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Dynamic failure of soil-nailed excavations in centrifuge

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ABSTRACT: A series of 14 dynamic centrifuge tests was conducted on models of soil nailed excavations. The models were subjected to various levels of horizontal shaking to investigate the failure mechanism and seismic stability of their prototypes. For all models, the depth of the prototype excavation was 7.6 meters and the centrifuge model scale factor was 50. The parameters that varied in the testing program were length, rigidity, inclination and distribution of the nails and the rigidity of the facing. Different failure surfaces were obtained for various model configurations under the strong shaking. This paper summarizes the testing procedure and presents illustrations of failure patterns. The investigation shows that centrifuge testing can successfully demonstrate the dynamic behavior of soil-nailed system and how different parameters can affect its stability and the geometry of its failure pattern.

1 INTRODUCTION

Soil nailing is an in-situ method of soil reinforcement for stabilizing excavations and slopes by placing passive inclusions in the ground. Prior experiences gained during the 1989 Loma Prieta Earthquake in the San Francisco Bay area (Felio et al., 1990; Tufenkjian and Vucetic, 1993) and from the series of centrifuge tests on soil-nailed excavation models (Vucetic et al., 1993) attested to the inherent seismic stability of soil-nailed system with grouted nails commonly constructed in California. However, for more reliable geotechnical design methodologies of this increasingly popular systems in earthquake regions, a thorough understanding of their seismic response is necessary. Towards that goal, another series of dynamic centrifuge model tests was conducted. This continued effort to evaluate the response and possible failure mechanisms of soil-nailed excavations under dynamic loads using centrifuge testing is discussed briefly in this paper.

2 DESCRIPTION OF MODEL AND SUMMARY OF TESTING PROGRAM

The series of four centrifuge model tests conducted earlier (Vucetic et al., 1993), called Phase I, is summarized in Table 1. The new test series, called Phase II, which is the subject of this paper, is summarized in Table 2. In both series of tests, the scale factor of 50 and the same moist sand were used. Also, the reference benchmark test in both series had the same model configuration such as shown in Fig. 1. In all tests, the models represented the prototypes of the excavations having heights of 7.6m, which is approximately equivalent to a height of a 2 to 3-story underground structure.

Figure 1 reveals the vertical spacing of the nails in the models and locations of 4 accelerometers and 4 LVDTs. Accelerometer 4 was for the control of the input excitation in flight, while accelerometers 1,2 and 3 measured the accelerations of soil mass during shaking. LVDTs 2,3 and 4 measured the lateral movements and associated rotation of the facing, while LVDT 1 measured the vertical settlement of the nailed soil mass. The measured signals were processed and recorded by a data acquisition system. The examples of the failure mechanism and LVDT records obtained in Phase I are shown in Fig. 2. The same type of test data were obtained in Phase II, except that for better accuracy three instead of two LVDTs were used to measure the horizontal movement and rotation of the facing.

In Phase I (Table 1), the effects of the nail length ratio and to a limited extent the axial and flexural rigidities of the nails were investigated (Vucetic et al., 1993). In Phase II (Table 2), besides the additional testing of the same effects, the effects of the inclination and density of the nails, distribution of nails with varying lengths, and the rigidity of the facing were investigated. Also, silty clay was used in one test instead of the reference moist sand.

Table 1. Summary of Phase I testing: all tests were done using wet sand, rigid facing, and horizontal nails with 4-5-4 spacing (Vucetic et al., 1993)

Test No.	Length Ratio: nail length / excavation height	Axial Rigidity of Nails	Flexural Rigidity of Nails
1	0.67 Benchmark test	Reg.	Reg.
2	**0.33**	Reg.	Reg.
3	**1.00**	Reg.	Reg.
4	0.67	**Small**	**Small**

As shown in Tables 1 and 2, the length ratio (nail length divide by excavation height) in the benchmark and most of the other tests was 0.67, which falls in the recommended range of 0.5 to 0.8 (Bruce and Jewell, 1987). The length ratio of 0.33 tested in Phase I corresponds to rather short nails, while the length ratio of 1.00 tested in both phases corresponds to rather conservatively long nails. In tests 11 and 12 of Phase II, two special configurations of decreasing and increasing length of nails with depth, respectively, were tested. The regular axial and flexural rigidities of the model nails correspond roughly to the prototype rigidities of the grouted soil nails with a steel rebar 25 mm in diameter grouted in a 150 mm diameter hole. In prototype structure, the nails are generally inclined at 10 to 20 degrees from the horizontal. In Phase II the effects of 15° and 30° nail inclinations were therefore tested and compared with the horizontally placed nails investigated in both, Phase I and Phase II. In all of the tests, except in test 13 in Phase II, the axial and flexural rigidities of the model facing corresponded to a rather rigid reinforced concrete prototype facing 150 mm thick. The model facing in test 13, labeled as soft, was made of the same material as in other tests but with half the thickness. Two layouts of soil nails in lateral direction that accommodate regular and larger spacing of the nails were tested in Phase II. These configurations are labeled in the last column of Table 2 as 4-5-4 and 2-3-2 spacings. The 4-5-4 spacing corresponds to the prototype spacing of 2.5 m, while the 2-3-2 corresponds to 3.4 m.

