Properties of Guardrail Posts for Various Soil Types

L. R. Calcote and C. E. Kimball, Southwest Research Institute, San Antonio, Texas

Pendulum tests on two typical guardrail posts installed in five different soil types are discussed. The purpose of the tests was to determine post property variations as a function of soil conditions. Results of the tests were then used for post input properties in the BARRIER VII computer program to estimate the ultimate effect of soil conditions on guardrail performance. It is shown that guardrail installations less than the recommended minimum length of 45.7 m (150 ft) can be expected to fail with the more severe impacts when installed in the poorer soils. For vehicle containment and redirection with barrier lengths of 45.7 m or greater, the end posts should be sufficiently anchored to develop the full strength of the post in the lateral direction, as well as the usual longitudinal anchorages.

In lieu of or in conjunction with expensive, full-scale vehicle tests on impact with highway guardrail systems, analytical simulations are often used. Because of its capability to model the geometric variables of the guardrail installation, an excellent computer algorithm for this purpose is the BARRIER VII program (1). However, it is necessary for inputs to this program that post, railing, and vehicle geometric and inertial properties be specified. The problem is not difficult for railing and vehicle properties but is quite complex for the properties of posts. For example, stiffnesses for elastic horizontal deflections and the deflections to failure must be specified for the posts in both the longitudinal and lateral directions at the railing height. Base moments and shear forces for failure must also be specified for the two directions. The failure mechanism of the post involves high rate impact loading and its effects on both the post material and the supporting soil. Because of these complexities, characterization of the post properties by analytical means is next to impossible to establish.

This paper describes a series of pendulum tests by which guardrail posts are characterized experimentally. Two of the commonly used post types were tested in five different general soil types. The results were then used as inputs for a series of BARRIER VII runs to establish the effects on guardrail performance. It will be shown that care must be exercised in the design of guardrails where soil conditions are of poor quality. This is particularly true for the shorter installations.

EXPERIMENTAL PROGRAM

To determine performance variations of posts as a function of soil conditions, an original pendulum test matrix was to consist of 80 tests as follows:

- Posts
  - W6 × 8.5 steel 1.83 m (6 ft) long with 1.12-m (44-in) embedment
  - 0.15 m × 0.20 m (6 in × 8 in) Douglas fir wood 1.60 m (5.25 ft) long with 0.89-m (35-in) embedment
- Axes
  - Major and minor
- Broad soil classifications
  - Sandy loam
  - Saturated clay
  - Stiff clay
  - Base material
  - Fixed support
- Repeatability
  - 4 tests of each configuration

Since previous tests had been run with a pendulum weight of 1814 kg (4000 lb) and an impact speed of 9.14 m/s (30 ft/s) (2, 3, 4, 5), these conditions were first used. However, unlike the previous tests, no pad was used in the impact area. On completion of the data reduction for the first 16 tests with a base material support, it was found that the rise portion of the force-time curve, which was of interest in determining the constants for BARRIER VII inputs, occurred much too fast (as low as 1 or 2 ms). Thus, the pendulum impact speed was reduced from 9.14 to 6.10 m/s (30 to 20 ft/s), and a 50.8-mm (2-in) plastic pad of Dow Ethafoam 600 was attached in the impact area of the post. This reduced the post inertia-peak effect and produced a rise time of about 15 to 20 ms, which is considered to be more realistic of actual field conditions where railing deformation and take-up of slack occurs in transmitting the impact loads to the posts. The final matrix of conducted tests, including the repeat tests for the base material and those of instrument malfunction, consisted of 102 tests.

Instrumentation for the pendulum tests consisted of a voice track, impact switch, speed trap, and two accelerometer channels recorded on magnetic tape at 1.52 m/s (60 in/s). The tapes were played back on visicorder traces at 0.81 m/s (32 in/s) for preliminary checks of the tests and then used for analog-digital reductions. Data were passed through a class 180 filter before digitizing. A sample rate of 16 000 Hz for four channels was used, and four records of 2048 words/record (0.5 s) were recorded on nine-track tape during the accelerometer calibration portion of the run. Sixteen records (2.0 s) were then taken for the speed trap, impact switch, and accelerometer test data. Data on the nine-track tape were then transmitted to a seven-track tape at the Institute's Hewlett-Packard computer facility.

