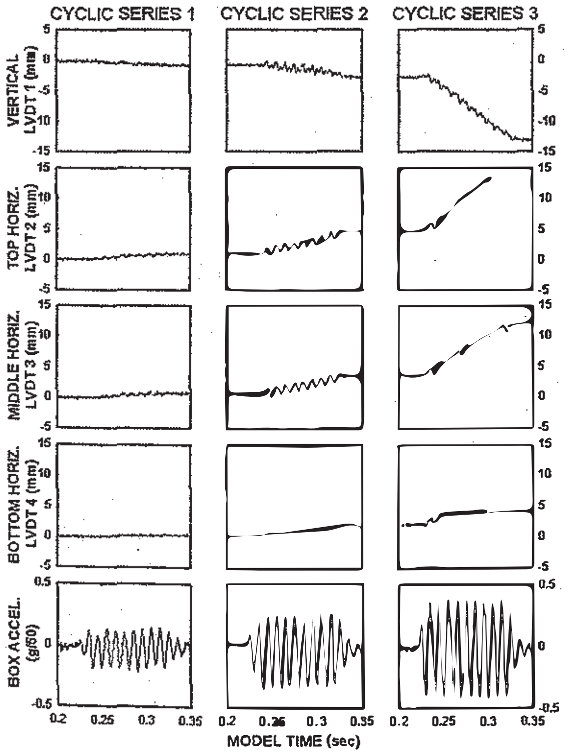


Figure 3. Accelerations applied and displacements recorded in Test A.

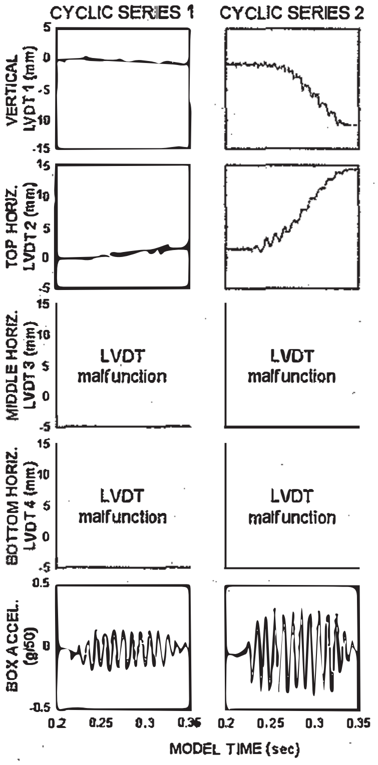


Figure 4. Accelerations applied and displacements recorded in Test B.

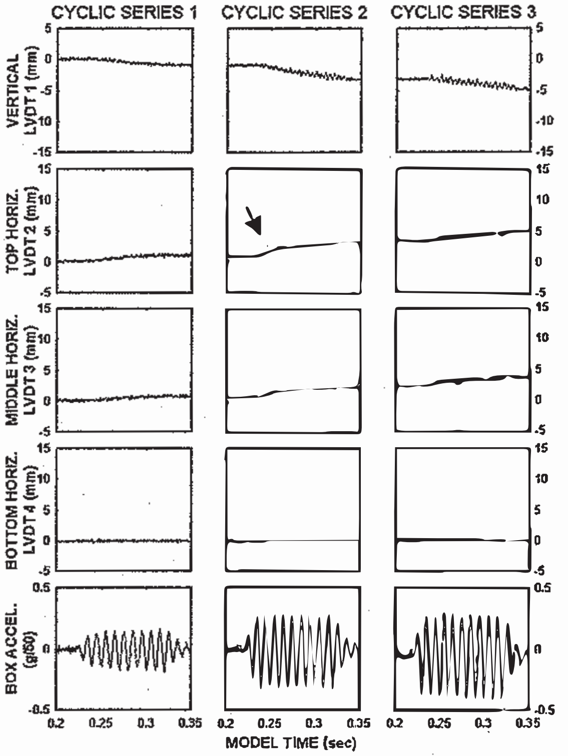


Figure 5. Accelerations applied and displacements recorded in Test C - cyclic series 1,2 and 3.