3 TESTING PROCEDURE

The testing procedure in Phase II was the same as in Phase I, except that in Phase II the friction between the soil and the box was essentially eliminated. This

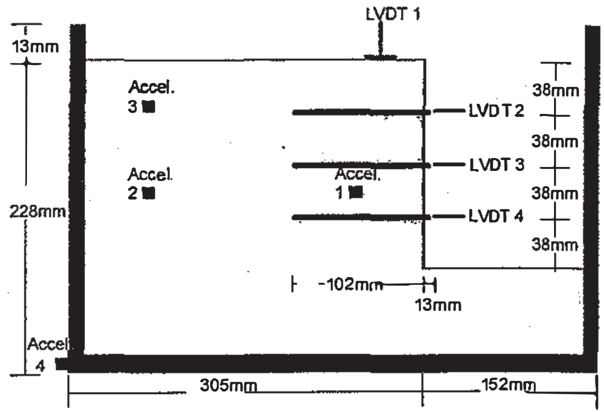


Figure 1. Longitudinal view of the model box

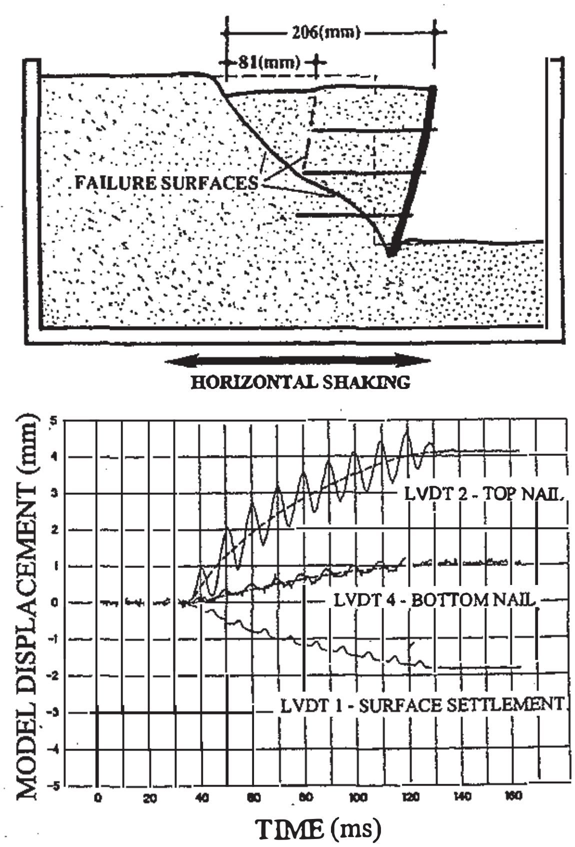
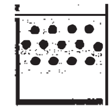
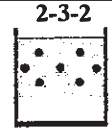
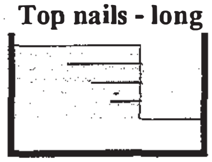
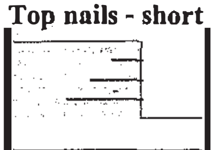


Figure 2. Failure mechanism of benchmark test and LVDT records obtained in Phase I (Tufenkjian and Vucetic, 1993; Vucetic et al., 1993)

Table 2. Tests conducted during Phase II testing program.