As a backup program for the data reduction, high-speed photography was attempted. A Locam camera with a film speed of 500 frames/s was first tried without success. After reduction of the pendulum impact speed to 6.10 m/s, a Hycam camera was used at 1000 frames/s. Though every frame was recorded in the data reduction, the results were still not satisfactory. Thus, the analysis attempt was terminated and the Locam camera was used for documentary purposes only. In cases of accelerometer or instrument malfunction, the tests were simply repeated.

The method for determining the BARRIER VII inputs from the pendulum data is illustrated by the dashed line in Figure 1. Note that the inertia peak was ignored since post weights are placed at the railing node in BARRIER VII. At the peak force in the small circle of the figure, the corresponding time, displacement, and force were read from the associated output plots. These values were then used to prepare the pendulum test results shown typically in Table 1 for the wood posts and in Table 2 for the steel posts. Average values of the

Figure 1. Method for determining BARRIER VII from pendulum data.

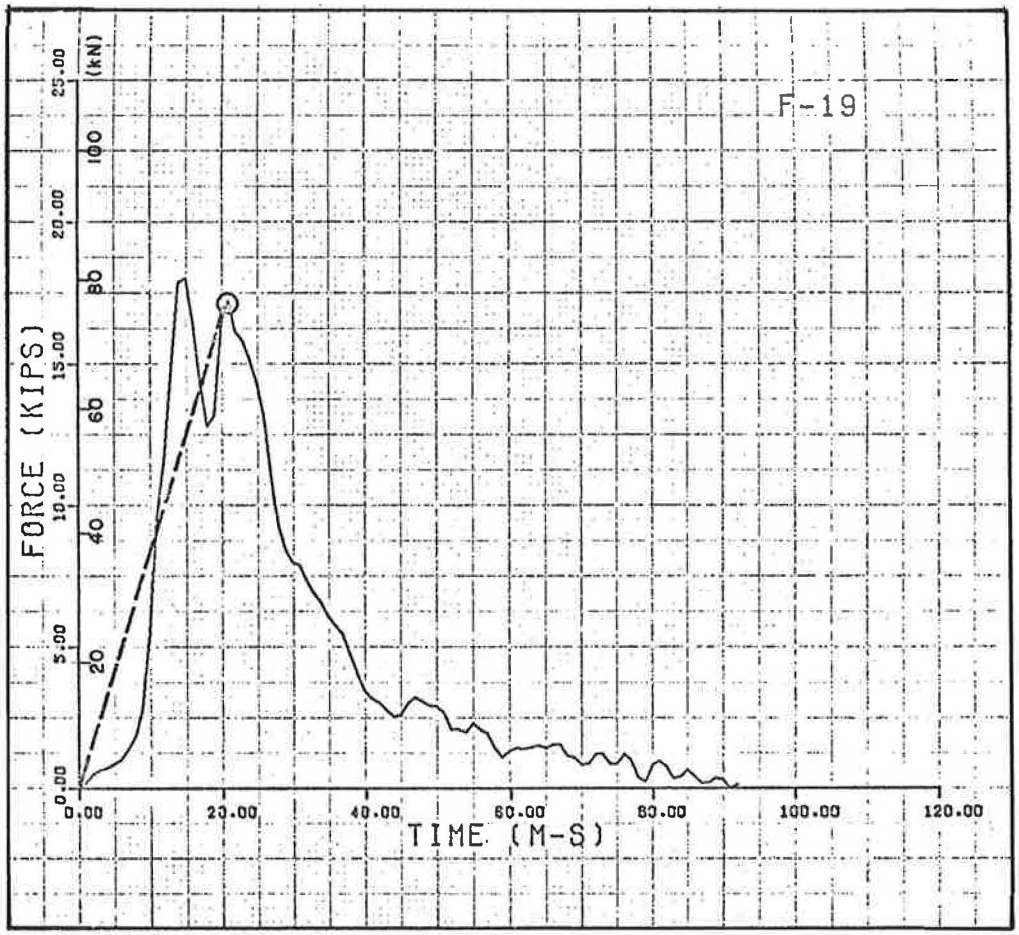

Table 1. Typical pendulum test results for 15.2 cm x 20.3 cm Douglas Fir posts (base material support).