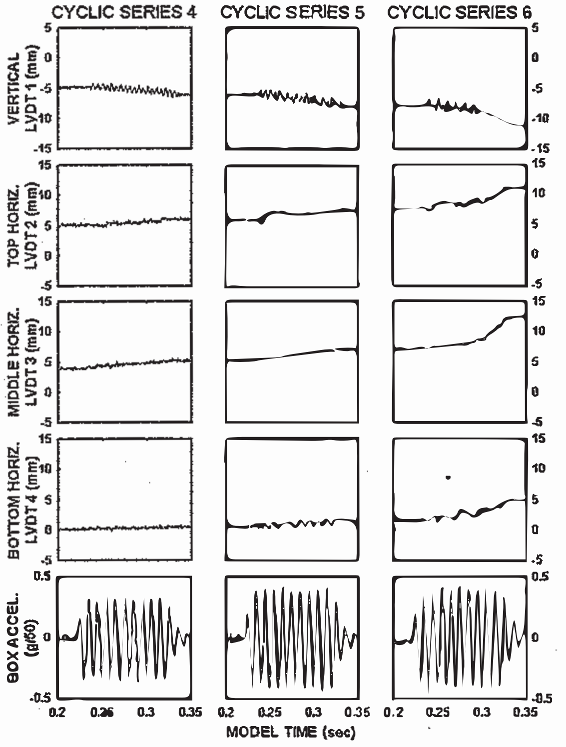


Figure 6. Accelerations applied and displacements recorded in Test C - cyclic series 4,5 and 6.

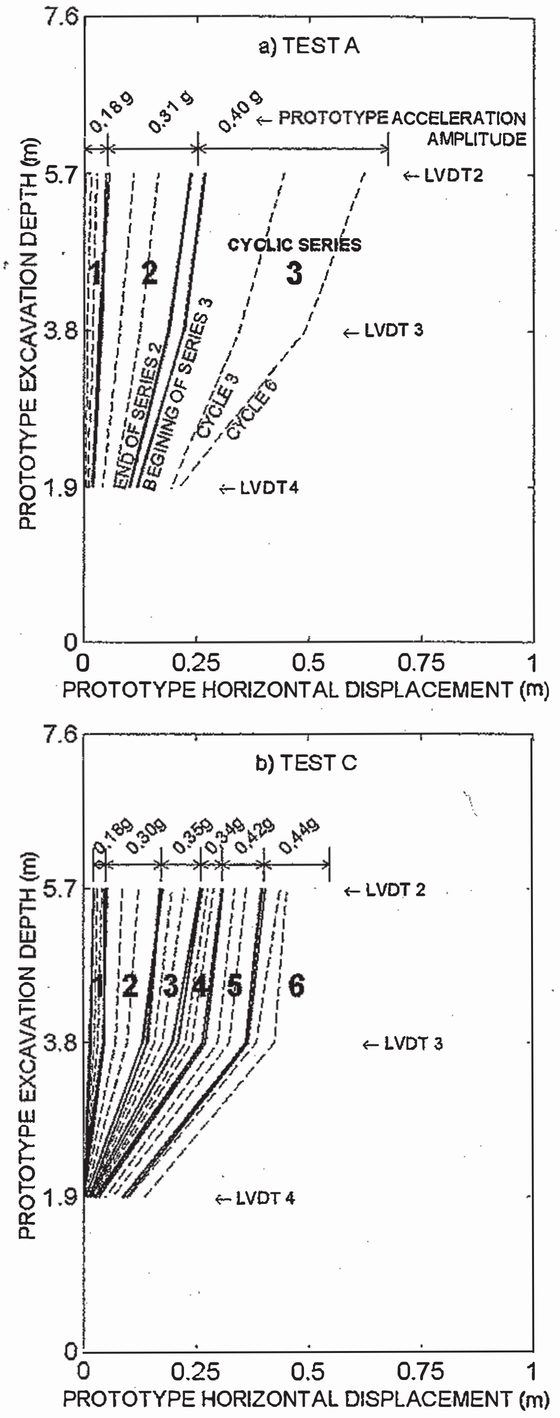
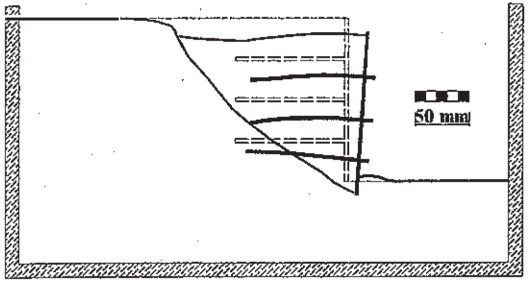
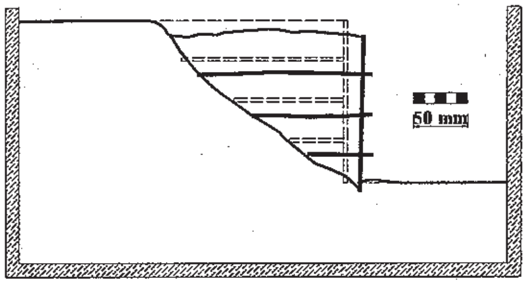


Figure 7. Simple presentation of the facing movement a) in Test A, b) in Test C.