Test No.	Length Ratio of Nails	Axial Rigidity of Nails	Flexural Rigidity of Nails	Nail Inclination	Soil Type	Flexural Rigidity of Facing	Spacing and Distribution of Nails
1	0.67 **Benchmark Test** (same as in Phase I)	Regular	Regular	0^0	Uniform Sand	Rigid	4-5-4 
2	0.67 **Benchmark Test** (improved boundary conditions)	Regular	Regular	0^0	Uniform Sand	Rigid	4-5-4
3	0.67	Regular	Regular	**15^0**	Uniform Sand	Rigid	4-5-4
4	0.67	Regular	Regular	**30^0**	Uniform Sand	Rigid	4-5-4
5	0.67	Regular	Regular	0^0	Uniform Sand	Rigid	**2-3-2** 
6	0.67	Regular	Regular	0^0	Uniform Sand	Rigid	**2-3-3**
7	**1.00 (Long nails)**	Regular	Regular	0^0	Uniform Sand	Rigid	**2-3-2**
8	**1.00 (Long nails)**	Regular	Regular	0^0	Uniform Sand	Rigid	**2-3-2**
9	0.67	**Small**	**Small** (rubber type)	0^0	Uniform Sand	Rigid	4-5-4
10	0.67	Regular	**Small** (cable type)	0^0	Uniform Sand	Rigid	4-5-4
11	**Top nails - long** 	Regular	Regular	0^0	Uniform Sand	Rigid	4-5-4
12	**Top nails - short** 	Regular	Regular	0^0	Uniform Sand	Rigid	4-5-4
13	0.67	Regular	Regular	0^0	Uniform Sand	**Soft**	4-5-4
14	0.67	Regular	Regular	0^0	**Silty Clay**	Rigid	4-5-4

was done by placing between the soil and the sidewalls of the model box a thin stretchable membrane that was lubricated with a water-based jelly on both sides.

The testing procedure included the following steps: (i) preparation of the soil, nails, facing, and the model box with elements for eliminating sidewall friction; (ii) the "building-in" of the soil by compacting it in the layers of different colors, with the simulatenous placement of the nails and accelerometers at predeterminded locations (in this step, the entire model box is filled with sand); (iii) centrifuge spinning and in-flight shaking of the box to further compact the soil under the prototype vertical stresses; (iv) removal of the box from the centrifuge platform and excavation to allow the installation of the model facing; (v) mounting of the facing and attachment of the four LVDTs as shown in Fig. 1; (vi) centrifuge testing that included several consecutive cyclic loading series of 10 uniform sinusoidal acceleration cycles with different amplitude in each series (the prototype amplitudes varied between 0.15g and 0.43g); (vii) removal of the model box from the centrifuge and elaborate excavation of the soil to observe and document details of the failure planes and related deformations; (viii) simultaneous sampling of the model sand to determine the distribution of void ratio and moisture content; and (ix) processing of the recorded test data.

4 ILLUSTRATIONS OF FAILURE PATTERNS

Photographs of the failure planes obtained by excavating the models at the end of the tests during Phase II are presented in Figs. 3 to 11.

Figure 3 shows that the failure pattern in the benchmark test in Phase II is the same as that in