Test No.	Maximum Force (kN)	Time (ms)	Distance (cm)	Remarks
Weak-axis tests				
F-83	49.8	22	13.2	Post fracture
F-87	28.9	19	11.5	Post fracture
F-91	35.6	22	13.5	Soil yield
F-96	49.4	16	9.7	Post fracture
Avg	40.9		12.0	k = 3.41 kN/cm
Strong-axis tests				
F-84	52.0	25	14.9	Soil yield
F-88A	28.5	24	14.6	Soil yield
F-92	32.5	19	11.8	Soil yield
F-95	32.0	20	12.1	Soil yield
Avg	36.5		13.4	k = 2.73 kN/cm

Note: 1 kN = 0.22 kip; 1 cm = 0.4 in.

Table 2. Typical pendulum test results for W6 x 8.5 steel posts (fixed support).

Test No.	Maximum Force (kN)	Time (ms)	Distance (cm)	Remarks
Weak-axis tests				
F-20	22.7	20	12.0	Post yield
F-24	23.6	21	12.7	Post yield
F-28	23.6	21	12.8	Post yield
F-31	20.9	21	13.2	Post yield
Avg	22.7		12.6	k = 1.79 kN/cm
Strong-axis tests				
F-19	77.0	21	12.6	Post yield
F-23	73.8	15	9.1	Post yield
F-27	73.4	20	11.9	Post yield
F-32	75.6	15	9.6	Post yield
Avg	74.7		10.8	k = 6.92 kN/cm

Note: 1 kN = 0.22 kip; 1 cm = 0.4 in.

maximum forces and distances were used to determine stiffnesses, and these values were finally used to prepare the BARRIER VII inputs shown in Table 3.

POST AND SOIL EFFECTS ON VEHICLE PERFORMANCE

The post properties from Table 3 were used as inputs for BARRIER VII runs to determine the effects on vehicle performance. As a first trial, the simulations were compared with Test 273 in Stoughton and others (6). This test had a short installation length of only 22.9 m (75 ft). Further, the test was quite severe; it used a 2250-kg (4960-lb) vehicle at a speed of 109.4 km/h (68 mph) and a 25° impact angle. However, the test site soil was extremely stiff, and the posts were driven into smaller predrilled pilot holes. The results of the tests, along with those of the simulations, are shown in Table 4. It can be seen that vehicle redirection is not predicted with the poorer soil types (negative velocity vectors). Using fixed support properties for the end posts does not improve the situation. The lesser severity and greater dynamic deflection with the fixed supports over the test were probably caused by the poorer quality wood used in the pendulum tests. Four static tests of the full-sized posts were conducted, and horizontal shear failures occurred at an average of 3.65-MPa (530-psi) shearing stress, compared with a 7.86-MPa (1140-psi) book value. Four static tests were then conducted on 0.05-m × 0.05-m (2-in × 2-in) specimens milled from the posts. These tests produced flexural failures with an average modulus of rupture of 58.8 MPa (8530 psi) compared with the 80.6-MPa (11 700-psi) book value.

Table 3. BARRIER VII post properties for various soil types.