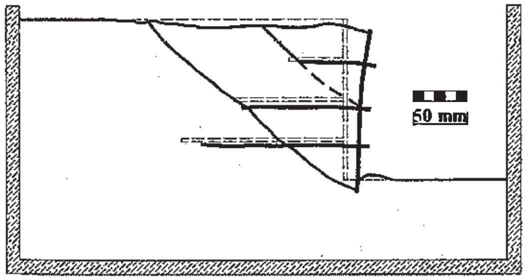
toe of the excavation where facing penetrated downwards into the soil. How the bottom nails extended into the soil behind the failure surface where they acted as anchors, and how the toe of the facing caused passive failure of the soil in front of it, is clearly visible on Figure 8a. It is also evident from the figure that during cyclic loading the nailed soil



a) TEST A (BENCHMARK)



b) TEST B (TOP NAILS - LONG)



c) TEST C (TOP NAILS - SHORT)

Figure 8. Geometries of failure observed on the models removed from the centrifuge.

mass acted as a block that was sliding incrementally on the inclined failure surface, and that the system ultimately failed after the bottom nails started to be pulled out. Such failure pattern and kinematics of the nailed soil mass have already been observed earlier on similar tests by Tufenkjian and Vucetic (2000).

It should be noted that the level of shaking required to fail Model A corresponds to extremely strong earthquake that is practically impossible to occur. In that sense, the behavior of Model A confirms that the soil nailed structures with grouted nails having length ratio of around 0.7 and built in a standard manner are seismically very stable (Vucetic et al., 1998).

The kinematics and failure of Model B are illustrated on Figures 4 and 8b. In the test on Model B LVDTs 3 and 4 malfunctioned, hence the presentation of the facing movement such as in Figure 7 could not be obtained. Nevertheless, Figures 4 and 8b clearly indicate that the reduction of the nail length with depth triggered the generation of failure surface along the ends of the nails with the slope practically identical to that of Model A. However, in this model there was no anchoring effect of bottom nails, which caused a substantial reduction of the seismic stability. Failure of Model B occurred after only two cyclic series.

The kinematics and failure of Model C are illustrated on Figures 5, 6, 7b and 8c. In this model, the anchoring capacity of the long bottom nails was the greatest, which resulted in the greatest overall seismic stability. The system completely failed after 6 cyclic series of ten cycles of large accelerations. However, as shown on Figure 8c a local failure surface developed behind the short nails at the top of the structure. The resulting local failure was accompanied by significant bending of the facing. Had the facing been less strong, this portion of the system would have failed earlier. A sudden jump in the record of the top horizontal LVDT 2 in Cyclic Series 2, which is marked in Figure 5 by an arrow, indicates that this local failure has most likely started at the beginning of Cyclic Series 2. Otherwise, the slope of the failure surface in Model C is practically the same as in Models A and B.

4 CONCLUSIONS

From the results of centrifuge tests on three models presented in this paper the following conclusions can be derived.

1. Centrifuge testing is a very useful tool for analysis of kinematics and failure patterns of complex geotechnical systems under cyclic loads, such as soil-nailed excavations.
2. In the models investigated, the main function of the top nails was to tie soil and nails into a "soft block" that under cyclic loads acts as a unit. On the other hand, the bottom nails have dual function. They tie soil together just like the top nails, but if they extend beyond the failure surface they also act as anchors.
3. The anchoring capacity of the bottom nails extending beyond the failure surface can significantly contribute to the seismic stability of soil-nailed excavations.
4. To achieve the greatest seismic stability of soil-nailed excavations with the given total length of nails (total nails expenditure) longer nails should be installed at the bottom of the excavation, while the top nails can be shorter. However, in such a configuration a special consideration should be given to the possibility and consequences of local failure in the zone of the top short nails.
5. Having the short nails at the bottom and long nails at the top of the soil-nailing system eliminates the anchoring capacity of bottom nails, thereby reducing seismic stability.

5 ACKNOWLEDGEMENTS

The centrifuge tests were conducted at the Rensselaer Polytechnic Institute (RPI) Geotechnical Centrifuge Research Center in Troy, New York. The excellent support and cooperation of Professor Ricardo Dobry, Professor Ahmed Elgamal and Dr. Korhan Adalier during the testing are gratefully acknowledged. The authors also wish to thank Professor Mark R. Tufenkjian from California State University, Los Angeles, for his help in preparing the testing program. The research was supported by the National Science Foundation (NSF) and Federal Highway Administration trough the NSF Grant no. BCS-9224479.

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