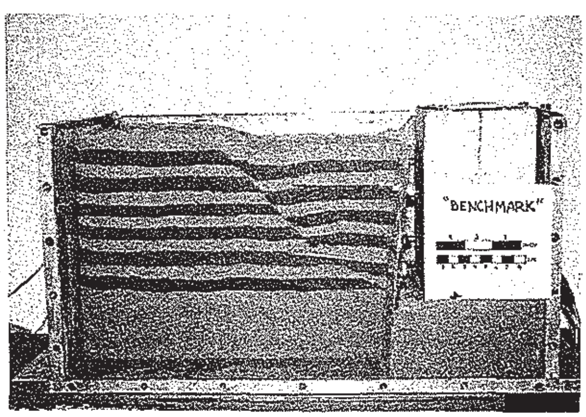


Figure 3. Test 2 - benchmark test with improved boundary conditions

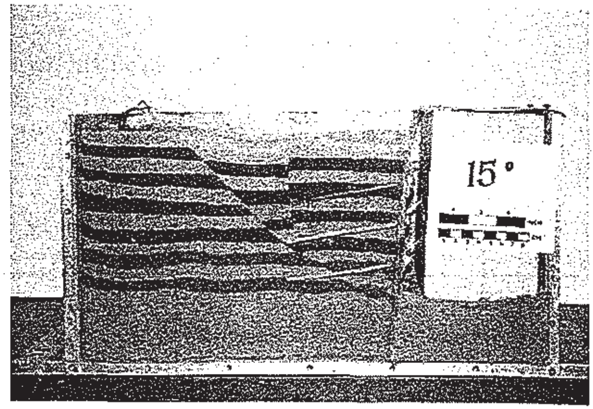


Figure 4. Test 3 - 15^0 nail inclination

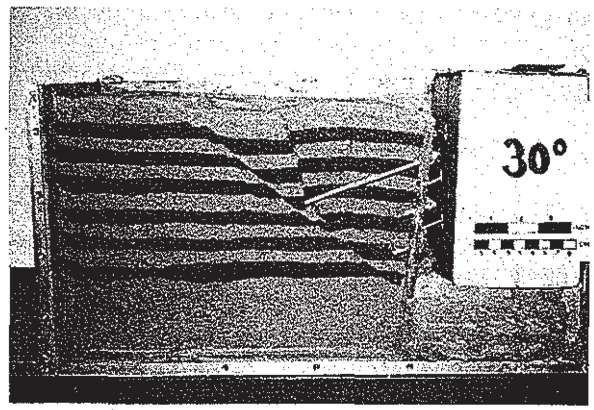


Figure 5. Test 4 - 30^0 nail inclination

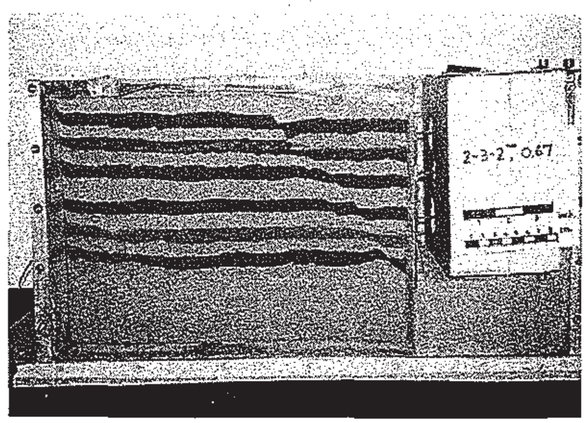


Figure 6. Test 5 - Reg. nails with 2-3-2 spacing

Phase I sketched in Fig. 2. Under strong horizontal shaking, the nailed soil mass moved laterally as a rigid block allowing the active pressure wedge to develop behind it. The same type of failure occurred in tests 3 and 4 with inclined nails, as shown in Figs. 4 and 5. Therefore, it seems that the inclination of the nails between 0^0 and 30^0 does not change the failure pattern. The above failure mechanism was originally proposed for static failure by Gassler and Gudehus (1983) and is usually referred to as "German-type".

Figure 6 shows that if the spacing of the nails is substantially increased, the "German-type" failure does not develop. Instead, the failure surface passes through the two bottom rows of nails and resembles the surface of the Rankine type of failure of a non-reinforced backfill. Evidently, as the spacing of the nails increases the effect of the nailing diminishes, and consequently, a Rankine failure surface with the inclination modified for the horizontal inertial forces develops. As shown in Fig. 7, even with the longer nails installed at larger spacing in test 7, the straight failure plane passed through all of the nails. This confirms that the nail spacing is a key design variable.

Figures 8 shows the failure of the system with the nails having smaller flexural and axial rigidities, such that they can easily bend and also significantly elongate under the load. It can be seen that in this case there are several straight failure surfaces that passed through the nails. Evidently, in such a system the nailing of the soil also loses its main purpose of creating a large block of nailed soil, i.e. the block that encompasses two top rows of nails that in the case of failure moves as a single unit such as shown in Fig. 2. An interesting feature of this failure is the occurrence of two distinctive failure surfaces inclined at different angles. Such surfaces correspond to two different intensities of horizontal shaking applied in this test, as explained already in Phase I (Tufenkjian and Vucetic,1993). In test 10, illustrated in Fig.9, where the nails with regular axial rigidity but still small flexural rigidity were installed, the failure pattern resembles again that of the benchmark test. The comparison between tests 9 and 10 therefore indicates that the axial rigidity of the nails may play a more important role than the flexural rigidity.

Figure 10 shows that placing the longer nails above the shorter forces the failure surface to pass along the tips of the nails. The stability of that configuration was considerably smaller than that of the benchmark test. However, the model with