Input Parameter	Soil and Post Types: Fixed Support, Steel	Fixed Support, Wood	Base Material, Steel	Base Material, Wood	Stiff Clay, Steel	Stiff Clay, Wood	Saturated Clay, Steel	Saturated Clay, Wood	Sandy Loam, Steel	Sandy Loam, Wood
k_A,[a] kN/cm	1.79	6.23	2.01	3.41	1.07	2.07	1.30	2.45	1.37	2.75
k_B,[a] kN/cm	6.92	7.97	4.31	2.73	2.03	2.49	1.98	2.14	3.40	2.24
M_{PA},[b] kN·m	39.9	38.4	26.1	19.5	14.2	12.3	8.1	8.3	15.7	12.1
M_{PB},[b] kN·m	12.1	28.0	10.9	21.8	8.1	11.6	6.4	8.8	8.3	13.5
F_{PA}, kN	22.7	52.5	20.5	40.9	15.1	21.8	12.0	16.5	15.6	25.4
F_{PB}, kN	74.7	72.1	48.9	36.5	26.7	23.1	15.1	15.6	29.4	22.7
δ_A, cm	12.6	8.4	10.1	12.0	14.1	10.6	9.3	6.7	11.4	9.2
δ_B, cm	10.8	9.0	11.4	13.4	13.1	9.3	7.6	7.3	8.6	10.1

Notes: 1 kN/cm = 0.56 kip/in; 1 kN·m = 8.84 in-kips; 1 kN = 0.22 kip; and 1 cm = 0.4 in.
Customary units were required for program inputs.

[a] A = major axis; B = minor axis. [b] Moments based on height to center of railing = 0.53 m (21 in).

Table 4. Comparison of soil supports for 15.2 cm x 20.3 cm Douglas Fir posts.

Test or Simulation	50-ms Vehicle Acceleration (g): Longitudinal	Lateral	Maximum Dynamic Deflection (m)	Exit Condition: Velocity Vector (°)	Vehicle Heading Angle (°)	Barrier Damage: Beam (m)	No. of Posts Damaged	Remarks
Test	6.75	6.95	1.13	-	-	11.4	3	Reported exit angle = 14°
Fixed supports	4.27	5.01	1.46	8.9	9.9	11.4	7	
Stiff clay support	2.31	2.32	2.38 at 0.30 s	-17.0	-8.5	-	10	Lateral failure of upstream anchor post
Sandy loam support	2.32	2.42	2.44 at 0.30 s	-17.1	-8.4	-	10	Lateral failure of upstream anchor post
Stiff clay with fixed end posts	2.31	3.40	5.53 at 0.65 s	-6.8	24.4	-	12	Lateral failure of downstream anchor post
Sandy loam with fixed end posts	2.32	3.18	5.24 at 0.62 s	-7.2	23.5	-	12	Lateral failure of downstream anchor post
Base material support	2.92	4.27	3.19 at 0.55 s	-2.0	13.3	-	12	Lateral failure of downstream anchor post
Saturated clay with fixed end posts	1.96	2.48	5.80 at 0.59 s	-10.0	19.2	-	12	Lateral failure of downstream anchor post

Note: 1 m = 3.3 ft.

Table 5. Comparison of soil supports for W6 x 8.5 steel posts.

Test or Simulation	50-ms Vehicle Acceleration (g): Longitudinal	Lateral	Maximum Dynamic Deflection (m)	Exit Condition: Velocity Vector (°)	Vehicle Heading Angle (°)	Barrier Damage: Beam (m)	No. of Posts Damaged	Remarks
Test	4.0	6.7	1.23	-	-	7.6	5	Reported exit angle = 8°
Fixed supports	5.25	6.03	1.36	14.2	16.5	11.4	6	
Stiff clay support	3.41	2.87	6.76 at 0.80 s	-4.5	34.9	-	11	Lateral failure of downstream anchor post
Sandy loam support	3.61	3.02	6.36 at 0.79 s	-3.7	31.7	-	11	Lateral failure of downstream anchor post
Stiff clay with fixed end posts	3.41	6.32	2.11 at 0.44 s	8.3	5.6	-	13	No change—numerical instability at 0.57 s
Sandy loam with fixed end posts	3.61	6.32	2.19 at 0.45 s	7.9	5.3	-	13	No change—numerical instability at 0.58 s
Base material support	4.54	5.12	1.35	15.9	7.0	11.4	7	
Saturated clay with fixed end posts	3.04	5.60	6.12 at 0.80 s	5.3	46.7	-	18	Lateral failure of downstream anchor post

Note: 1 m = 3.3 ft.

Thus, the posts used in the pendulum tests were not of the best quality. Nonetheless, the results in Table 4 clearly indicate that such short installations can be expected to fail under severe impacts unless the posts are of good quality and are sufficiently anchored in the soil to cause the post strength to control the failure mechanism.

Table 5 shows the results for Test 120 from Michie and others (7). The test installation was longer at 34.3 m (112.5 ft) and had a less severe impact—a 1730-kg (3813-lb) vehicle at a speed of 91.4 km/h (56.8 mph) at a 28.4° impact angle. However, the impact point was so far down the guardrail that only the last two posts show unnoticeable permanent deformation in the test photographs. The table shows that again, with the poor clay and sand support, the vehicle is not predicted to redirect. However, by using the fixed support properties for the end posts, redirection is achieved before the lateral failures of the downstream anchor posts occur. Thus, if an installation of this length were to be constructed in poorer soils, a concrete footing should be used on the end posts so that the post strength will control the lateral failure.

A guardrail length of 45.7 m (150 ft) was finally used for a 2041-kg (4500-lb) vehicle at a speed of 96.5 km/h (60 mph) at a 25° impact angle to correspond with the accepted containment standard of Bronstad and Michie (8). The results are shown in Table 6. Note that fixed lateral post properties were again used on the three poorer soils. Vehicles were redirected in all cases (positive velocity vectors) but were not turned completely around with the three poor soils (negative heading angles).

Table 6. Post and soil effects on vehicle performance.

Condition	50-ms Vehicle Acceleration (*g*) Longitudinal	50-ms Vehicle Acceleration (*g*) Lateral	Maximum Dynamic Deflection (m)	Exit Condition Velocity Vector (°)	Exit Condition Vehicle Heading Angle (°)	Barrier Damage Beam (m)	Barrier Damage No. of Posts Damaged
Douglas fir posts							
Fixed supports	4.32	5.95	1.37	13.8	10.8	11.4	6
Base material support	2.70	3.43	2.15	10.1	0.6	19.1	12
Stiff clay support[a]	1.97	2.82	2.91	2.2	-5.8	19.1	20
Saturated clay support[a]	1.81	2.39	3.08	8.0	-9.0	19.1	23
Sandy loam support[a]	2.06	2.95	2.66	2.5	-6.4	19.1	20
Steel posts							
Fixed supports	4.84	5.68	1.73	14.1	8.8	15.2	8
Base material support	3.29	4.33	1.91	11.7	0.5	19.1	9
Stiff clay support[a]	2.45	3.19	2.45	6.5	-1.5	19.1	15
Saturated clay support[a]	1.91	2.46	3.09	9.5	-7.5	19.1	23
Sandy loam support[a]	2.57	3.28	2.40	6.1	-1.6	19.1	15

Note: 1 m = 3.3 ft.

[a]Fixed support properties used for end posts.

CONCLUSIONS

Satisfactory full-scale vehicle guardrail or median barrier tests on installations of less than 45.7 m (150 ft) are usually achieved with exceptionally good post and soil conditions. The results discussed here, as established by BARRIER VII simulations with post properties determined by a series of pendulum tests, indicate that barrier failure problems can be expected for severe impacts on short installations with the poorer soil types. Thus, it is recommended that guardrail lengths be not less than 45.7 m unless precautions are taken to ensure the integrity of each post, particularly if the available space behind the barrier is limited. This can be accomplished by the use of concrete footings or greater embedment depths for the posts. For vehicle containment and redirection with barrier lengths of 45.7 m or greater, the end posts should be sufficiently anchored to develop the full strength of the post in the lateral direction, as well as the usual longitudinal anchorages.

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