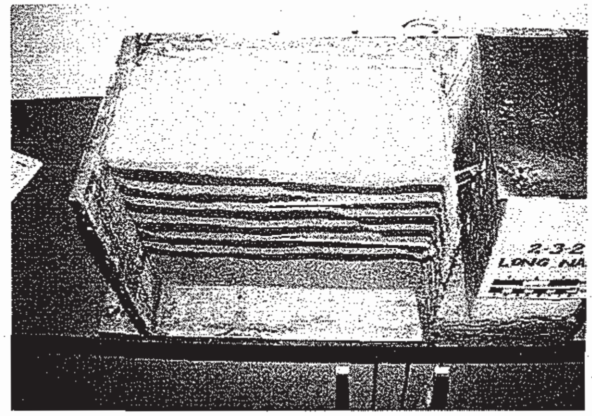


Figure 7. Test 7 - Long nails with 2-3-2 spacing

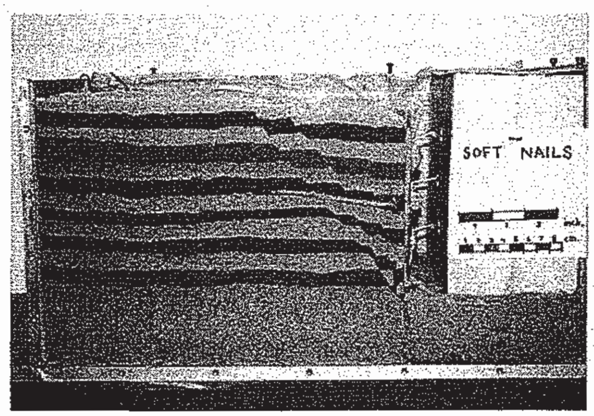


Figure 8. Test 9 - Soft nails

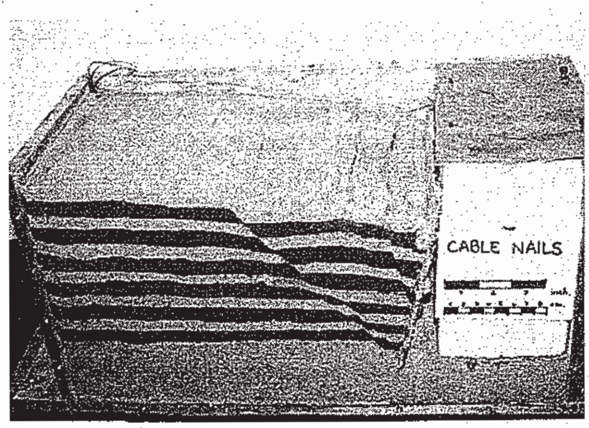


Figure 9. Test 10 - Flexible cable type nails

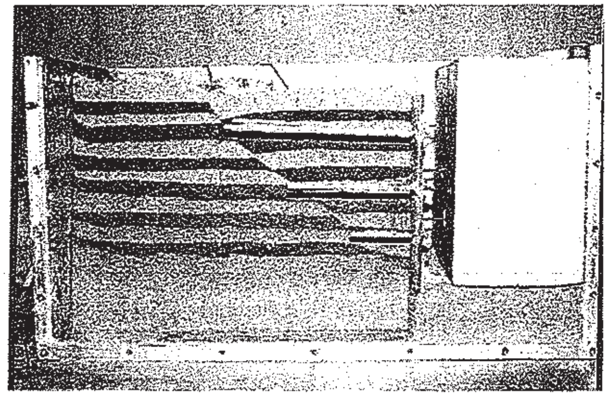


Figure 10. Test 11 - Long top nails

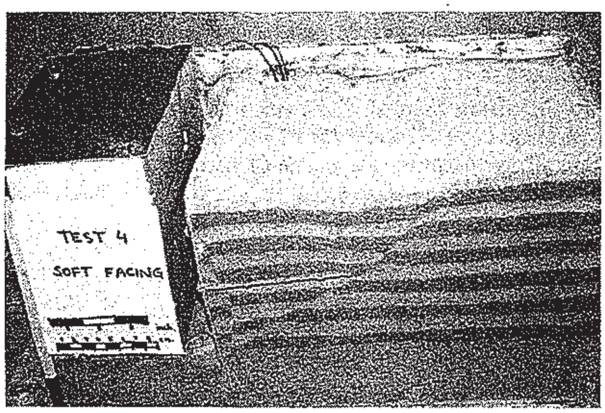


Figure 11. Test 13 - Soft facing

shorter nails on the top and longer at the bottom that was tested in test 12 exhibited excellent stability.

Figure 11 shows the failure pattern of the model with flexible facing (test 13). The overall stability was comparable to that of the benchmark test. However, it can be noticed that right behind the facing a local failure of the soil occurred due to the excessive deformation of the facing.

5 CONCLUSIONS

The results of 14 dynamic centrifuge tests on the models of soil-nailed excavations that are summarized and illustrated in this paper attest to the usefulness of dynamic centrifuge testing. The photographs provide a general picture of the failure mechanisms and qualitative behavior of different types of soil-nailed excavations under strong shaking. They show effectively the role of various design configurations in influencing the stability and failure pattern. The study of the time histories of accelerations and displacements recorded during the centrifuge tests, which are not presented here, will enable detail analysis of the evolution of displacements and deformations leading to the failures that are here just briefly described and illustrated.

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